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Building information modelling for sustainability appraisal of conceptual design of steel-framed buildings

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Abstract

In the construction sector, capturing the building product in a single information model with good interoperable capabilities has been the subject of much research in at least the last three decades. Contemporary advancements in Information Technology and the efforts from various research initiatives in the AEC industry are showing evidence of progress with the advent of building information modelling (BIM). BIM presents the opportunity of electronically modelling and managing the vast amount of information embedded in a building project, from its conception to end-of-life. Researchers have been looking at extensions to expand its scope. Sustainability is one such modelling extension that is in need of development. This is becoming pertinent for the structural engineer as recent design criteria have put great emphasis on the sustainability credentials in addition to the traditional criteria of structural integrity, constructability and cost. Considering the complexity of nowadays designs, there is a need to provide decision support tools to aid the assessment of sustainability credentials. Such tools would be most beneficial at the conceptual design stage so that sustainability is built into the design solution starting from its inception. This research work therefore investigates how contemporary process and data modelling techniques can be used to map and model sustainability related information to inform the structural engineer's building design decisions at an early stage.

The research reviews current design decisions support systems on sustainability and highlights existing deficiencies. It examines the role of contemporary information modelling techniques in the building design process and employs this to tackle identified gaps. The sustainability of buildings is related to life cycle and is measured using indicator-terms such as life cycle costing, ecological footprint and carbon footprint. This work takes advantage of current modelling techniques to explore how these three indicators can be combined to provide sustainability assessment of alternative design solutions. It identifies the requirements for sustainability appraisal and information modelling to develop a requisite decision-support framework vis-à-vis issues on risk, sensitivity and what-if scenarios for implementation. The implementation employed object-oriented programming and feature modelling techniques to develop a sustainability decision-support prototype. The prototype system was tested in a typical design activity and evaluated to have achieved desired implementation requirements.

The research concludes that the utilized current process and data modelling techniques can be employed to model sustainability related information to inform decisions at the early stages of structural design. As demonstrated in this work, design decision support systems can be optimized to include sustainability credentials through the use of object-based process and data modelling techniques. This thesis presents a sustainability appraisal framework, associated implementation procedures and related object mappings and representation systems that could be used to achieve such decision support optimization.

Keywords: BIM, Sustainability, decision support, conceptual design, structural engineering

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List of abbreviation

2D	Two Dimensional
3D	Three Dimensional
AEC	Architectural, Engineering and Construction
BIM	Building Information Modelling
CIMSteel	Computer Integrated Manufacturing of Construction Steelwork
CIS	Construction Integration Standards
IDEF0	Integration DEFinition language 0
IFC	Industry Foundation Classes
ISO	International Organisation for Standards
OOP	Object-Oriented Programming
NIBS	National Institute of Building Science
SD	Sustainable Development
SSE	Steel Sustainability Estimator
STEP	Standard for Exchange of Product Data
RDL	Report Definition Language
WECD	World Commission on Environment and Development
XML	Extensible Markup Language

Chapter 1

Introduction

1.1 Background

The impacts from products of construction and other sectors alike are now generally considered from three angles – economic, environmental and social – based on the triple bottom line concept (Elkington, 1998). The time period of these impacts that suffices sustainability considerations span from the present to the 'infinite' future as spelt out in the Brundtland Report (WECD, 1987). This vast time span has imposed some complexity in the assessment of the sustainability of products (Fiksel, 2003). Researchers have therefore suggested a life cycle approach (Finnveden et al., 2009) to tackling the associated challenges to avoid shifts and overlaps in the product system. These complexities are further compounded in the building artefact because of its peculiar characteristics of large size, fragmentation, long-life span and composition of a variety of contrasting materials. As such, sustainability in the built environment has been difficult to define (Maver and Petric, 2003). Notwithstanding, the construction industry is geared towards contributing to the larger effort of achieving sustainable development through Sustainable Construction (Ding, 2005). The launch of the UK's steel construction sector's sustainability strategy in 2002 is central to the further offshoot of Sustainable Steel Construction (Burgan and Sansom, 2006). The goal of the strategy is to see how steel can be used to deliver more sustainable construction at the design, execution, in-use and deconstruction stages.

To achieve the maximum influence on building cost and impacts in the building life cycle, it is widely acknowledged that the design stage presents the best opportunity to incorporate sustainability measures into the project development process (Ding, 2008; Kohler and Moffatt, 2003). However, tools to inform the structural designer on sustainability at the early phases of design have not been sufficiently explored. With the emergence of BIM, the construction industry is presented with the opportunity of expanding the BIM scope to account for n-dimensional building performance elements such as sustainability (Aouad et al., 2006; Lee and Sexton, 2007).

The construction sector across the globe looks forward to when BIM becomes fully matured and accepted as a medium for presentation of all construction information and transactions. In the UK, a BIM working group was commissioned by the government to examine the construction and post occupancy benefits of BIM for the building and infrastructure market. It was recommended that there should be a structured Government/Sector strategy to increase the uptake of BIM over a five-year horizon (BIM-IWG, 2011). This is geared towards the plan to improve government estates in terms of cost, value and performance. The working group also identified Whole Life Cost and Carbon Performance as the two key variables that are important in decision making process. For correct decisions to be made, timely and accurate information (data) must be available. Likewise, for timely and accurate information to be readily available there must be some efficient and effective decision-support tools. The performance of such tools increases with the degree of the improved IT-base on which it is implemented. This determines the ease and effectiveness of synthesizing the vast amount of unprocessed data usually associated with elements that cumulatively influence building's economic, social and environmental performances.

1.2 Research motivation

Construction has a high economic significance with strong environmental and social impacts (Burgan and Sansom, 2006). The construction industry is a major consumer of both renewable and non-renewable natural resources and at the same time an active generator of pollutants and waste (Ding, 2008). Hence, the construction industry is inevitably concerned about devising means to mitigate these impacts through the ideals of sustainable construction.

The awareness of the need for sustainability in construction is on the increase. This entails quests to balance the sector's economic, environmental and social benefits with the detrimental impacts to the present and future generations. In one of the Institution of Civil Engineers (ICE) priority actions (Figure 1.1) towards green economy, engineers have been called to engage in projects at the inception stage and contribute to the task of balancing Capital and Operational Carbon to minimise whole life emissions (ICE, 2011). It is envisaged that as buildings become more energy efficient, in-use impacts reduce and embodied impacts become significant part of the total (Kaethner and Burridge, 2012). Thus, greenhouse gases (GHG) emission reduction strategies and other building performance optimization techniques such as life cycle costing, energy profiling and lean construction all constitute efforts towards sustainability. These efforts are increasingly becoming IT-based to keep pace with the world's contemporary developments. Also, contemporary IT systems present more effective and efficient performance tendencies as they constitute products of cumulative continual improvements in research (Dawood and Sikka, 2009). This understanding is well demonstrated in the Innovation and Growth Team report on Low Carbon Construction recommending BIM to be mandated for non-domestic building projects in excess of £50m (HMG, 2010).

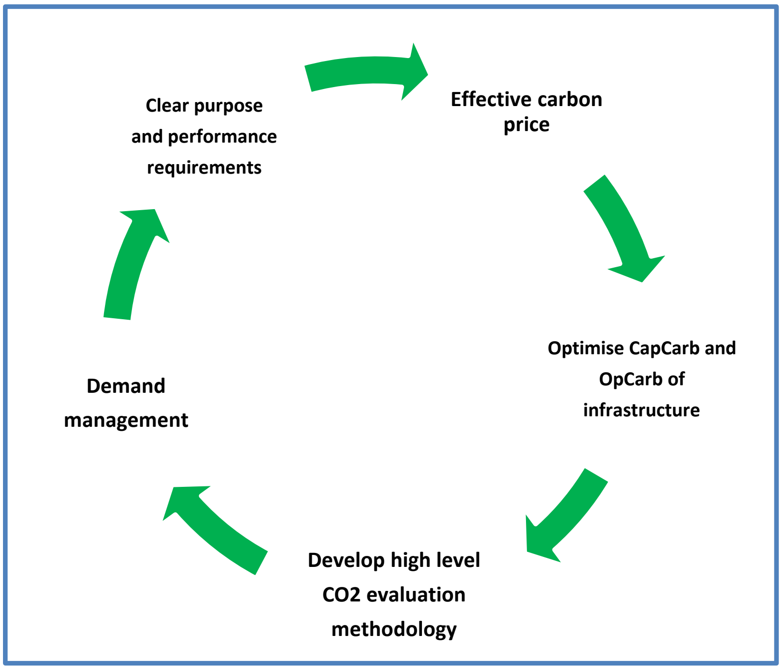


Figure 1.1: ICE priorities for building a sustainable future (ICE, 2011)

More recently, the Government Construction Client Group canvassed for a wider BIM application by recommending all projects to be delivered at BIM maturity 'Level 2' by 2016 (BIM-IWG, 2011). Maturity 'level 2' is characterized by the existence of separate BIM disciplines working towards achieving full collaboration and integrated data management. This recommendation has been further released as part of the Government Construction Strategy by the Cabinet Office in the pursuit of growth in exploiting the potential for public procurement of construction and infrastructure (Carbinet Office, 2011). Selecting best strategic option before detailed design and construction begins can lead to greatest resources savings in infrastructure project. As laid out in ICE Priority 4, It is therefore crucial to develop a high level evaluation methodology for use at appraisal stage of projects to aid investment decisions (ICE, 2011). These premises constitute key motivations for this research work.

1.3 Sustainability appraisal in construction

Despite the existence of many sustainability appraisal systems worldwide the dispersion (diffusion) of sustainability assessment is still low (Berardi, 2011). Berardi asserted that progress in sustainability assessments and sustainability rating systems will help to improve diffusion in the construction sector. This has been demonstrated to some extent by the EU Energy Performance of Building Directive to place energy consumption certificates and plaques in assessed buildings (EC, 2003). Reasons for such low dispersion and unfamiliarity with sustainability performance measures are well-known. Buildings are complex and composed of generally high order products that incorporate different technologies assembled according to unique processes (Ding, 2008). Also, the fragmentation of the industry is bound to introduce diversion of interest and views on issues surrounding sustainability assessment in the sector. Berardi (2011) therefore suggested that building sustainability should be evaluated for every subcomponent, the integration of subcomponents in functional units and assembled systems (e.g. the air conditioning system, the envelope), as well as for the entire building.

While acknowledging the existence of sustainability assessment and energy labeling of building products as approaches to sustainability evaluation of building, they essentially constitute database for sustainability analysis (in *ibid*). This is because the complex nature of the building makes it require a holistic and integrated evaluation system (Ding, 2008). It gets even more complex with requirements extending to the evaluation of social and economic parameters (Fiksel, 2003). This puts the realization of a universally accepted assessment system still far from reach.

Notwithstanding, in recent times, the industry has witnessed the release of a number of international standards related to building sustainability. The key ones of interest are ISO 15392:2008 and BS EN 15643–1:2010 respectively detailing the general principle of sustainability in building construction and the general framework of assessment of buildings. Sustainable buildings are expected to satisfy technical and functional performance requirements while targeting the achievement of economic, environmental and social aspects of sustainability (ISO 15392, 2008). Assessment of these three dimensions may be done separately, depending on scope and must be reported as such. It is also possible to link results from the three sustainability dimensions based on the same functional equivalence (BS EN 15643-1, 2010). This can form the basis for comparing building levels. As awareness and progress towards standardization in the industry keeps improving, researchers have emphasized that it is more useful to include sustainability issues in the early stages of project development (Todd et al., 2001; Ding, 2008; Berardi, 2011; Kohler and Moffatt, 2003). This has a greater tendency to influence the economic, environmental and social performance of projects. It is therefore important to target the design stage for incorporating building performance issues such as sustainability. For contemporary IT development, BIM provides the opportunity for exploiting sustainability among other n-dimensional issues to inform the design process (Aouad et al., 2006; Lee and Sexton, 2007). BIM, currently in a maturing process, entails an information representation system characterized by parametric objects governed by rules of geometry, attributes and relations (Eastman et al., 2008; Tah et al., 2010). Modeling requirements are therefore essential for including sustainability analysis into BIM to aid conceptual design decision making.

Two groups of requirement, sustainability modeling and software implementation, were used to guide this research work. The sustainability modelling requirements based on life cycle criteria identified after Kohler (1997) include:

- *System limit*: The boundaries of a system or product in time and space, within which that system can be affected by or create some effect on some other system/product.
- *Energy and mass flows*: From conception to end-of-life, the flows of energy and mass that constitute the building need to be fully accounted for in sustainability appraisal.

- *Functional unit*: The envisaged performance characteristics (functions) of a product is the driver for creating and eventual 'putting to use' of that product. A common building model has been suggested to be the 'building as-built'.

- *Time constants*: There is a time-scale attached to every component in the building and to the building as a whole. This time-scale relates to cradle-to-gate of various products and typical ranges from nano-second for light to tens or hundreds of year for the building life.

On the aspect of software implementation, the high level requirements modified after Staub-French (2003) and Nepal (2011) are:

- *Generality*: This entails generality in aspects of representation, reasoning and management of project model views and approaches (Haymaker et al., 2004). Stakeholders should find developed system simple enough to understand, as well as being versatile in considering task-specific needs.
- *Formality*: The representation of features, processes, information and concepts need to observe a formal structure interpretable by computer. It should also include attributes and functions that allow for a good degree of automation as necessary
- *Flexibility*: This is a requirement aimed at capturing the satisfaction of a relatively wide range of audience. It tends to reflect the considerations made for user preferences in the operation and manipulation of developed systems.
- *Ease-of-use:* Software systems generally have ease-of-use by target audience as a key requirement. System should be explicit enough for domain practitioners to understand the logical flow of the presentation structure of the system. It is worth ensuring that users do not have to be software programmers to understand the underlying concepts of the system.

1.4 Research Problem

In addition to the challenges associated with defining and quantifying sustainability in the built environment, current sustainability accounts have been based on the completed structure. This apparently compromises the usefulness of sustainability ratings in design-decisions making process. One good way to achieve this is to establish quantitative terms for qualifying sustainability and incorporating it right at the early stages of the project development process to guide decisions as progress is made. Owing to the inherent traditional fragmentation of the industry, it is logical that the various professional platforms think along the lines of their particular responsibilities in the project process with the possibility of collaboratively unifying the different platform-based sustainability ratings at salient project stages. For the structural engineer, tools dedicated to depicting sustainability to inform design-decisions on options are generally lacking. The research therefore seeks to answer the question of ***how process and data modelling techniques can be used to map and model sustainability related information to inform the structural engineer's building design decisions at an early stage***. This work is directed at modelling sustainability as part of the building information development process of steel-framed buildings at conceptual design stage. It is envisage that contributions from this work can serve as an exemplar for structural firms and related information modelling research projects.

1.5 Aim and objectives

The research aim is to investigate how the use of building information modelling technology can influence conceptual design decisions based on the life cycle information and the sustainability of alternative design solutions. This is targeted at quantifying the sustainability of design solutions to inform conceptual design decisions, as an integral part of building information modelling (BIM). To achieve the overall aim, the research objectives have been set as follows.

- Ascertain the challenges associated with contemporary building information modelling and decision-support tools in building design and construction.
- Identify requirements for modeling sustainability implications of alternative design solutions for the building product.
- Establish a modelling framework capturing relationships amongst various factors influencing design decisions based on sustainability considerations.
- Implement a sustainability design-decision-support prototype system based on established framework.
- Validate the system for the suitability of the framework implementation from the point of view of typical design environments for steel structures.
- Evaluate the system on its effectiveness in improving the sustainability appraisal of conceptual design.

1.6 Methodology

A combination of research methods have been used in this work. Commonly employed approaches such as quantitative and qualitative methods, case-studies, model development and evaluation methods (Zave, 1997; Cheng and Atlee, 2007; Runeson and Höst, 2009) are being combined in this research in order to achieve the stated objectives. Review of appropriate literatures in the research area has been carried out in the first stage of the research work. It was further employed as a tool to ascertain appropriate methodologies for achieving the set objectives in stages.

Figure 1.2, which follows conventional research processes in IT, shows the schematic representation of the research methodology being adopted. It is further discussed in line with the objectives.

1. *Ascertain the challenges associated with contemporary building information modelling and decision-support tools in building design and construction.*

   Engineering designs and the overall project development is becoming increasingly IT-based. The development of related support systems has been an active area of research. For the building product, such support systems are being extended to 'n' dimensional issues such as sustainability, accessibility, security etc. A literature review has been carried out to study these aspects of engineering design optimization and information modelling in the project development process. This helped in identifying research gaps associated with modelling building performance issues as part of the design process. The sources of literatures have been textbooks, journals, internet, conference papers, international organisational reports, research thesis etc. Knowledge has also been gathered from workshops, seminars, lectures and conferences.

2. *Identify requirements for modelling sustainability implications of alternative design solutions for the building product.*

   To achieve this objective, review work concentrated on previous and currently completed research works as well as innovations in building life cycle management vis-à-vis progress in sustainable building design and construction. This is directed at gathering the required information about sustainable construction, life cycle information, material cost and information modelling process for mapping into a sustainability building information model. The overall target of this objective is to establish building sustainability requirements for the purpose of developing a modelling framework.

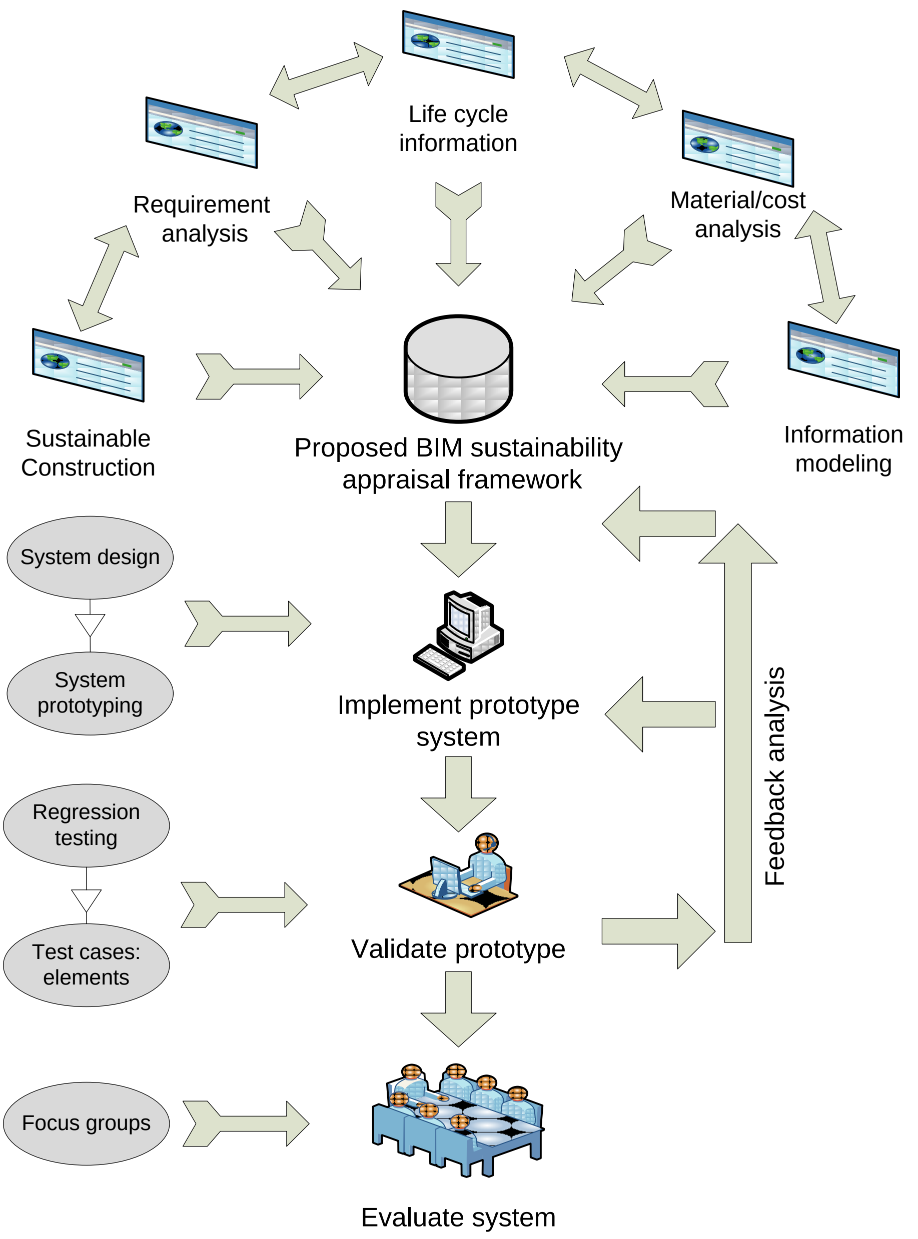


Figure 1.2: Research methodology

3. *Establish a modelling framework capturing relationships amongst various factors influencing design decisions based on sustainability.*

   This objective is targeted at developing a modelling framework from abstractions made from the modelling requirements for building sustainability. This has been gathered from literatures and key related works as well as feedbacks from preliminary experimentation on the implementation of the modelling framework. Also helpful are various modelling technologies and innovations for integrating the information related to the different stages of building life cycle into the early phases of project development. The modelling framework for the research has been drawn to set the stage for the application of identified appropriate modelling technique.

4. *Implement a sustainability design-decision-support prototype system based on established framework.*

   The modelling framework ascertained from the previous objective is the compass that directs and drives the realisation of this objective. The implementation is divided into two major phases in line with the guiding framework. The first phase is to implement the framework in an object oriented environment to an appreciable sophistication of the prototype and secondly to integrate the prototype into a building information modelling process. In this way the prototype could be used to aid the conceptual design process when BIM authoring tools are used in the information modelling process of building design. C# programming language of Microsoft .NET Frameworks was found suitable for this implementation as it allows the easy integration of database systems, report definition languages, web-based formats and existing BIM authoring programmes. The implementation combines object-oriented paradigm with other modelling techniques and algorithms such as feature modelling, sensitivity/risk analysis and multi-criteria-decision analysis to realise this objective.

5. *Validate the system for the suitability of the framework implementation from the point of view of typical design environments for steel structures.*

The prototype is proposed for steel-framed-buildings. Typical software development cycle of continuous testing of system elements and incorporation of analysis from feedback has been employed to validate the various components of the prototype to maturity. The development cycle is iterative and is based on the Rapid Application Development (RAD) model (Figure 1.3) described by Maner (1997).

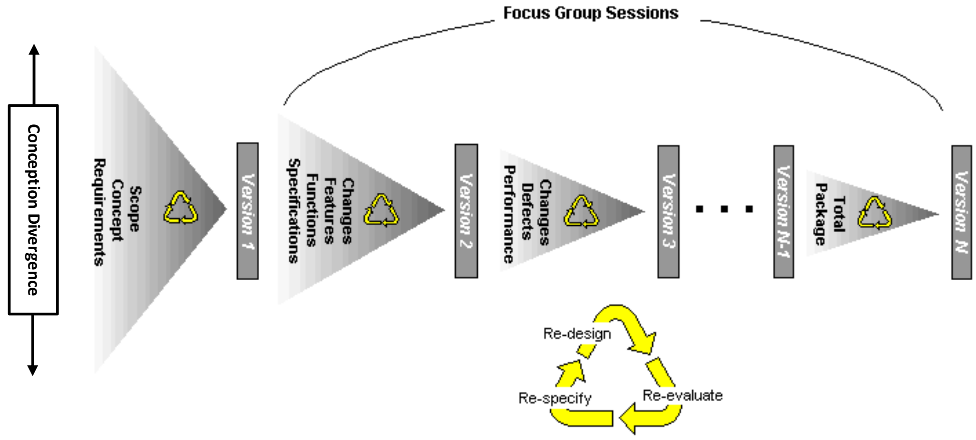


Figure 1.3: Rapid application development using iterative prototyping (Maner, 1997)

The RAD methodology employs cycles of re-specify, re-design and re-evaluate on the prototype system from its conception to when it achieves a high degree of fidelity and completeness. The prototyping process is therefore characterized by increased speed of development and experiences of series of births rather than deadlines. This allows for iterative progressive refinement of the prototype until it becomes the final desired operational system. As an adaptive process, RAD may not exhibit well-defined software development phases but has the advantage of being capable of modelling systems with significant user interface components. It is good for achieving early usability testing and exposing new or unexpected requirements.

To achieve the overall validation of the prototype, case-study research methodology has been employed. This entailed testing the prototype on typical conceptual design exercise to demonstrate how the sustainability requirements and modelling framework have been satisfied in the implementation of the prototype.

6. *Evaluate the system on its effectiveness in improving the sustainability appraisal of conceptual design.*

A number of evaluation methods exist for models developed from this type of research work dealing with information and process modelling. Usually it starts with self-evaluation; then extends to peer-evaluation and finally to organisational or industry evaluation. While self-evaluation may be undertaken by the researcher as the work progresses, a group of carefully selected peer and organisational reviewers have been employed to carry out the later evaluation stages of the building sustainability model. This covers appropriateness, suitability, applicability, ease of understanding and use.

1.7 Research Scope

This research combines the area of sustainability and information technology which are individually vast. It is therefore important to specify the scope of this research with respect to the key aspects relating to building life cycle stage, sustainability dimensions, structural framing options, detail of building elements considered, modeling platform and the implementation scope.

1.7.1 Building life cycle stages

The building life cycle primarily consists of planning and design, construction, operation and end-of-life stages. A Holistic approach requires combining all these stages in sustainability analysis. The early stage of planning and design presents the best period for greatly influencing sustainability related impacts of the building. As such, this research focuses on the conceptual design stage where engineers select best ranked solution among design alternatives. It is at this stage that the usefulness of decision-support tools in informing the design process can be maximized.

1.7.2 Sustainability dimensions

Economic, environmental and social dimensions are the three aspects of sustainability internationally acknowledged. It is possible to carry out separate assessment on each of the three dimensions depending on the scope of the assessment (BS EN 15643-1, 2010). In this research, it is only the economic and environmental dimensions that have been considered. The social aspect is not considered for the following reasons.

- The influence of social factors on conceptual design process of steel-framed buildings is relatively minimal. This is because social benefits of projects have already been envisaged by the client at conception and do not significantly affect alternative steel-framing design options during conceptual design.
- The methodologies for accounting for social dimensions of sustainability are still in their infancy. Also, the author did not find any existing literature on how social aspect of sustainability affects conceptual design iterations.

1.7.3 Structural framing options

The structural framing option in this research is structural steel. Other available options include in-situ concrete and precast concrete. Structural steel was chosen in order provide a focus for the research however; there are possibilities to extend the implementation to account for other framing options.

1.7.4 Detail of building elements considered

There are vast number elements that make-up a building. The degrees of contribution of these elements to the overall building sustainability vary. From the structural point of view, key elements in the structural systems that are accessible for maintenance, re-use and recycling are the most important. This research therefore ignores the substructure in the sustainability analysis. As such elements considered within the structural framing system include columns, beams, structural floor systems, cladding systems and roofs.

1.7.5 The implementation scope

The scope of implementation is limited to developing the prototype as proof of concept rather than completeness. The research is therefore based on the implementation of an incomplete software system capable of fulfilling the desired research objective of demonstrating the sustainability modelling framework. However, the possibility of improving the prototype in terms completeness and detail has been considered in the implementation.

1.8 Structure of thesis

The thesis is made up of seven chapters and appendices.

- ***Chapter 1: Introduction***

  This chapter presents the research background and motivation, the research problem, the research aim and objectives, and the research methodology. The scope of the research is also stated here.

- ***Chapter 2: Sustainability decision-support tools and information modelling***

  In this chapter, sustainability in the building design process and the role of information technology in informing building design were examined. Also included here are an overview of decision support tools and challenges associated with sustainability-related tools in informing contemporary design process. This chapter covered the identified challenges in sustainability decision support and the existing gaps.

- ***Chapter 3: A proposed BIM sustainability appraisal framework***

  This chapter presents the development of the sustainability modelling framework and its components. It covers the identified requirements for carrying out the implementation of the sustainability modelling framework, the selection process of the sustainability indicators and their underlying theories, modelling databases and the process of selecting favourable design. The implementation environment, encompassing design aspects and computer programming, is also discussed.

- ***Chapter 4: Developing the sustainability appraisal prototype***

  The actual implementation of the sustainability modelling framework is discussed in this chapter. It is presented under representation of the modelling framework, generation of the prototype and the operation of the prototype. Descriptions of the prototype and its components have been given under these three sub-headings.

- ***Chapter 5: Example case study - using the prototype***

  In order to demonstrate the usefulness of prototype and its efficacy, a case study is presented in this chapter. The case study is carried out on a 3-storey steel-framed office building with three design options for comparison. In addition, IFC model of a 2-storey building was also considered.

- ***Chapter 6: Evaluation***

  This chapter presents the evaluation results of the prototype application. It discusses the objectives of the evaluation process and the evaluation methodology. It also presents aspects related to the development of the evaluation questionnaire and finally discusses the results of the evaluation.

- ***Chapter 7: Conclusion and recommendations***

  In this chapter the main research findings and the future application of these findings are presented. The chapter also states the final conclusions and the main research contributions to knowledge.

1.9 Summary

This chapter laid the foundations for the research work reported in this thesis. It presented the research background, formulation of the research problem and the aim and objectives. An insight into the research methods employed was given including the definition of the research scope and the thesis structure.

Chapter 2

Sustainability decision-support tools and information modelling

2.1 Introduction

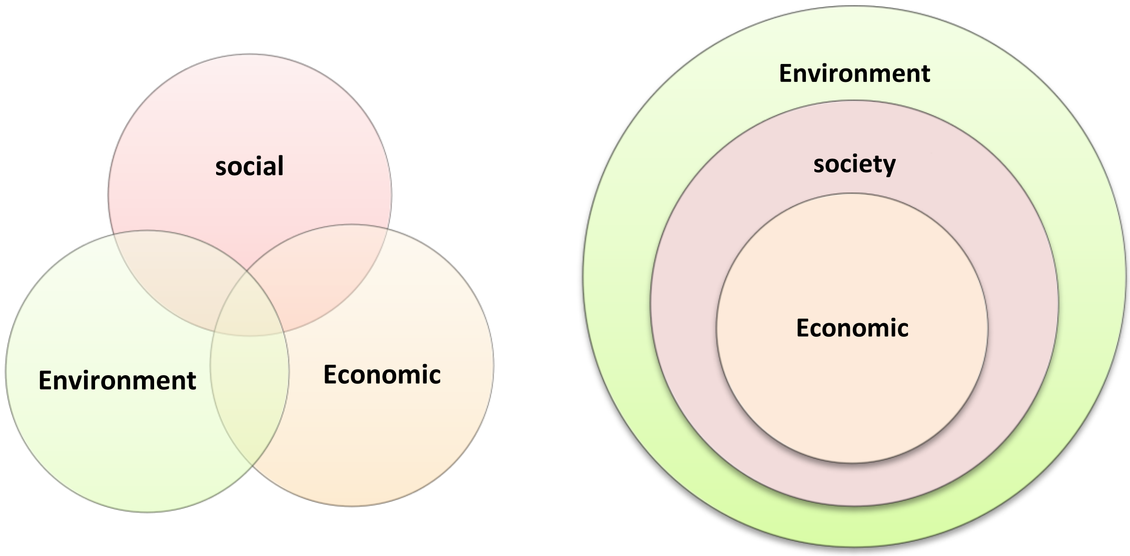
This chapter presents the review of sustainability in buildings, sustainability decision support tools and related information technology issues. It examines research papers, reports and standards on these subjects. The chapter concludes with an attempt to outline the challenges faced with sustainability decision support tools in informing contemporary design process.

2.2 Sustainability and the building design process

The quest for sustainable development is a world-wide concern and comprised of various facets of human endeavour. Construction is one of such facets where sustainability needs to be ensured. This is because construction artefacts constitute key performance indicators of human advancement. In turn, building as an artefact serves as where most of human activities are domiciled. Despite efforts of best practice towards improvements in the building design and construction process, the impact of already built houses, those to be built in the future and related human activities on sustainable development still remain a cause for concern. As such, sustainability is becoming an important consideration in the construction sector. The construction sector is getting increasingly IT-based. This places a demand on contemporary IT implementations to incorporate sustainability issues into the information modelling process for building design and construction. To draw knowledge from existing works, the sub-sections examine the broad nature of sustainable development, identify the major contributors to sustainable development and how sustainability is defined and pursued in the construction sector.

2.2.1 The broad nature of sustainable development

Economic, social and environmental aspects have been globally recognised as the three key contributors to sustainable development (SD). The empirical relation among these three elements is popularly presented from two angles: the triple bottom line approach where the elements form unions and the constrained approach of the environment being the super-set of the other two (Figure 2.1). It is when development spreads uniformly across these three interdependent elements without compromising the health and safety of the present and future generation that it can be said to be sustainable. The UK sustainable development goal states that (DEFRA, 2005) "*the goal of sustainable development is to enable all people throughout the world to satisfy their basic needs and enjoy a better quality of life, without compromising the quality of life of future generations*". This is not different in interpretation with global view and it is aimed at living a quality life today without ultimately jeopardizing the well-being of future generations.



(a) Triple bottom line **(b) Constrained development**

Figure 2.1: The three elements of sustainable development (Pepper, 2007)

Spence and Mulligan (1995) noted the growing understanding of SD as a single global system and mentioned that it has the combined dual aim of accelerating human development globally; while at the same time avoiding the depletion of resources and biological systems of the planet to such an extent where future generations will be impoverished. This also corroborates the statement from the "Brundtland Report" of the World Commission on Environment and Development (WCED, 1987), which is widely acknowledged as the genesis of the term "Sustainable Development".

In recent times, key sectors for SD have been identified and strategies for improvement are on high scale. One of such sectors is the construction industry which has high economic significance; and strong environmental and social impacts (Burgan and Sansom, 2006). Internationally, this has earned the attention of policies from the Organisation for Economic Co-operation and Development (OECD) made up of some of the foremost developed countries

(OECD, 2003). It suffices also to mention here that international efforts to reduce global warming over the last decade have consequently attracted most countries to joining the international treaty – the United Nations Framework Convention on Climate Change (UNFCCC, 2010). This has given rise to the Kyoto Protocol negotiated in December, 1997; and the 2009 Copenhagen Accord on tackling climate change through the reduction of the emission of greenhouse gases (GHG), which are all cumulative global efforts directed at sustainable development.

In the UK, the priority the Government places on balanced development has led to a number of promotional activities, through the UK Department of Environment, Food and Rural Infrastructure (DEFRA) and Department of Environment Transport and the Regions (DETR). Their efforts have produced the publication of a number of reports including the series "Sustainable development indicators in your pocket" and "A Better Quality of Life". These reports give account of various sustainability initiatives, targets and government actions. The UK strategy seeks to pursue four key elements: social progress which recognises the needs of every one; effective protection of the environment; prudent use of natural resources; and maintenance of high and stable levels of economic growth and employment (HMG, 1999). More recent works on SD have further developed guiding principles for the UK.

(a) Guiding principles for sustainable development

The vast issues surrounding SD demands a systemic approach if progress needs to be measured against some developed performance indicators (HMG, 2005). As such five guiding principles have been drawn to help streamline actions in the UK. These principles are as follows.

1. *Living within environmental limits*

    Respecting the limits of the planet's environment, resources and biodiversity – to improve our environment and ensure that the natural resources needed for life are unimpaired and remain so for future generations

2. *Ensuring a strong, healthy and just society*

    Meeting the diverse needs of all people in existing and future communities, promoting personal wellbeing, social cohesion and inclusion, and creating equal opportunity

3. *Achieving a sustainable economy*

    Building a strong, stable and sustainable economy which provides prosperity and opportunities for all, and in which environmental and social costs fall on those who impose them (polluter pays), and efficient resource use is incentivised

4. *Using sound science responsibly*

    Ensuring policy is developed and implemented on the basis of strong scientific evidence, whilst taking into account scientific uncertainty (through the precautionary principle) as well as public attitudes and values

5. *Promoting good governance*

    Actively promoting effective, participative systems of governance in all levels of society – engaging people's creativity, energy and diversity

These principles are dependent on one another. The first two principles could be reached from achieving the latter three which should be pursued jointly since a sustainable economy can only thrive well with good governance that also support advancement in science and technology to achieve balanced progress.

(b) Sustainability indicators

Owing to the vast nature of issues in SD, performance indicators have been developed to enhance the assessment of progress that may have been achieved overtime. The indicators fall in line with economic, social and environmental aspects of SD. The measurable indicators have been developed based on nationally and international considerations in the UK (DEFRA, 2005). Generally, eleven of the indicators that appear to have some relationship with the construction industry and the building sector are listed in Table 2.1. These indicators are associated with the various phases of the building life cycle – from material mining to end-of-life.

Table 2.1: Key indicators of sustainable development

S/No	Indicator main category	International parameters
1	Greenhouse gas emissions	CO_2 and other GHGs
2	Electricity generation	Renewable energy
3	Resource use	Domestic material consumption; Energy consumption; Water abstraction
4	Waste	Municipal waste generation, recycle percentage and composting
5	Natural resources	Bird population; Agricultural inputs; protected areas; Fish landings; Emissions of air pollutants;
6	Economy and population	Economic output; Total investment; Social expenditure; Demography; Household size
7	Society	Crime
8	Employment and poverty	Employment; Childhood poverty; Young adults
9	Education	Education
10	Health and mortality	Health; Smoking; Obesity; Road fatalities;
11	Social Justice/Environmental quality	Air quality and health; Slums

2.2.2 The major contributors to sustainable development

The construction industry has been recognised as one of the key sectors with significant impact on sustainable development (Bakens, 2003; SFC, 2008). It is one of the largest employer of labour and a pillar of the domestic economy of any nation. The Egan's report of 1998 noted that construction in the UK contributes an equivalent of about 10% GDP and employs about 1.4 million people (Egan, 1998). More recent reports on the sector estimates workers to be over 2 million engaged in over 300,000 businesses and its worth to be currently £110 billion per annum with output at 7% of GDP less building whole-life economic contributions (Carbinet Office, 2011). On the contrary, the construction sector has also been noted to be one of the highest contributors to environmental pollution and extraction/use of nature's resources – thus taking almost as much as it is giving. This makes it imperative to develop means of ensuring that the ideals of sustainability are upheld in the industry. Other key areas that matter on issues of sustainable development are Government, Oil and gas, Manufacturing, Transport and Aviation, Banking, Business and Markets amongst others. In all, the importance of the construction industry cannot be over emphasized as it is involved in providing services in the form of structures and infrastructures for the other sectors to operate.

The construction industry is probably the world's largest single employer and has a considerable economic contribution to development. According to UNEP (UNEP, 2003), Construction is the largest industrial sector in Europe and in the United States and contributes 10-11% and 12% respectively of GDP in these two continents. It represents 2-3% of GDP in developing countries and also accounts for over 50% of national capital investment in most countries. The construction industry provides around 7% of world employment (28% of industrial employment) with a workforce of about 111 million world-wide.

2.2.3 Sustainability in building construction

Views on what actually constitutes sustainable development are varied (Kua and Lee, 2002; Fiksel, 2003), however many of such views are built on the three cores of economic, environmental and the social foundations of human growth. These three aspects summarise the intrinsic relationship sustainable development has with the construction industry and more specifically the building (Figure 2.2). Environmental sustainability may be achieved through the protection of resources and the ecosystem. Long-term resource productivity and low use cost can contribute to the economic aspects while the building also serves as source of contribution to health, comfort, social and cultural values of the society.

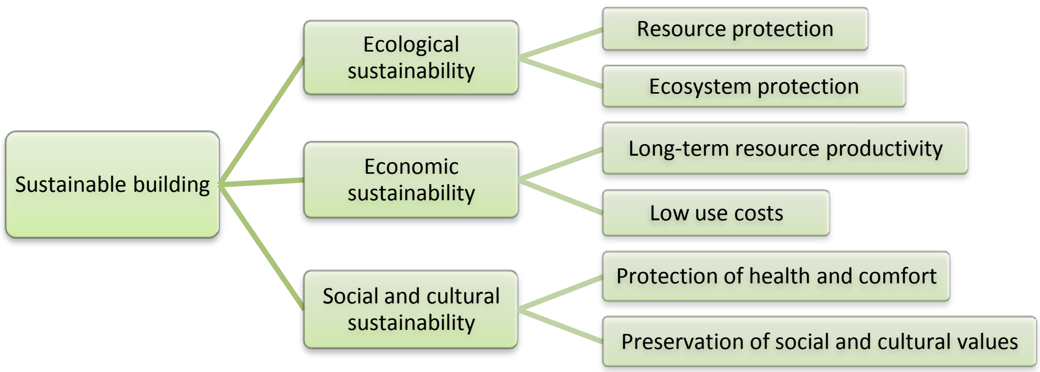


Figure 2.2: Three dimensions of sustainable building (Kohler, 1999)

Figure 2.3 which is a best practice illustration of the concept of sustainability assessment further reflects the various important elements in building sustainability. It combines clients requirements, regulatory requirements, functional requirements, technical requirements with those of the environment, economic and social elements for the building. Integrated building performance encompasses environmental, social and economic performance as well as the technical and functional performance which are intrinsically related to each other (BS EN 15643-1, 2010). The building sustainability arm of European Committee for Standardization (CEN/TC 350) is working on ways to standardize aspects related to assessment procedures and communication of results from defined indicators.

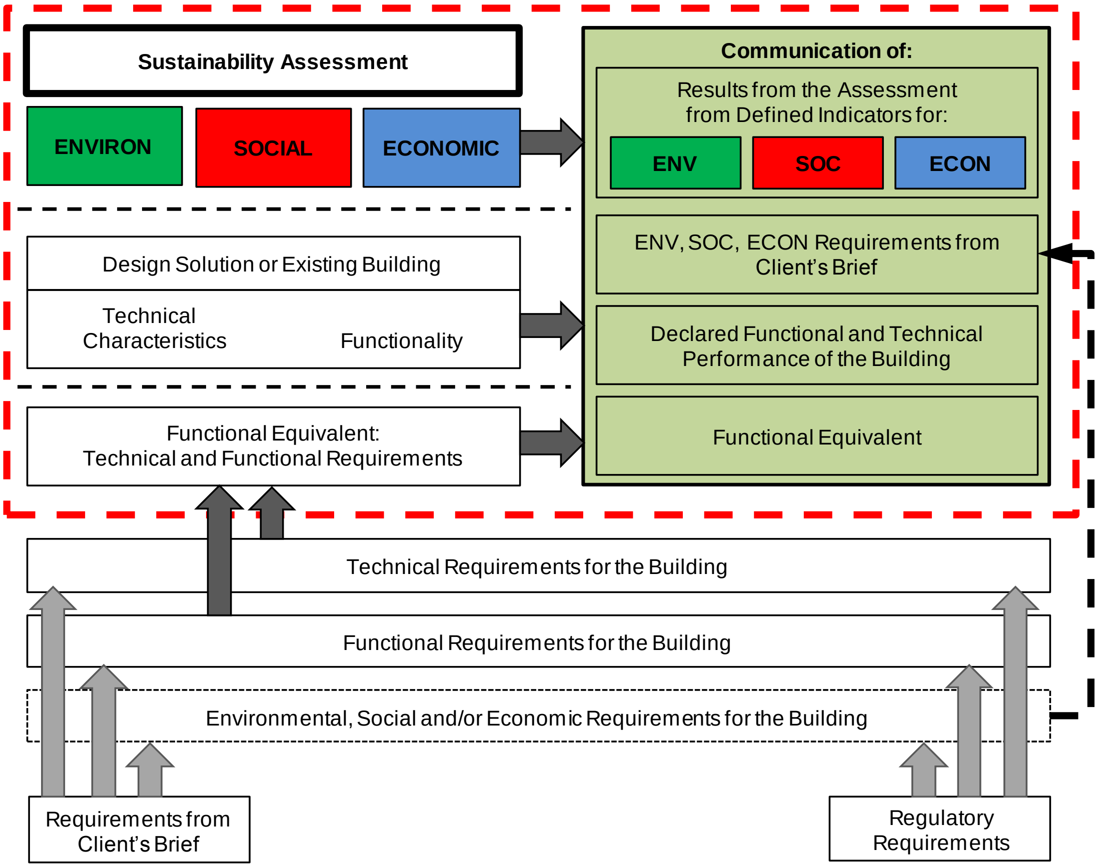


Figure 2.3: The concept of sustainability assessment of buildings (BS EN 15643-1, 2010)

2.2.4 *Sustainable steel construction*

Improving sustainability in steel construction is the focus of efforts from the steel industry to contribute to sustainable construction similar to other construction sectors. In response to these developments, the British Steel

Construction Association (BCSA, 2010) established a sustainability charter to develop steel as a sustainable form of construction in terms of economic viability, social progress and environmental responsibility. The theme of the charter is to develop and publish key performance indicators to benchmark sustainability in steel construction and encourage members to monitor and measure their own progress against 12 requirements. Some of these requirements include the mandatory adoption of a published sustainability policy, monitoring of progress against specific management targets, use of environmental impact assessments and the use of an accredited quality management system (QMS) to BS ISO 9001. Measuring sustainability in the built environment has been an area of active research owing to the variability of performance indicators, life cycle information, system boundary limits, and the definition of the functional unit across regions.

For steel, sustainability considerations has been geared towards minimizing waste during construction; adaptation to flexibility and life-extension during the structure's use; and ensuring materials are recovered and recycled or reuse at the end-of-life phase (Burgan and Sansom, 2006). Steel has a good potential for meeting such sustainability ideals because of the use of standardized components and connections; advanced product and fabrication technology; and sophisticated assembly and construction techniques (in *ibid*). An overview of the sustainability advantages associated with steel as a construction material is given in Table 2.2. However, to successfully incorporate sustainability considerations in full, all these aspects need to be well thought out and planned during the design stage.

Unlike already established design criteria such as serviceability limits states, sustainability issues are still essentially abstract and challenging to deal with during planning and design. This research work therefore proposes a framework for the quantification of sustainability to guide the engineer's early design iterations. This will help to create awareness of sustainability measures among designers and promote their application to guide the design process. Thus, a record of the sustainability measure associated with design solutions of buildings provided by the structural engineer will also be useful for information purposes.

Table 2.2: Attributes of steel in sustainable construction (Widman, 2005)

Attribute	**Comment on steel construction**
Usability	Steel construction is prefabricated in efficient factory processes with minimum use of resources, and enables long span, high–rise and flexibility
Speed	Steel structures are installed rapidly on site which reduces local disruption
Weight	Steel structures are light, and therefore efficient on materials, energy, transports and emissions. The low weight also enables vertical extension and optional location.
Waste	Steel construction is very material efficient generating low amounts of waste, and most of the waste is recycled
Performance	Steel is a high performance, dimensionally accurate material, produces with modern computerised technology
Logistic	Steel structures are delivered to site 'just in time' for installation, and can be produced locally
Durability	Steel structures have very long design life and high quality remains
Health	Steel construction is dry construction, low emitting materials, controlled and safe process and leads to high quality architecture
Recyclability	All steel can be recycle, steel is recycled without quality losses, and all steel has recycled content
Reusability	Steel buildings or components can be dismantled and reused.

2.2.5 Assessing building sustainability

Uher (1999) identified the development of key principles/indicators as one of the main areas of research in sustainable construction. He suggested energy consumption and land used for projects as two ideal absolute indicators. This is based on the premise that construction works are highly energy intensive and land is always required for expansion to accommodate construction activities and products. However, the implementation and strategy for employing such indicators in assessing sustainability was not addressed and, in the authors' opinion, remains a challenge. Notwithstanding, the contemporary progress made in the development of tools for building's environmental performance assessment is worth mentioning despite their inadequacy of being used for sustainability assessment (Haapio and Viitaniemi, 2008). Quite a number of countries have developed building environmental performance assessment tools tailored to their local conditions. Some of these tools also have the potential of being applied internationally as reviewed in (Ding, 2008; Haapio and Viitaniemi, 2008). The tools have been classified into three groups: product comparison; decision support and whole building framework. The more widely used tools such as – Building Research Establishment Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED), developed in the UK and USA respectively, belong to the third group which portrays a more comprehensive application than the other two.

While applauding the efforts of various research establishments in developing building environmental performance assessment tools, there have also been some criticism warranting further research. In addition to complexity and regional variations, Ding (2005; 2008) hinged the development of a sustainability index on the critique that these tools are difficult to apply at the early project phases and largely ignore the economic aspect of sustainability. Haapio and Viitaniemi (2008) also pointed out the difficulty with subjectivity in indicator assessment from the user's point of view - as architects and engineers may consider indicators differently. In the authors' opinion, this triggers an interesting point – all building professionals ought to be responsible for the information on sustainability of their design specification and materials as they do for the integrity of their designs. As depicted in Figure 2.4, there is need for various professionals to consider sustainability issues in addition to design requirements and code constraints at the various stages of project execution. This premise remains one of the key motivations for this research work.

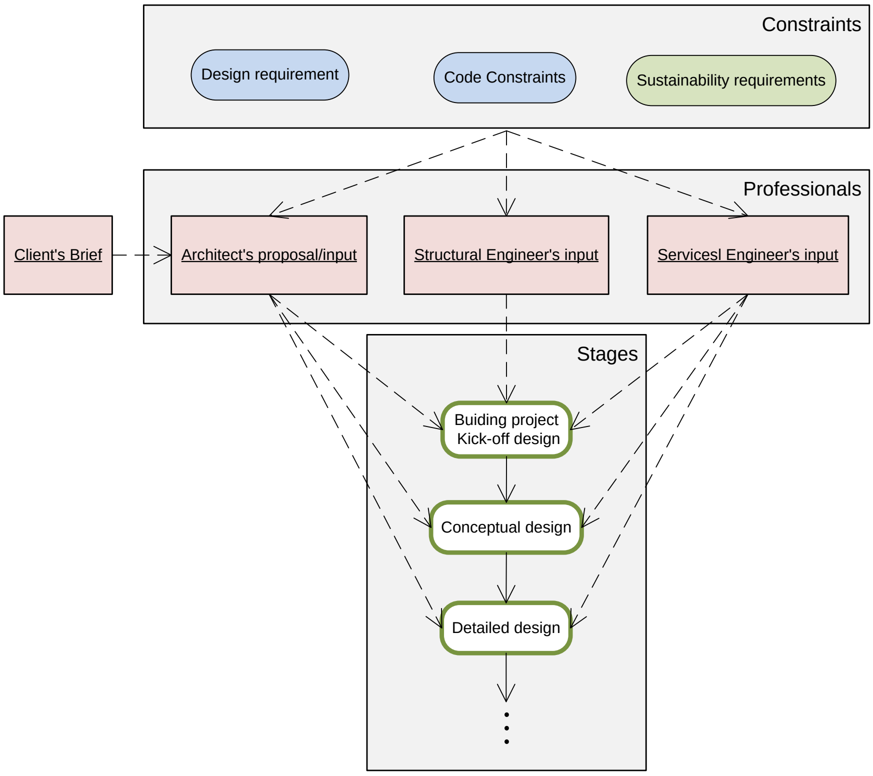


Figure 2.4: Incorporating sustainability into project constraints

2.2.6 *Building design and considerations for sustainability*

Among the lifecycle stages of the building product, the design stage presents the best opportunity to influence costs and impacts (Ding, 2008; Kohler and Moffatt, 2003). This makes targeting the design stage for incorporating building performance issues such as sustainability important. However, the design process for sustainable buildings remains mostly undefined and is reinvented on each project (Magent et al., 2009). For the structural engineer, the context of sustainable construction is associated with the design of structures for sustainability over the entire life cycle of the building. Sarja (2009) suggested a new structural engineering approach of integrated life cycle design (lifetime design) capturing financial and environmental costs. Financial cost is depicted by life cycle costs as present value or discounted annual cost entailing manufacturing, construction, maintenance, repair, changes, modernization, rehabilitation, re-use, recycling and disposal. Environmental costs, on the other hand, encompass non-renewable natural resources (materials and energy) and the production of air, water or soil pollution. Integrated life cycle design targets the fulfilment of multiple requirements of users, owners, and society in an optimised way during the entire life cycle of a building or other facility. To limit the number of parameters used for final sustainability decisions in optimizing lifecycle quality, Sarja aggregated the numerous complex design parameters into four:

(i). Life cycle functionality
(ii). Life cycle costs
(iii). Life cycle ecology (environmental costs)
(iv). Life cycle human conditions

Similarly, in this research the sustainability indicators chosen for developing the sustainability modelling framework has been aggregated to economic and environmental aspects in similitude to (ii) and (iii) above. The other two, functionality and human conditions largely relates to issues of structural integrity and social sustainability which are outside the scope of this work.

2.3 The role of information Technology in building design

The fragmented nature of the AEC industry is linked to the complex and unique nature of the building product which requires the participation of individual/groups from distinct professional platforms. These professional platforms, however, are not independent as their specifications and designs must accommodate, interact and relate with one another throughout the building's life cycle. The drive for effectiveness and efficiency in managing the inter-dependence among the platform has given rise to principles such as concurrent engineering, collaborative engineering, distributive collaboration etc in the AEC industry. In all these, IT plays the key role of being the kernel for modelling, storing, exchanging information/data within and across platforms. Information probably remains the most invaluable construction 'material' that must be shared by stakeholders in the industry (Tolman, 1999). Dawood and Sikka (2009) further assert that the construction industry is information-based by nature. The role of international standards, open formats and product models such as IFC, gbXML, etc in enhancing the management of information in the industry cannot be over-emphasized. In overcoming the associated shortcomings with AEC information management, researchers, have had the vision of capturing all the information embedded in the building product in a single information model. This has developed gradually, improving in efficiency and degree of application overtime. The subsections give accounts of some vital applications in IT and their significance to this research.

2.3.1 3D Modelling and CAD

The efforts of first generation (1970's) of 3D modelling, known as Solid Modelling, produced the boundary representation approach (B-Rep) and Constructive Solid Geometry (CSG) (Eastman et al., 2008). B-Rep used Boolean operations (union, intersection, and subtraction) to define shapes whereas CSG assesses a final shape from a tree of operations and algebraic expressions. These approaches could be used to develop engineering assemblies such as engines, process plants or buildings as they supported 3D facetted and cylindrical object modelling based on attributes. Early CAD systems improved on the capabilities of these approaches in the fields of Mechanical, aerospace, building and electrical product design. This allowed for the improvement of early concepts of product modelling, integrated design analysis and simulation but was often limited by the available computing power. These early efforts form the foundation of modern parametric modelling.

2.3.2 Parametric modelling

A mixture of university research and industry development on the extension of B-rep and CSG yielded object-based parametric modelling capabilities developed for mechanical systems design (Eastman et al., 2008). It basically entails defining and controlling shape and property instances according to hierarchy of parameters at assembly, sub-assembly and individual object levels. Parameters such as distances, angles, and rules (attached to, parallel to, distance from) are used to define objects. The parameters help the system in checking and updating details of objects when instantiated during design activities and to alert users if the associated parametric conditions have not been satisfied.

Unlike the traditional CAD systems based on lines where users need to correct every single related detail manually, a parametric system has the ability to automatically adjust to changes. Parametric systems automatically correct or modify every related detail of a change made to a particular aspect of a model. This is a very vital productive feature of parametric modelling. Current building information modelling tools are essentially parametric models of the building artefact composed of predefined objects and object families with properties, behaviour and rules.

2.3.3 Building information modelling

The AEC industry is now conversant with BIM due to the wide campaign for international acceptance as a medium for construction related transactions. It is forecast that drawing production-focused computer aided drafting (CAD) and the next generation of IT will involve processes of generating, storing, managing, exchanging and sharing of building information in an interoperable and reusable way (Cruz, 2008). Though the scope is yet to be fully defined (NIBS, 2007), its benefits in project implementation and information management are envisaged to be significant. BIM has the tendencies for continuous expansion to closely mimic, as much as possible, the vast amount of information embedded in typical building project.

To ensure a clear articulation of the levels of competence expected in the BIM adoption process with supporting standards and guidance, a BIM maturity model (Figure 2.5) has been devised in the UK. It was initially developed by Bew Richards in 2008 but now receiving support from the Government Client Group on how it can be applied to projects and the contract industry (BIM-IWG, 2011). The model defines levels from 0 to 3 in order to categorize types of technical and collaborative working for a concise description and understanding of processes, tools and techniques to be used. This model creates a clear and transparent view of BIM with respect to the building supply-chain for the client's understanding and progress made to-date in construction IT applications. The world is believed to be currently operating at maturity Level 2 where managed

3D environment is held in separate BIM disciplines and with possibility of holding and managing 4D programme data as well as 5D cost elements.

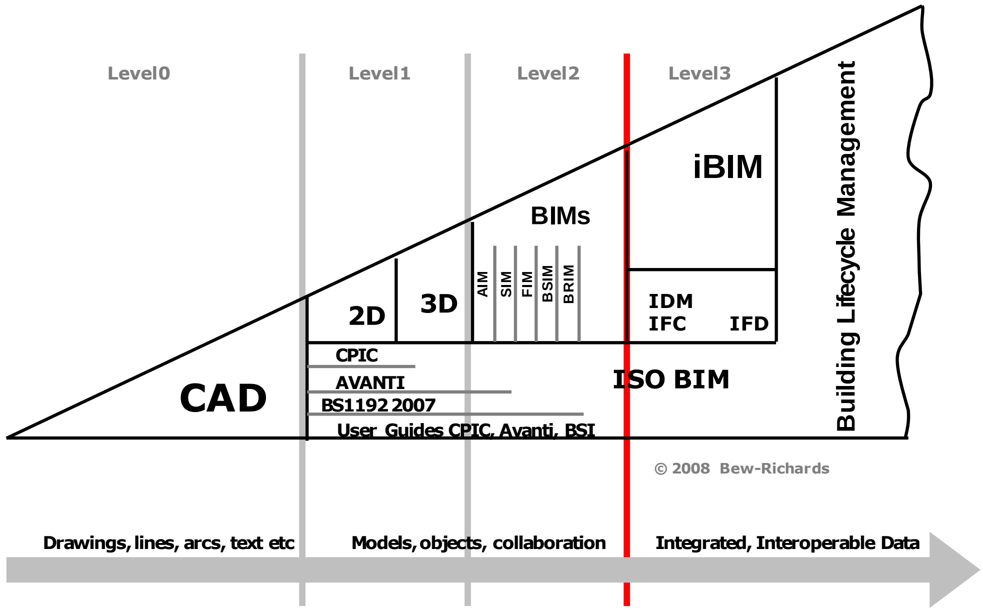


Figure 2.5: BIM maturity levels (BIM-IWG, 2011)

Thus, the possibility of expanding the BIM scope has already been demonstrated by researchers in various plausible extensions. An example is the multi-dimensional computer model (3D to nD modelling project) developed by researchers at Salford University, United Kingdom. The project aims to facilitate the integration of time, cost, accessibility, sustainability, maintainability, acoustics, crime and thermal requirement into the modelling of building information (Lee et al., 2006). Modelling nD aspects is demanding and involves extending the building information model to incorporate the various building life cycle design information which are vast and cut across the different building professional platforms. This warrants issue-specific approach; hence researchers have begun tackling specific aspects or components. In the construction stage of the building lifecycle, efforts to fuse 4D technology (construction scheduling) with BIM for better construction performance are also underway (Hu et al., 2010; Zhang and Hu, 2011). Disaster preparedness aspect in the building operation phase is geared towards improving training games by modelling hot dynamic conditions and the building behaviour over time in the event of fire (Ruppel et al., 2010; Ruppel and Schatz, 2011; Tizani and Mawdesley, 2011).

In the planning and design stage, the benefits of the early incorporation of sustainability principle in guiding project decisions and design iterations have been well emphasized (Kohler and Moffatt, 2003). One area of challenge has been the development of standard sustainability tools to guide professionals in making conceptual design decisions among alternative solutions. Although a number of sustainability assessment tools exist, it has been difficult for engineers to apply them to conceptual design iterations via the emerging BIM process. The Building Research Establishment Environmental Assessment Method (BREEAM), used in the UK, is yet to be incorporated into BIM. It is currently being used to guide project development and to rank buildings (design, construction and use). In the US, research efforts to incorporate Leadership in Energy and Environmental Design (LEED) criteria into BIM tools have been on-going. Nguyen et al (2010) has attempted using BIM to evaluate sustainability of architectural design by storing the LEED criteria indicators as project parameters in Revit Architecture software. These parameters are extracted when applied to a project to compute the maximum possible LEED ratings. While this work targets architectural designs, it is limited to the LEED sustainability parameters and will not be of direct benefit to the structural engineer’s conceptual design iterations. The tendencies of subjectivity associated with different professional assessing sustainability indicators have been noted by Haapio and Viitaniemi (2008). This calls for building professionals to start thinking towards the direction of being responsible for the information on sustainability of their design specifications and materials as they do for the integrity of their designs.

2.3.4 Data exchange

The building design process uses as well as generates huge amount of information. The fact that no single computer application can support all the tasks associated with building design and production necessitates the need for the exchange of information within and across design platforms. The seamless and interoperable transfer of information in the AEC industry has been an area of great concern and active research.

Early exchange formats, such as DFX and IGES, were file-based and could only transfer geometry (Eastman et al., 2008). Later on in the 1980's; the EXPRESS data model was developed via ISO and Industry-led efforts to support product and object models. The EXPRESS language has multiple implementations including text format and is machine readable. More recently developed formats for file exchange include Structured Query Language (SQL) and eXtensible Markup Language (XML) implementations.

Currently the two main building product data model based on EXPRESS language include the Industry Foundation Classes (IFC) and CIMSteel Integration Standard Version 2 (CIS/2). IFC is an open format for building planning, design, construction and management and CIS/2 for structural steel engineering and fabrication.

2.4 Sustainability decision-support tools and building design

Since sustainability covers economic, environment and social dimensions of development, tools that aid sustainability decision making in the building design process are numerous. They are best discussed in line with the three dimensions. This is because existing tools rarely combines the three sustainability dimensions in assessment. Also, there are varying level of maturity that has been achieved with the various categories of tools. Although economic-related tools seem to be the oldest, environmental-related tools appear to be more researched in recent times. Tools used for assessing social sustainability are generally the least matured.

2.4.1 Social sustainability decision-support tools

Tools for the assessing social aspect of sustainability are few in the construction sector as a result of the ambiguities surrounding the definition social elements required for sustainability assessment (Adetunji, 2005). The reasons for such ambiguities go beyond issues relating to large number of stakeholders involved in construction or affected by construction artefacts. It basically stems from the fact that social assessment methodologies are still in their infancy (Kloepffer, 2008). According to Kloepffer, the major challenges associated with social sustainability assessment seem to be the following:

- How to quantitatively relate existing indicators to the functional unit of systems
- How to obtain specific data for regionalized social life cycle assessment
- How to decide between many potential indicators (most of them qualitative)
- How to properly quantify all impacts related to social sustainability
- How to evaluate and compare results from social assessments.

Some of the above challenges are still encountered in the efforts to establish social sustainability standardization in the construction industry. Lessons from best practice stipulate that social dimension should concentrates on the assessment of aspects and impacts of a building expressed with quantifiable indicators. (BS EN 15643-3, 2012). These indicators are represented through eight different categories which include accessibility, adaptability, health and comfort, loadings on the neighbourhood, maintenance, safety/security, sourcing of materials and services and stakeholder involvement. Weidema (2006) appears to have summed these categories into one, human well-being, and suggested that it should be measured in terms of Quality Adjusted Life Years (QALY). QALY is yet to be widely used for social sustainability assessment in the construction industry. The closest to this, is the development of a disability adjusted life-year (DALY) model to assess human health damage due to construction dust (Li et al., 2010). The DALY model is part of a proposed LCA-based environmental impact assessment model for construction processes aimed at helping contractors in selecting environmentally friendly construction plans.

2.4.2 Economic sustainability decision-support tools

For the assessment of economic sustainability, life cycle costing (LCC) appears to be the main and widely used tool for analysis (Swaffield and McDonald, 2008; Chiurugwi et al., 2010). Although LCC (the sum of all costs over the life of a structure) is old and can be traced back to the early 1930s (Wubbenhorst, 1986; Christensen et al., 2005), its methodologies are yet to be standardized (Kloepffer, 2008). In a survey of LCC literatures on infrastructure design, Christensen et al (2005) noted that the techniques employed in LCC range from application of standard engineering economic principles, mathematical programming techniques, sensitivity analysis to risk and multi-attribute analysis. In addition to LCC, the international standard on the assessment of economic performance of buildings identified 'financial value' over the building life cycle as another approach (BS EN 15643-4, 2012). In this approach, discounted revenue is subtracted from the cost over the building life cycle.

There are a few research works on the application of LCC in construction IT. Some of these include Building Life-Cycle Cost computer programme and Life cycle costing integrated system.

(a) Building Life-Cycle Cost (BLCC)

BLCC computer programme was developed by the National Institute of standards and Technology (NIST) under the sponsorship of the federal Energy Management Programme of the U.S. Department of Energy (NIST, 2010). It has been in use since the 1970s to evaluate building-related renewable energy/energy conservation projects and also water conservation project. The first version, BLCC4, was DOS-based. The windows-based version, BLCC5, has been improved to its current version, BLCC 5.3-10 as at 2012. BLCC5 is a Java-based programme with an XML file format containing a user's guide and six energy/water-related modules tailored to the United States of America's infrastructure development rules.

(b) Life cycle costing integrated system

The early works on life cycle costing integrated system was sponsored as part of an EPSRC-funded research collaboration project between Robert Gordon University, Glasgow and the University of Salford, Manchester. The developed system is a computer integrated environment that provides a framework /mechanism for collecting and storing LCC data for a simplified application in analysing building elements (Bakis et al., 2003). The system is made up four basic components: Resource Database, Design Tool, Management Tool and the project Database. The Resource Database stores the performance and cost data used for the Life Cycle Costing estimations; the Design Tool uses the stored information to assist the designer in selecting the most appropriate LCC option of building element; and the Management Tool assists the facilities manager in the LCC-aware management (maintenance tasks) of buildings during the occupancy stage. The Project Database serves as dedicated storage for records of analysis for each building from where information could be collected to update the project database.

Recent efforts by the University of Salford on this research have been directed at incorporating IFC implementations into the LCC integrated system as a prototype of an nD modelling tool (Fu et al., 2004; Fu et al., 2007). The purpose for this direction is to reduce interoperability setbacks of LCC applications in the delivery of building design information across different computer modelling/design systems.

2.4.3 Environmental sustainability decision-support tools

The environment could be viewed as a super-set of the society which in turn is a super-set of the economy as stipulated in constrained approach of describing sustainability. In other words, all economic systems and transactions take place in the society which occupies certain space in the environment. However approaches to environmental sustainability assessment tend to consider environmental indicators to be exclusive of economic and social factors in line with the triple–bottom line approach. Typical environmental assessment indicators tend to address impacts related to energy consumption, land and water use, as well as greenhouse gas emissions and consider economic and social issues to be separate (Todd et al., 2001).

The existing classification system of assessment tools commonly discussed by researchers is the work reported by Trusty (2000) under the auspices of Athena Sustainable Material Institute (Todd et al., 2001; Haapio and Viitaniemi, 2008). It is known as the Athena classification system and comprised of three levels as shown in Table 2.3. Various combinations of these tools have been made by researchers in recent times for review and comparison purposes (Todd et al., 2001; Haapio and Viitaniemi, 2008; Sharifi and Murayama, 2012). As such, this section further discusses only some selected tools, from and outside the table, related to civil and structural engineering sustainability assessments of buildings.

Table 2.3: Athena classification of assessment tools

Classification	**Description**	**Examples of tools**
Level 1	***Product comparison tools and information sources.*** Used for primarily for procurement stage may include economic as well as environmental data or can be used to construct LCA.	BEES, TEAM^{TM}, the environmental resource guide, LCAExplorer, SimaPro
Level 2	***Whole building design or decision support tools.*** Focuses on specific area such as life cycle cost, life cycle environmental effect, lighting, operational energy, or a combination of these.	ATHENA^{TM}, BEAT 2002, BeCost, Eco-Quantum, Envest 2, DOE2, E10 EQUER, LEGEP and PAPOOSE
Level 3	***Whole building assessment frameworks or systems.*** Provides broad coverage of environmental, economic, social and other issues deemed to be relevant to sustainability. Blends objective and subjective data. May be used for new designs or existing buildings.	BREEAM (Canada/UK), LEED (US), GBTool (International) EcoEffect (Sweden), EcoProfile (Norway), ESCALE (France), Environmental Status Model

- **BREEAM** (Building Research Establishment Environment Assessment Method) developed by the Building Research Establishment and consultants (UK) is the first environmental certification scheme for buildings (Todd et al., 2001; Sharifi and Murayama, 2012). It covers the assessment of offices, retail superstores and super-markets, industrial buildings, bespoke projects and home (known as EcoHomes). The criteria for assessment include management (policy and procedure), operational energy and CO_2 emissions, health and well-being, pollution, transport, land use, site ecological value, materials and water consumption efficiency. It employs the weighting principles to combine indicators. The final score rating range from fair/pass, good, very good to excellent (sun flower). Certificates are awarded for the various ratings.

  In the recent Target Zero study of framing material for sustainable building in the UK, BREEAM has been the tool for assessing and benchmarking the various designs and building types. Target Zero is a programme of work sponsored by Tata Steel and BCSA to provide guidance for clients and designers to help with the early stages of sustainability decision-making (TARGETZERO.INFO, 2012). It considers five different building types – schools, offices, warehouses, supermarkets and mix-use – and spells out the most cost effective routes towards achieving zero carbon operation, considering the use of low and zero carbon technology.

- **LEED®** (Leadership in Energy and Environmental Design) is a product of the United States Green Building Council (USGBC). It is a third-party certification programme nationally accepted for encouraging and assessing design, operation and construction of high performance green buildings. The goals of LEED are to ensure that buildings are environmentally compatible, provide a healthy work environment and are profitable. It can be used for commercial offices and residential buildings on criteria related to credit categories of sustainable sites, energy and atmosphere, water efficiency, materials and resources, indoor environmental quality and innovation in design (Azhar et al., 2011). Grades such as silver, gold and platinum are used to rate buildings in LEED.

- **CEEQUAL** (Civil Engineering Environmental Quality Assessment and Award Scheme) was developed by a team led by the ICE, supported by the Institution's Research & Development Enabling Fund and the UK Government (CEEQUAL, 2012). The Scheme, now owned by fourteen organisations, is a sustainability rating system operated through CEEQUAL Ltd. It is an evidence-based Assessment and Awards Scheme for improving sustainability in civil engineering. Areas of assessment cover infrastructure for modern life, landscaping and the public realm. It operates in three forms: CEEQUAL for UK and Ireland Projects, CEEQUAL for International Projects and CEEQUAL for Term Contracts. Criteria for assessment include New Project Strategy (optional), Project Management, People and Communities, Land use (above and below water) and Landscape, The Historic Environment, Ecology and Biodiversity, Water Environment (fresh & marine), Physical Resources Use and Management and Transport.

- **ENVEST** (ENVironmental ESTimator) is a software tool developed by Building Research Establishment (BRE), UK and can be used to assess the life cycle costs and environmental impacts of proposed buildings and explores various design options (BRE, 2012). In the current version, Envest 2, designers can input their building designs information such as height, number of storeys, window area, etc and the choices of elements (external wall, roof covering, etc). These inputs are analysed to identify those with the most influence on the building's environmental impact and whole life cost. Envest 2 can also predict the environmental and cost impact of various strategies for heating, cooling and operating a building. It presents environmental data in a range of 12 impacts, from climate change to toxicity, as well as a single Ecopoint score, for ease of communication and for comparison with costs. Costs are calculated according to Net Present Value (in Pound Sterling) and discounted at 2002 Treasury rates or a discounted rate set by the user.

- **SpeAR®** (Sustainable Project Appraisal Routine) was developed by ARUP in 2000 based on the UK Sustainable Development Indicators from 'Quality of Life Counts', EU and UN indicator sets and the Global Reporting Initiative (GRI) indicators (ARUP, 2012). It was later reviewed in 2011 to achieve more flexibility, international-applicability and to consider emerging sustainability issues. It can be used for all kinds of projects including design and delivery of new infrastructure, master-plans and individual buildings. Its functions covers baseline appraisal, gap analysis, identification of key performance indicators, project performance monitoring and evaluation and assess implications of design changes. It also has some relevance in the evaluation of projects upon completion, and during operation. In addition to

SpeAR, ARUP has also included elements of environmental impact in the GSA structural analysis and design software. The embodied energy, embodied carbon and recycled content of structural members or user-defined parameter can be assigned for various material types (Steel, Concrete, Rebar, Aluminium, Glass, and Wood) by the software during analysis and design activity (Oasys, 2012).

2.5 Challenges with sustainability decision-support tools

Contemporary building design process is progressing from traditional CAD systems towards the adoption of BIM in the projects development process. This comes with information management and programming challenges as BIM is yet to be fully matured (NIBS, 2007). The challenges that come with the tasks of incorporating sustainability decision support systems to the emerging BIM process are in two folds. The first relates to the deficiencies observed by researchers in already existing assessments tools and the second entails issues relating the integration of BIM with decision support tools to aid early design iterations in areas such as structural engineering.

2.5.1 Challenges with building performance assessment tools

Existing building performance assessment tools have created significant impact in sustainable construction across the globe. Most construction professionals are now aware of when and how to use such tools to assess their designs or buildings. In some countries such as the UK, USA and China; the government is working towards setting sustainability assessment of certain projects as an important aspect of the project development process. While the awareness of building performance assessment keeps increasing, researchers have raised concerns for the need to improve the assessment approach to existing tools for more holistic results, increased usefulness of analysis outcomes and the ease of application.

Reviews of building performance assessment tools have been presented by various researchers (Todd et al., 2001; Ding, 2008; Bribian et al., 2009; Lee et al., 2009; Ortiz et al., 2009) in the bid to develop innovations. There have also been case-studies and applications of existing tools in the US, Japan (Taki), Hong Kong, Thailand, Shangai – to demonstrate usability and explore shortcomings – carried out by Sheuer et al. (2003), Li (2006), Chau et al. (2007), Kofoworola and Gheewala (2009) and Wang et al. (2010) respectively. While admitting the contributions of building performance assessment programmes in promoting the need to ensure sustainability in the Built Environment, the challenges and limitations in these programmes have been consistently highlighted. Combinations of the points raised about LCA programmes include the following.

(i). Most programmes focus on evaluation of environmental impact of already existing buildings

(ii). Evaluated environmental burdens are generally limited to global warming potential (GWP), acidification, energy consumption; and to a less extent – inefficient land use, water shortage, air pollution, traffic congestion, ecological system deterioration, high energy consumption and poor waste management

(iii). Presentation of LCA results requires a simple structure to ease understanding by users. This may further require striking a balance between completeness in the coverage scope and simplicity of use.

(iv). Current environmental assessment methods are designed to evaluate projects at later design stage (when it may be too late to make changes or modification) to provide information on environmental performance. As such LCA requires simplification and adaptation for various purposes such as use at early design phases.

(v). The financial aspect in evaluation frameworks is often not reflected which allows room for imbalance as projects needs to be socially, environmentally and economically (financially) viable.

(vi). The feasibility stage for projects where optimum selection of projects options could be done; is largely by-passed to consideration of economic issues at the later design stage.

(vii). Most tools are localised and does not allow for national or regional variations in terms of climate, development level, and appropriate technology and historic value

2.5.2 Challenges of integration assessment tools with BIM

While BIM promises to be a good digitized representation of the physical building, it is not yet all encompassing (NIBS, 2007). The inclusion and accessibility of other design information such as cost estimation, selection of construction methods, construction scheduling, productivity analysis and project management associated with various construction practitioners still need tackling (Zhang et al., 2011). The following has been identified as challenges with BIM and performance tool integration.

(i). BIM is still in the process of maturing and most building environmental assessment tools have not been integrated into BIM. Such integration requires modelling and object-based programming implementation with a BIM environment.

(ii). Current sustainability analysis tools such as Revit Ecotec® are services oriented and still require the exchange of data with a product model before analysis could be executed.

(iii). Lack of dynamic parametric modelling of transactions between BIM and sustainability assessment tools.

2.6 Summary

This chapter reviewed sustainability decision-support tools and related information technology applications in the building design process. Several decision-support tools exist for assessing one or a combination of the three dimensions of building sustainability. They vary in the sustainability criteria, ease of application, sophistication and reliance on IT, system for reporting impacts etc. With the emergence of BIM and the construction industry's clamour for its adoption for project transaction, most of the decision-support tools will need to be reviewed in the direction of being compatible or integrated with BIM. Assessment tools have also been very general or operational energy focused. This undermines contributions professional platforms such as structural engineering can make towards the overall building sustainability if structural engineers carry out their design with appropriate sustainability consciousness and guide. It is therefore important that no matter how small the proportion of sustainability contribution a professional platform might be making towards the overall, various platforms should be abreast with their contributions and how to effect improvements. This premise sets the stage for the next chapter which discusses relevant requirements towards BIM-related sustainability modelling in the structural engineering platform.

Chapter 3

A proposed BIM sustainability appraisal framework

3.1 Introduction

In this chapter, general requirements for modelling sustainability in buildings, the proposed BIM modelling framework and its components are discus. This research explores requirements for modelling sustainability in buildings to develop appraisal framework to guide the implementation aspect of the work. This is to ensure that implementation of the appraisal framework is not carried out in isolation from the context of sustainable development in order not to undermine existing experiences and practices in construction industry and the society at large (Nuseibeh and Easterbrook, 2000).

3.2 Requirements for modelling sustainability in buildings

Software systems requirement engineering is the process of discovering the purpose for which a software system is intended (Nuseibeh and Easterbrook, 2000). This constitutes a very important aspect of software development. Generally, systems requirements should be purposeful in having an objective to fulfil; appropriate in expressing representations that are necessary to achieve the system's objectives; and truthful in terms of expressing representations that are actually required (Aouad and Arayici, 2010). In line with objectives of this research, the elicitation of the requirements is of two categories: requirements for sustainability appraisal and requirement for the prototype implementation. They were identified from the requirement elicitation process to formalise a framework for the sustainability appraisal of buildings based on contemporary building information modelling protocols. The sources of information for the elicitation process are literatures and similar research work on the subject, stakeholder involvement and refinement through regression testing of framework. The purposes, appropriateness and a description of various aspects of these requirements are discussed.

3.2.1 Requirements for sustainability appraisal

For an appreciable level of acceptability, the three key sustainability pillars of economic, environment and social aspects need to be reflected in the selection of criteria for appraising building sustainability (Todd et al., 2001). However, the social aspect is not considered in this work since the related accounting principles is still maturing (Kloepffer, 2008) and it has insignificant influence on conceptual structural design decisions. As such the sustainability appraisal requirements are discussed with respect to the economic and environmental aspects of sustainability alone.

In defining sustainability, the time element of the 'future' generations - not compromising their benefits – is crucial in setting goals as well as requirements for appraisal. The author is of the opinion that life cycle approach presents a good means for considering this time dimension. This appears to be affirmed by Sarja (2002) in stating that sustainability must always be treated according to life cycle principle. Life cycle approach in building has been advocated to being holistic and essential to sustainable construction concept in the built environment (Kohler and Moffatt, 2003). It is tailored towards the principle of terotechnology which is concerned with the economics of specifications and design focused on life cycle requirements (BS 3843-1, 1992).

In one the early presentation of life cycle approach as a new application in building Kohler (1997) identified five life cycle based criteria; system limit, energy and mass flows, functional units, time constants and processes. These constitute the key sustainability appraisal requirements aggregated into four aspects (Figure 3.1) as further discussed.

(i). System boundary

The boundaries of a system or product refer to the limits, in time and space, within which that system can be affected by or create some effect on some other system/product. The assumed boundary for any assessment varies according to the defined goals (EN ISO 14044, 2006). The outcome from the sustainability assessment of a product based on the interactions with its environment is largely influenced by the assumed system boundary. For the building artefact, the ecosystem is recommended as an appropriate system boundary for sustainability modelling purposes. With respect to time, typical system boundaries used for building simulations and assessment activities usually include cradle-to-gate, cradle-to-site and cradle-to grave (end-of-life).

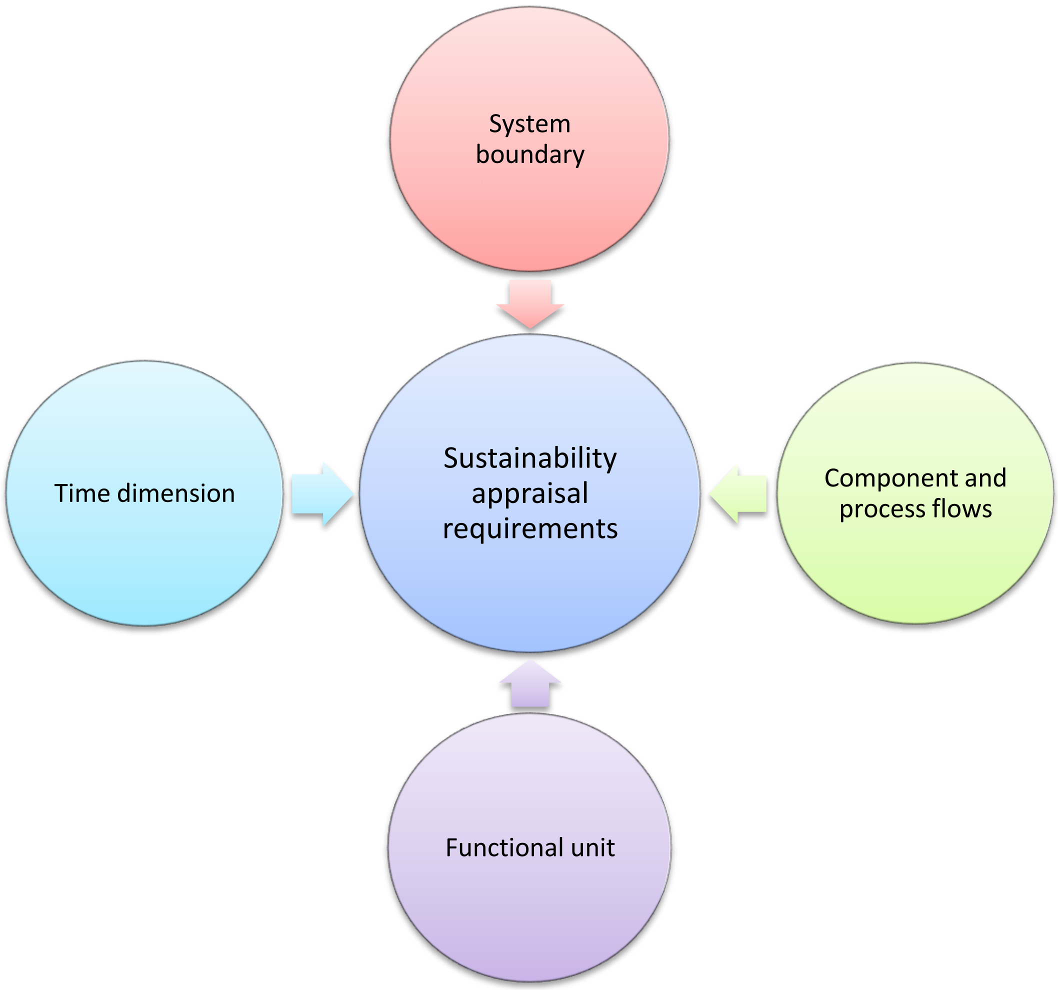


Figure 3.1: Requirements for sustainability appraisal

(ii). Component and process flows

The inherent flows of energy and mass that constitute the building, from conception to end-of-life ought to be fully accounted for in sustainability appraisal. The different aspects constituting these flows are given in Table 3.1. Financial flows, in the form of money, are actually associated with all forms of the physical flows. Money is directly or indirectly expended in procuring all other forms of flows and therefore moves in opposite direction to other flows. The author is of the opinion that this is also true for information flows including situations where remuneration is offered for useful information or knowledge gained from services such as training. Thus in all phases of the building artefact, operations and activities can be evaluated using the principles of mass flow, energy flow, information flow, resource flow, financial flow and process flow. Building evolves from stage to stage throughout its life cycle: events that impacts upon it and cause these changes need to be adequately reflected in the appraisal process (Rezgui et al., 1996). Process flow allows for the capturing of the dynamic work flows associated with the various phases of buildings. Existing construction, cost, energy and mass flow data in catalogues and elsewhere are valuable resources for ready integration into building models.

Table 3.1: Energy and mass flow activities in building (drawn from Kohler (1997))

Flows	**Components**	**Associated elements**
Physical flows	Material	Building materials, water
	Energy	Embodied energy, operation energy
	Waste	Building materials , waste from use phase
	Emissions	From wastes into air or water
Financial flows	Internal costs	Expended on materials, energy, wastes and services
	External costs	Procurement of materials, energy, wastes and other services
Information flows	Documents	From planning and management activities
	Communication in all forms	Planning activities, Data processing with regards to other flows.

(iii). Functional unit

The envisaged performance characteristics (functions) of a product is the driver for creating and eventual 'putting to use' of that product. A system may have a number of possible functions with varying degree of relevance to the goals and scope of an assessment activity. A functional unit defines the quantification of functions of a product identified to be relevant to the goals and scope of an appraisal (EN ISO 14040, 2006). It is useful in providing a reference and common basis for the comparability of outcomes from the assessment of different systems.

For the building, the issue of functional unit is very important because of the different life cycle phases which are manned by separate professional. It tends to arouse different interests and goals/scope during assessment activities. Hence, it is paramount to have a generally acceptable reference for holistic appraisals. A common building model has been suggested to be the 'building as built' (Björk, 1992; Kohler, 1997). Thus the functional unit of the building can be given a specific value during planning; however, Kohler suggests that a default value of a large number of similar buildings can be assumed since similar buildings types tend to be generally similar in functions.

(iv). Time dimension

Time is a vital requirement for many activities on earth. This is true also for the building. There is an associated time-scale for every component of a building and for the building as a whole. As shown in Figure 3.2, time scales vary from nanosecond for light propagation to hundreds of years for replacement of bearing structure (Kohler, 1997). Thus time is tied to the various life cycle phases of the building and the activities comprising these phases. Assessments should integrate different time levels and allow for the combination of real and virtual components. For the structural engineers, requirements such as design life, fire resistance of the structure goes a long way to guide specifications associated with designs.

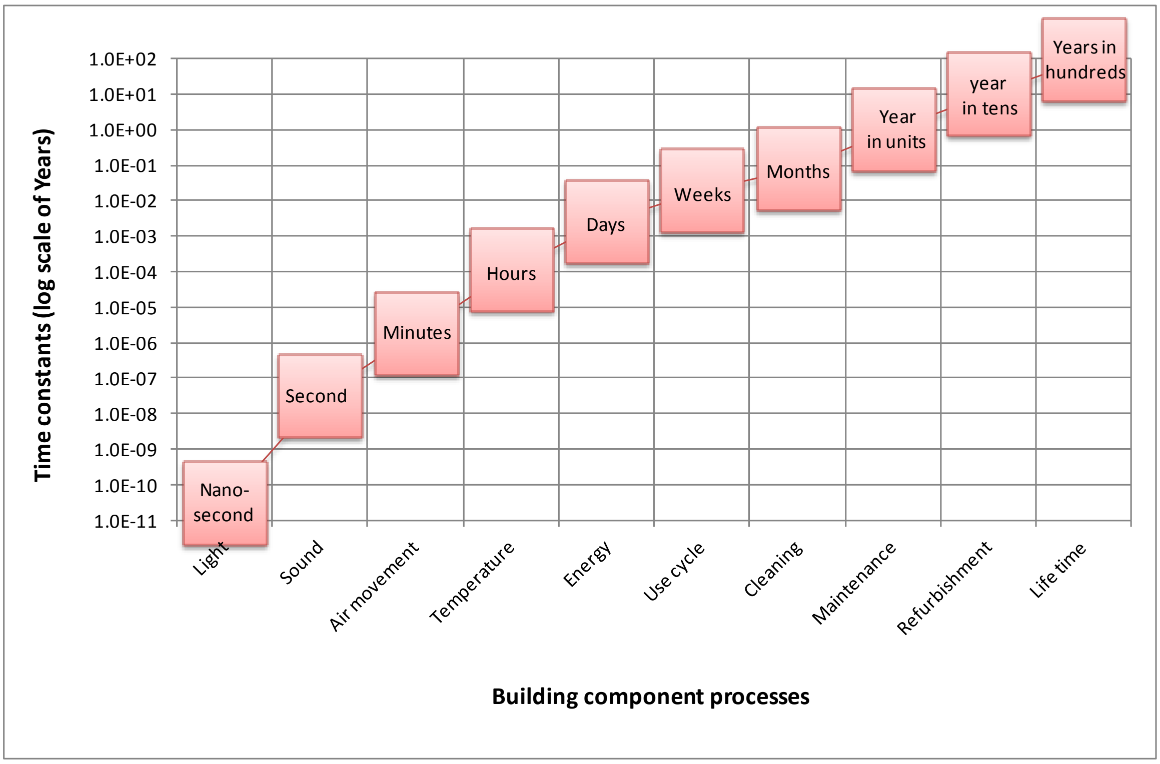


Figure 3.2: Time constants in building (modified after Kohler (1997))

3.2.2 Requirements for prototype implementation

The requirements for implementation vary greatly from one business process to another. For software systems, requirements are always derived from existing knowledge that need to be organised in order to adequately describe the system (Robillard et al., 2002). The understanding of stakeholders' needs, the application domain and vision/goal of the system is essential for a good requirement development. Following extensive review of relevant literatures, the implementation requirements of the proposed sustainability framework closely follow after those identified by Staub-French (2003) and Nepal (2011). In their successive works on developing an ontology of design feature extraction from a building model to support construction estimation, these authors proposed a solution that is easy-to-use and represents domain concepts relevant to practitioners in a generic, formal and flexible way. In addition to these, this research adds that a proposed system should also exhibit a good degree of scalability and adequacy in generating result in good time. These implementation requirements (Figure 3.3) are discussed next.

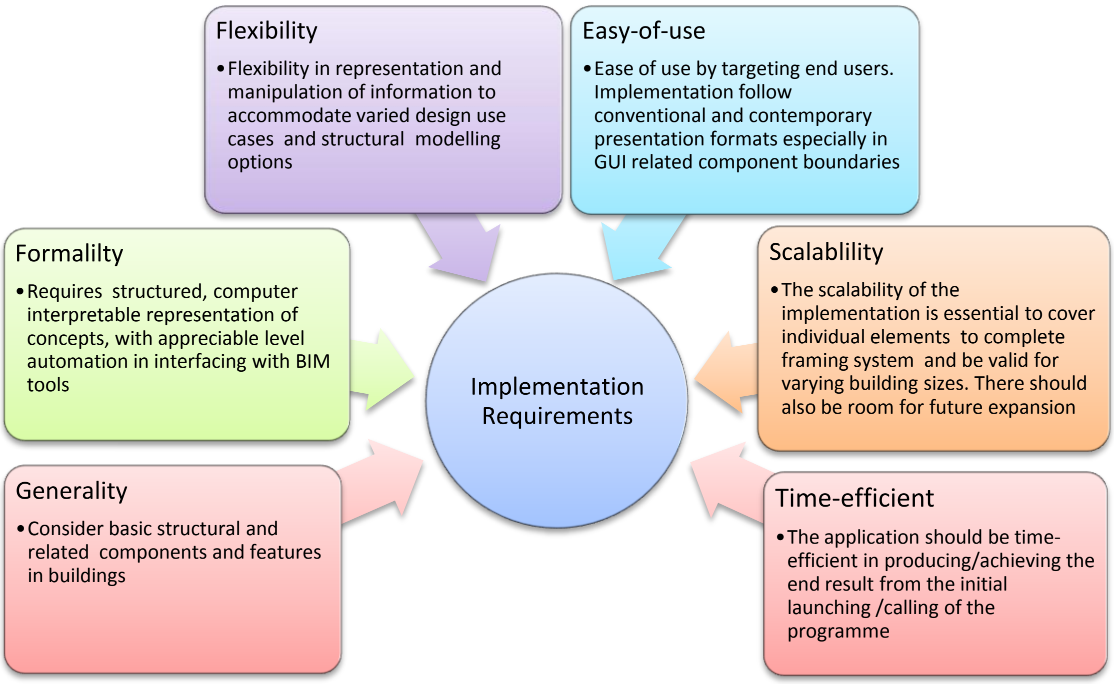


Figure 3.3: Implementation requirements

(i). Generality

Generality in terms of representation, reasoning and management of project model views and approaches, is one of the key modeling requirements for addressing the characteristics of AEC projects (Haymaker et al., 2004). The target is that stakeholders related to the associated operation domain should find developed systems simple enough to understand, as well as being versatile in considering task-specific needs. This can be in the area of applicability of the system to different project types (Li, 2009). To achieve this, the author suggests that the system will need to consider features or components that are generic in the various domains of the AEC industry.

(ii). Formality

It is important that representation of features, processes, information and concepts observe a formal structure interpretable by computer. The representation should include attributes and functions that allow for a good degree of automation as necessary. With the emergence of BIM as the newly proposed modelling technology for projects in the AEC Industry, the extent of formality should support and be able to interact with BIM representation. BIM is based on OOP principles governed by attributes and rules. Adherence to the essential object-oriented principles of encapsulation; structured interfaces; small, simple and stable interfaces; and minimal programming alterations/additions are essential in minimizing the cost of maintenance of a software system (Graham, 1998). The author believes that maintenance in this context includes aspects of actual system development, implementation improvements, expansion of scope and upgrading to contemporary standards and needs. A good way of achieving this is by choosing to implement proposed systems in contemporary OOP languages and observing the essential object oriented principles in laying out associated representations.

(iii). Flexibility

Flexibility within the scope of implementation is a requirement that is tailored towards capturing the satisfaction of a relatively wide range of audience. Flexibility tend to reflect adequate consideration of user preferences with respect to configuring interfaces, range of features considered in implementation and varying scenarios of design cases. Flexibility is also required in the area of representation and manipulation of information to accommodate varied user preferences, design cases and structural modeling options. Van Leeuwen and Watger (1997) identified that it is flexibility in the representation of entities in an information model that makes extension of such models possible when the need to incorporate emerging new definitions arises.

(iv). Ease-of-use

Ease-of-use by target end users is one the key requirements of software systems. The implementation of systems follow conventional and contemporary presentation formats especially in graphical user interface (GUI) related component boundaries. The user should be able to follow the programme through with very minimal guidance or reference to manuals. System should be explicit enough for domain practitioners to understand the logical flow of the presentation structure of the system. It is worth ensuring that users do not have to be software programmers to understand the underlying concepts of the system (Nepal, 2011).

(v). Scalability

The scalability of a software system determines the length of time it will remain relevant within the domain of use. It has been noted as one of the important features of system architectures that have encouraged their prolong use in collaborative design systems (Fahdah, 2008). The author adds that this is also true of many implementation systems. For this research work, scalability is relevant in the sizes of building considered. Is it possible to have varied dimensions of building plan area and also consider varied number of floors? How many design solutions can the system compare at any particular time? These are typical elicited scalability questions used to guide the regression testing process and improvement of the implementation.

(vi). Time-efficient

Users could be discouraged from running a software systems if excessive time is going to be expended in its operation to produce desired result. An application should be time-efficient in producing/achieving end result from the initial launching/calling of the application. In course of the implementation process, the author discovered that a logical flow of the various components of a system can help users to smartly and easily go through a programme in good time. An efficiently enhanced data input and output system is one of the contributory factors to achieving adequate operation time. The increasing improvement in computing power has been an advantage in this requirement; however the ingenuity of the programmer in the representation of information in the form of objects, classes and their associated attributes and governing rules remains a key in the time-efficient performance of a system.

3.3 The conceptual sustainability appraisal framework

High level requirements for modelling sustainability implications in building design were discussed in the previous chapter. These requirements guide the development of the sustainability appraisal framework presented in Figure 3.4. The figure illustrates the relationship between the components of the framework based on IDEF0 notations. It agrees with frameworks proposed by Svanerudh (2001) and Nguyen et al. (2010) respectively on improving design support systems and using BIM to evaluate the sustainability of architectural designs.

Starting from the top of the figure is the demarcation for the three major modelling components in the conceptual framework. First, there needs to be a building information model (conceptual model) in a design/modelling environment, secondly information or features need to be extracted (feature extraction) from the building model, and thirdly extracted information has to be synthesized (feature modelling) to obtain desired results. For the case of the building artefact, a feature refers to any component or element of the building which may be architectural, structural, services-related or common to the three domains. The process of recognising and identifying features from already designed artefacts and using acquired information for the purpose of building up another model (feature model) is termed feature extraction. A more vivid illustration showing the contents of these three components is given in Figure 3.5. Next from the top is the control. The sustainability indicators constitute the control of the system which uses features extracted from the conceptual model as input into the system. The modelling database contains information that works as Mechanism based on the functional instantiations. The output of the system gives scores of design options obtained from multi-criteria decision analysis.

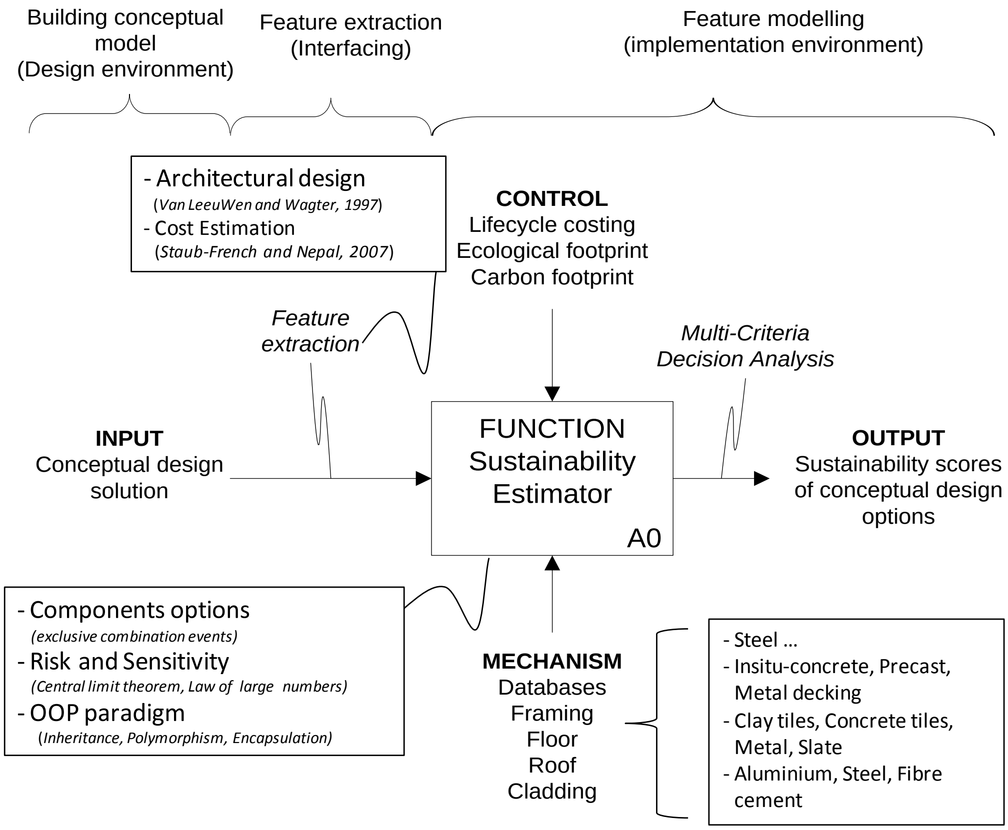


Figure 3.4: Components of the conceptual framework

From Feature-based modeling (FBM) perspective, the framework (Figure 3.5) consists of the conceptual model, the feature extraction activity and the feature modeling aspect (discussed in Section 3.5). The conceptual model is essentially a building product model in a BIM-enable tool. The BIM-enable tool should be capable of allowing the extraction of feature components for sustainability analysis built into the feature modeling process. The proposed sustainability modeling framework reflects the economic and environmental aspects of the sustainability of steel framed buildings. It uses LCC techniques to account for the economic sustainability and a combination of carbon footprint and ecological footprint measures to account for environmental sustainability. The appraisal framework has been implemented in a prototype system which is dependent on significant amount of data from secondary sources. This encompasses methods for construction and fabrication of steel materials, associated costs, life cycle information; combined with the application methodologies of the selected sustainability indicators. The implementation work of this research uses object oriented programming (OOP) in C# application within the .NET Framework environment to develop a sustainability computer-integrated prototype. The output of the prototype is fine-tuned by sensitivity and risk analysis to increase the reliability of the probabilities in the estimations of sustainability indicators.

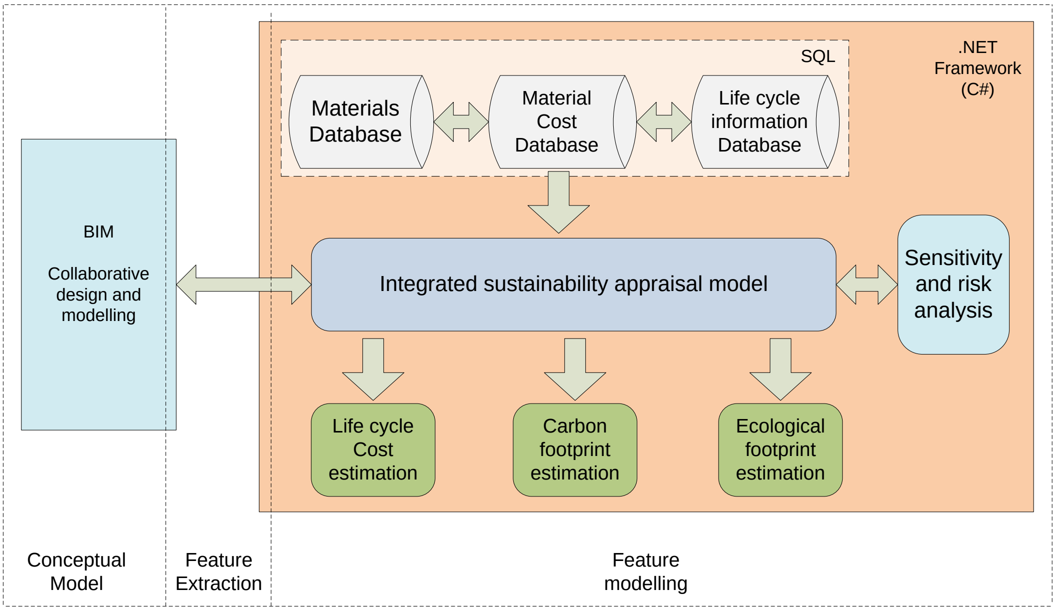


Figure 3.5: Proposed sustainability modelling framework

3.4 Selection of environment for framework implementation

The environment for the implementation of the framework is in two aspects: (1) the design environment in which the building model (drawing) is created and (2) the programming environment where the required objects, components, classes and their corresponding attributes are instantiated. These environments, which have been carefully chosen, evolved in course of the implementation of the sustainability appraisal framework.

3.4.1 Design environment

Computer based environments for carrying out engineering designs vary and have improved in intelligence over the years. The earlier CAD systems produced plotted drawings based on vectors, line types and layer definitions (Eastman et al., 2008) which has moved on to contemporary object–based modelling technology associated with objects, attributes, processes, relationships and rules. The latter, also known as parametric modelling, have been developed in a number of commercial platforms such as Autodesk Revit, Bentley Systems, ArchiCAD, Digital Project, Tekla Structures and Dprofiler.

In this research, a platform - which has (1) a dedicated building modelling and design (structural engineering and architectural) section (2) supports object or feature extraction (3) accommodates interaction with external plug-in object-oriented interface - is required. The Revit platform was found to be suitable. The Revit .NET API allows programming with any .NET compliant language such as Visual Basic.NET, C#, and C++/CLI (Autodesk, 2010).

3.4.2 Programming environment

Among the options of programming languages in the Visual Studios .NET that can interact with the design environment, C# came out as the most favoured. Although, the initial code development phase of the implementation was carried out independent of the design environment (in this case Revit Structures^{TM}), C# had the advantage of having an in-built class library, possibility of quick development of applications and good flexibility for accessibility, communication and adaptation to other software systems (Deitel and Deitel, 2008). In this respect, instantiations that require applications of XML, database systems (SQL) and appropriate report definition language (RDL) have been made easy to deploy.

3.5 Feature based modelling

Three approaches have been identified in FBM; design-by-features, feature recognition and a hybrid of both (van Leeuwen et al., 1996). Design-by-feature develops designs from high level features generated from primitives and/or user-define features embodying design intents largely based on geometry. In the feature recognition approach, as the name implies, features are extracted from already designed artefacts based on recognition (data interpretation and analysis by computer algorithms or user) to build up a feature model. Feature recognition is proposed in this research to extract relevant structural domain information from a product model (BIM) for the purpose of performing sustainability analysis. The representations of the four key activities (Figure 3.6) applied in this research are presented below.

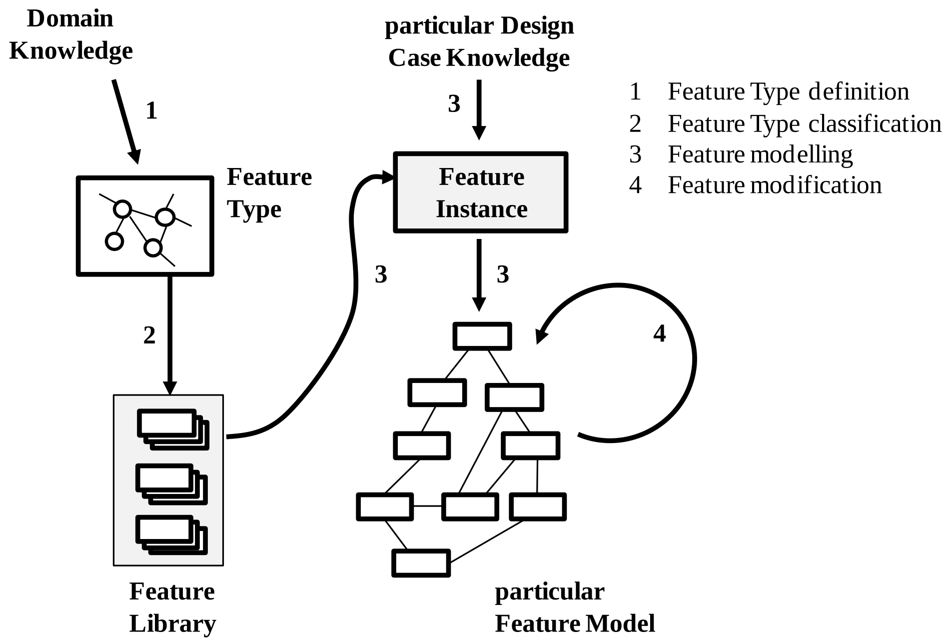


Figure 3.6: Activities in feature based modelling (van Leeuwen et al., 1996)

3.5.1 Feature Type definition

Feature type may be generic or specific. It is generic when it forms the building's core model and is among the formalized common concepts in the AEC industry; and on the other hand specific, if the feature is not part of the common AEC concepts and systems (Van Leeuwen and Wagter, 1997). Since a prototype implementation is intended in the research, the features selected are largely of the generic type. They include column, beam, floor, roof and cladding systems. These features could also be termed as "component features" (Staub-French et al., 2003; Staub-French and Nepal, 2007).

3.5.2 Feature Libraries

Feature types are classified into sections contained in the Feature Library which is a function of a particular domain area in the AEC industry. The Feature library in this research is implemented through MS SQL Database Management System within the .NET Frameworks and contains various instances of the feature type mentioned in the previous section. Figure 3.7 shows the UML schema diagram of the Feature Library with respect to column Feature Type. Column is a feature type that belongs to a section within the AllSectionData, UC254x254x73 is a type of column representing one of the examples of a feature instance and has material properties, cost, boundary conditions (end connection) etc.

3.5.3 Feature modelling

This refers to the instantiation of a selected feature type that suits the type of information to be modelled (van Leeuwen et al., 1996; Van Leeuwen and Wagter, 1997). This aspect is executed in the C# object oriented environment through interfacing with BIM enabled tool such as Revit Structure™. It entails recognizing and extracting the considered feature types from a particular design model (drawing) compare and abstract relevant information from the feature library for appropriate collation and onward sustainability analysis.

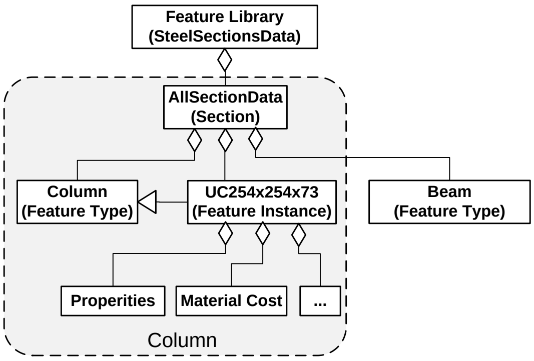


Figure 3.7: Column mappings in the Feature database

3.5.4 Feature modification

The modification of features that could take place during the operation of the prototype is largely related to the issues concerning the chosen sustainability indicators. However, the intention for feature modification include the possibility of altering the values of various attributes of features, deleting or introducing new relationships between features which trigger features to respond in some particular manner (Van Leeuwen and Wagter, 1997). Some of the modifications associated with feature modeling process used in the structural sustainability modeling include: altering of cladding area; specification of discount rates and estimated maintenance costs; indication of associated lifecycle boundaries for the sustainability analysis etc.

3.6 Selection of sustainability indicators

Ortiz et al (2009) reviewed recent developments in life cycle assessment related to sustainable construction and highlighted the need to develop sustainability indicators in the building life cycle stages that could be applied worldwide. It is essential that such indicators mimic as closely as possible the essence of the sustainable development concept encompassing economic, environmental and the social criteria (van Leeuwen and Fridqvist, 2006; Singh et al., 2007). Though the methodologies to accounting for the social pillar of sustainability are still in their infancy (Kloepffer, 2008), its influence on the conceptual design process of steel-framed buildings is relatively minimal. This is because the social benefits of projects have already been envisaged by the client at conception and do not significantly affect alternative steel-framing design options. Hence, this work is centred on the economic and environmental pillars. These aspects are further discussed.

3.6.1 Economic Indicator

The economic justification of projects is generally tied to cost which often conflicts with design goals related to achieving the best product. As such, one important task for designers is to balance cost with design decisions (Seo et al., 2002). However, as typical, cost is incremental and composed of components. Designers are often faced with a further challenge of deliberating on the extent of cost components to be considered in such scenarios. Lowest initial capital-cost has been widely used to guide decision making in construction projects (Bull, 1993) but recent sustainable development requirements reveal the need for adopting life cycle approach. This premise points to Life cycle costing (LCC) which is relatively not new in business fields as its methodological framework is based on economics (Steen, 2005). Thus, LCC information on product and project options can enhance making better decisions encompassing the needs of future generation (Kloepffer, 2008).

The life cycle cost of a structure includes the totality of all the cost incurred in its life time (cradle-to-grave). This encompasses initial costs, including costs of design and construction; operation (utilities) cost; periodic maintenance (including repair); and eventual dismantling or demolition. In optimising the life-cycle cost of steel structures, Sarma and Adeli (2002) noted four main factors that influence the lifecycle cost of steel structures significantly. These are the cost of the rolled section used for initial construction of structure; number of different sections types used in the structure; weight of rolled sections used in the structure; and the perimeter of the rolled section in the structure. These are tagged respectively *a*, *b*, *c*, and *d* in Figure 3.8 which illustrates the cost function relationship. Furthermore, these factors are embedded in various components of Equation 1.0, which is general for civil engineering structures. This equation gives the life cycle cost ($C_{Lifecycle}$) based on Single Present Worth which discounts future costs and inflation based on the discounting factor ($\frac{1}{(1+i)^{y_n}}$). Where, *i* is the discount rate and y_n stands for the time in period of years associated with the different cost components 1 (Maintenance) to 6 (Dismantling). It is interesting to note against expectations that connections, *e,* was not considered to be one of the factors that significantly influence life cycle costs.

$$C_{Lifecycle} = C_{Initial} + \sum \frac{1}{(1+i)^{y_{n1}}} C_{Maintenance} + \sum \frac{1}{(1+i)^{y_{n2}}} C_{Inspection} + \sum \frac{1}{(1+i)^{y_{n3}}} C_{Repair} + \sum \frac{1}{(1+i)^{y_{n4}}} C_{Operating} + \sum \frac{1}{(1+i)^{y_{n5}}} C_{Failure} + \sum \frac{1}{(1+i)^{y_{n6}}} C_{Dismantling} \quad (1.0)$$

3.6.2 Environmental indicators

No single indicator is able to comprehensively monitor and account for the totality of human impact on the environment (Best et al., 2008). Thus, indicators capturing different aspects need to be combined and interpreted jointly depending on defined goals. As such, carbon footprint and ecological footprint have been identified as the ideal indicators in this research work. These indicators which can be applied at scales ranging from a single product, a process, a sector, up to individuals, cities, nations and the whole world; have been found to be complementary and represent the environmental consequences of human activities (Alessandro et al., 2010). Carbon footprint informs on the impact placed on the atmosphere while ecological footprint is on the biosphere.

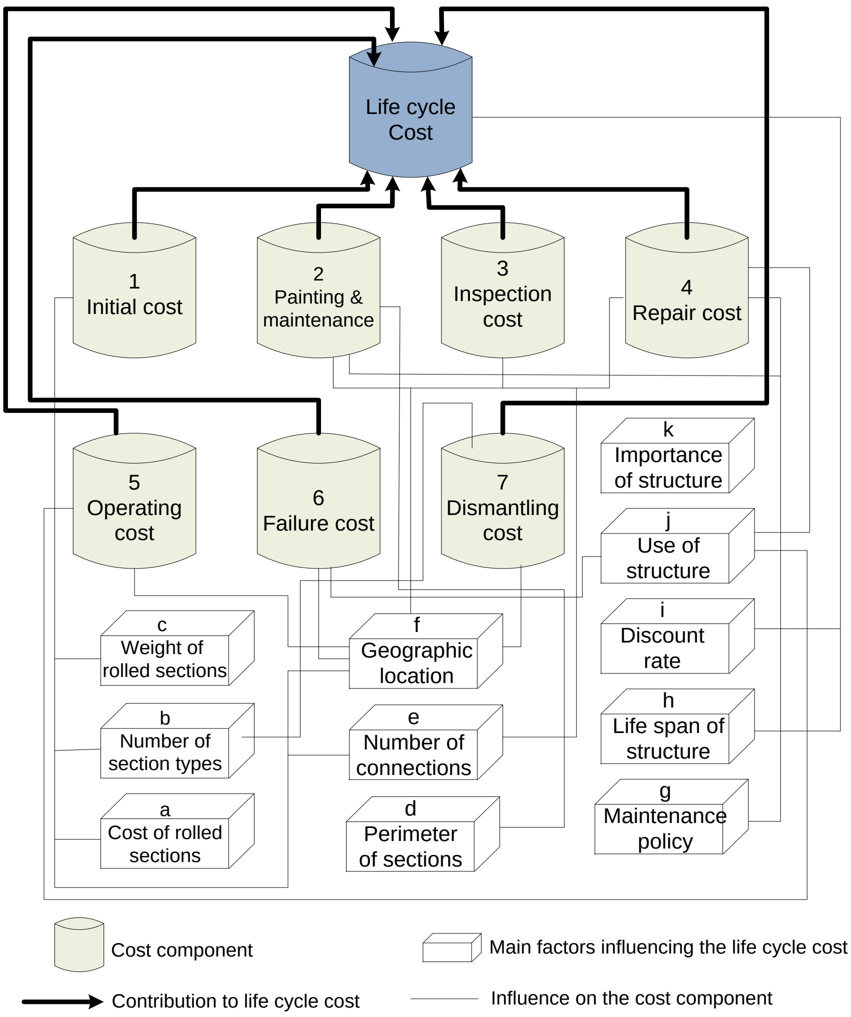


Figure 3.8: Life cycle cost functions and component relationships (Sarma and Adeli, 2002)

3.6.3 Carbon footprint

In clearing up the numerous conceptions on carbon footprint, Wiedmann and Minx (2007) defined the term as a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product. This implies a life cycle methodology and exclusively discourages events of under-counting or double-counting emissions. The two methodological approaches in calculating CO_2 emissions: bottom-up (based on life cycle Process Analysis) and top-down (in Environmental Input-Output analysis) have been extensively discussed in PAS 2050 (Minx et al., 2007).

Carbon dioxide (CO_2) is the dominant gas release by human activities that contribute to global warming and as such become the centre of attraction in the reduction of greenhouse gas emissions (Rawlinson and Weight, 2007). In the UK, Part L of the Building Regulation now uses CO_2 emissions to benchmark building performance (HMG, 2010). Also, the World Steel Association adopted a cradle-to-grave approach (system expansion) to estimate the carbon and energy impacts of steel construction products in the UK (BCSA and Corus, 2010) in analysing the environmental impact of steel manufacture as shown in Table 3.2.

Table 3.2: Carbon and energy impacts of steel construction products in the UK (BCSA and Corus, 2010)

	Plates	**Sections**	**Tubes**	**Hot Dip Galvanised**	**Purlins and side rails**
CO2 (t/t)	0.919	0.762	0.857	1.350	1.100
Energy (GJ/t)	17.37	13.12	15.42	21.63	19.38

3.6.4 Ecological footprint

Ecological footprint concept was developed by Mathis Wackernagel *et al* in the early 1990's and has generated considerable research efforts attracting the attention of policy makers and business establishments (Schaefer et al., 2006). Thus, ecological footprint reports of government establishments and the likes in the UK are now commonly found on the internet servings as evidence of efforts towards monitoring sustainability. Wackernagel et al, (2004) expressed that ecological footprint measures how much life-supporting natural capital, expressed in biologically productive area, is necessary to meet the resource demand and waste absorption requirements of a given population with links to demographic trends, economic expansions, changes in resource efficiency and economic prosperity. Efforts of the developers of this relatively young accounting tool to define its scope of application, provide answers to questions on interpretation and conceptual challenges have been well attended to in (Wackernagel, 1994; Wackernagel et al., 2004; Wackernagel et al., 2005)

On the aspect of human settlements and infrastructure, ecological footprint (EF) assumes that artefacts occupy agriculturally fertile lands hence the productivity of cropland is used as the basis for expressing the ecological footprint in global hectares (gha) of built-up area (A) as given in Equation 2.0. The equivalence factor (EqF) is the crop yield attainable in an area with an assumed level of input (water or fertilizer). The bio-capacity of different regions or countries can be obtained by scaling associated EF with a Yield Factor (YF), which gives the relative productivity measure of a given country with the global average of the same bioproductive area.

$$EF_{buit-up}\ (gha) = A_{built-up}(ha) \times EqF_{built-up}\ (gha/ha) \qquad (2.0)$$

3.7 Modelling databases

Every business or system has data (Stephens and Plew, 1998) that need to be managed. Many software systems are developed on the collections of data (databases) and managed through various existing database management systems (DBMS). In this research, data relating to materials, costs, lifecycle inventories etc. are required to implement the sustainability framework. As mention in the previous chapter, secondary data from existing processes and catalogues may be required for modelling the sustainability appraisal aspects of building. Table 3.3 shows some readily available information on primary energy and carbon emission for the various construction materials considered in the research. The information in the table is based on cradle-to-gate boundary conditions collected from secondary data sources as collated by the Sustainable Energy Research Team (SERT) at the University of Bath, UK (Hammond and Jones, 2011).

3.8 Reduction of uncertainty and risks

The BIM sustainability appraisal framework also includes aspects of uncertainty and risk analysis. This is required to reduce the degree of uncertainty that may be associated with outputs envisaged from the framework since it is based on assumptions about future behaviours (BS ISO 15686-5, 2008). While sensitivity helps to check the effects of choices made regarding the variability of methods and data on the output of a system, risk analysis assists in the identification of a distribution of probable outputs from the system. Researchers argue that a sensitivity analysis should precede risk analysis in other to identify the most sensitive variable which should form the element of investigation in typical risk analysis procedures (Christensen et al., 2005).

Table 3.3: Energy and carbon inventory for construction material (Hammond and Jones, 2011)

Material	Primary Energy (MJ/kg)	CO_2 Emission ($kgCO_2/kg$)	K CO_2e Emission gCO_2e/kg)
Steel			
Sections	21.5	1.42	1.53
Plate	25.10	1.55	1.66
Floor			
In situ Concrete	1.03	0.153	0.163
Metal Decking - Composite	18.8	1.3	1.38
Precast Floor - on Steel Beams	1.17	0.176	0.188
Roof			
Clay Tiles	6.5	0.45	0.48
Mineral Fibre Tiles	37	2.70	-
Metal (Aluminium)	155	8.24	9.16
Wood Shakes (sawn hardwood)	10.4	0.86	0.87
Cladding			
Fibre Cement (profile - 6m)	15.3	1.28	-
Metal (Aluminium - 0.7mm)	155	8.24	9.16
Metal (Steel - 0.7mm)	18.8	1.3	1.38
Over Purlin Linings - Plasterboard	6.75	0.38	0.39

3.8.1 Sensitivity analysis

Sensitivity analysis involves the perturbation of model variables over predetermined ranges to determine their relative effect on the model outcome (Christensen et al., 2005). It entails changing the values attributed to individual variables within specified bounds in repeated calculations to reveal the appropriateness of systems outputs (Ashworth, 1996). While sensitivity analysis reduces the degree of uncertainties with outputs, it may also help to identify the most significant assumptions required and the flexibility of constituent variables (BS ISO 15686-5, 2008).

In the proposed appraisal framework of this research the variables for perturbation are in two categories. One category is the option of material types used for framing, floor, roof and cladding works. While the option of framing material is limited to steel for the purpose of keeping the scope of the work suitable for prototyping, there is a minimum of three choices of material types for the other three building components as shown in Figure 3.4. Small changes in these material types can cause significant change in the overall measure of building life cycle cost. Having a good knowledge of such influences can assist designers in effective planning. The other category relates to the cost components of the various material types in line with Equation 1.0 for life cycle cost. Also, it is worth ascertaining which of initial cost, maintenance, inspection, repair, operation, failure and dismantling costs significantly affects the overall estimated life cycle cost of the building.

Notwithstanding, shortcomings exists with sensitivity analysis in that it is not able to identify dominant alternative among options, inability to simultaneously assess the influence of several variables of a model and the absence of defined probability distributions to explore particular values of variables (Christensen et al., 2005). For these shortcomings, risk analysis is used.

3.8.2 Risk analysis - Monte Carlo simulations

Risk analysis helps to quantify risk factors and identify the influence of each factor on the costs (Dawood and Bates, 2002). In risk analysis, probability mass functions or frequency distribution are used to describe values assigned to model variables through statistical sampling methods (Christensen et al., 2005). Monte Carlo simulation is a widely employed statistical technique in risk analysis

(Ashworth, 1996; Amar, 2006; Kwak and Ingall, 2007; BS ISO 15686-5, 2008). The theoretical background of the Monte Carlo Method and its application in this work are discussed.

(a) Theoretical background of the Monte Carlo Method

Monte Carlo, a name suggested after the capital of Monaco known for the game of chance, is a methodology that uses sample means to estimate population means (Dunn and Shultis, 2012). It is based on two fundamental statistical results, the Law of Large Numbers (LLN) and the Central Limit Theorem (CLT). According to Dunn and Shultis, Monte Carlo method is centred on obtaining an estimate of an expected estimated value of population mean or true mean as

$$\langle z \rangle = \int_a^b z(x) f(x) dx. \qquad (3.0)$$

Where, a and b are the bounding interval, $z(x)$ is a function and x is a random variable described by probability density function (PDF), $f(x)$.

If one forms the estimate of the sample mean as

$$\bar{z} = \frac{1}{N} \sum_{i=1}^{N} z(x_i), \qquad (4.0)$$

where x_i are suitably sampled from $f(x)$, the law of large numbers states that, as long as the mean exists and the variance is bounded,

$$\lim_{N \to \infty} \bar{z} = \langle z \rangle. \qquad (5.0)$$

Or, alternatively

$$\frac{1}{N}(\mathrm{z}_1 + \mathrm{z}_2 + . . . + \mathrm{z}_\mathrm{N})_{N\to\infty} \longrightarrow \langle z\rangle. \tag{6.0}$$

That is, eventually the normalised summation of Equation 4.0 approaches the expected value of Equation 3.0, where the nodes, x_i are sampled from the PDF $f(x)$ and weights of the nodes are equal to $1/Nf(x_i)$.

On the other hand, the Central Limit Theorem (CLT) gives the estimate of the uncertainty in the estimates. That is, how good the estimate of the answer is. It states that for an estimate, obtained from a distribution with mean $\langle z\rangle$ and standard deviation $\sigma(z)$,

$$\lim_{N\to\infty} Prob\left\{\frac{|\bar{z} + \langle z\rangle|}{\sigma(z)/\sqrt{N}} \leq \lambda\right\} = \frac{1}{\sqrt{2\pi}}\int_{-\lambda}^{\lambda} e^{-u^2/2}\, du. \tag{7.0}$$

Deductions from Equation 7.0 states as follows

1. The CLT says that the asymptotic distribution of $(\bar{z} + \langle z\rangle)/[\sigma(z)/\sqrt{N}]$ is unit normal distribution or equivalent, $\bar{z}$ is asymptotically distributed as normal distribution with mean $\mu = \langle z\rangle$ and standard deviation $\sigma(z)/\sqrt{N}$.
2. Nothing is said about the distribution function used to generate the N samples of z, from which the random variable $\bar{z}$ is formed. No matter what the distribution is, provided it has a finite variance, the sample mean $\bar{z}$ has as approximately normal distribution for large samples. The restriction to distributions with finite variance is of little practical

consequences because, in almost all practical situations, the variance is finite.

3. As $\lambda \to 0$, the right side of Equation 5.0 approaches zero. Thus, the sample mean $\bar{z}$ approaches the true mean $\langle z \rangle$ as N→ ∞, a result that corroborates the law of large numbers.
4. Finally, The CLT provides a practical way to estimate the uncertainty in a Monte Carlo estimate of $\langle z \rangle$, because the sample standard deviation can be used to estimate the population standard deviation $\sigma(z)$ in Equation 7.0.

Thus, the CLT provides an estimate of the uncertainty in the estimated expected value. Most importantly, CLT shows that uncertainty in the estimated expected value is proportional to $1/\sqrt{N}$, where N is the number of histories or samples of the PDF $f(x)$. If the number of histories is quadrupled, the uncertainty in the estimates of the sample mean is halved. Hence, Monte Carlo simulations thrive on increased number of sample runs.

Generally the Monte Carlo Method uses distribution functions with well-known mathematical formulations to describe variables (Jackel, 2002). Some of the frequently used distributions for Monte Carlo analysis include Uniform, Normal, Bernoulli, Binomial, Geometric, Poisson, Exponential, Gamma distributions etc.

(b) Application of the Monte Carlo Method

Risk analysis is one of the most tasking phases of the risk management (Dawood and Bates, 2002). It entails two major aspects; quantifying risk factors and determining their influence on aggregated costs. The application of the Monte Carlo Method in this research work dwells more in identifying the influence categories of cost component items and elements, as factors, have on the measure of life cycle cost. In this work a normal distribution is assumed for the variables which include building material types used for framing, floor, roof and cladding termed as the component element categories. The normal distribution curve is suitable because once the sustainability measure such as the life cycle cost is estimated; it is possible to obtain the minimum and maximum variation from the estimate by applying a predetermined factor for the sample range. This range then provides the known variable for generating the normal distribution curve. Table 3.4 gives the list of categories of building materials types and the number of available options for combination. There are a total of 12 material types which can be exclusively combined in 48 possible ways. To adequately assess the optimum use of material types, the sustainability performance (in terms of life cycle costing, ecological and carbon footprint) of the various plausible combinations of material choices need to be analysed. This requires the application of the principle of exclusive combinations to aid the identification of the best ranked combination option.

Table 3.4: Building components material type combination

Component	Material Options	Combinations
Framing	steel	1
Floor	In-situ concrete, Precast, Metal decking	3
Roof	Clay tiles, Concrete tiles, Metal sheets, Slate	4
Cladding	Aluminium, Steel, Fibre Cement, Plasterboard on metal	4

The Monte Carlo Method provides a further opportunity to examine the associated risk with the identified best performed option or any other chosen combination. Thus, random numbers can be generated, for example, around the estimated life cycle cost of the identified best performed option. These generated random values of life cycle cost make up the sample for which the sample mean can be calculated. The application of computer programming technology makes generation of such random values, in terms of scale and number of trials, possible in successive simulation runs. Trial runs can be increased in accordance with the Law of Large Numbers to reduce the degree of uncertainty in the estimated sample mean. In addition, the probability of occurrence of the sample mean can be obtained from a corresponding cumulative density function curve.

3.9 Choosing the most favourable design solution

In implementing the aspect relating to the selection of the best option among design alternatives, Multiple Attribute Decision Making (MADM) is employed in developing the sustainability score of the various design solutions. This is a more suitable option of multi-criteria decision analysis since the number of conceptual design options to be compared will be finite, as suggested by Yeo et al (2004) with their respective attributes obtained from running the prototype. The method also allows for the comparison of attributes with different units of measurement by the use of weighting factors. Thus the desirability score for each option is given by Equation 3 (Norris and Marshall, 1995). It gives the summation of the contribution of each attribute with respect to the cardinal numerical score for each alternative conceptual design solution.

$$D_j = \sum_{i=1}^{n} w_i \; x_{ij} \tag{3}$$

where, D_j = Desirability score for a particular alternative

n = Number of attributes associated with the options

w_i = Weight (normalised) of attribute or criteria

x_{ij} = Score of the alternative on the particular criteria

3.10 Summary

Two combinations of requirements were identified from the requirement elicitation process to formalise a framework for the sustainability appraisal of buildings based on contemporary building information modelling protocols. They were discovered from literatures and similar research work on the subject, stakeholder involvement and regression testing of framework implementation. One combination is the requirements for sustainability appraisal which includes system boundary, component and process flows, functional units and time dimension. The requirement for implementation is the second combination which include generality, formality, flexibility, ease-of-use, scalability and time-efficient are those identified. These requirements guided the development of the sustainability framework and subsequent implementation.

The components of the proposed sustainability framework were discussed in this chapter. It covered the underlying theories and reasons for including the various components in the framework. Feature-based modelling constitutes the umbrella of the framework as regards to implementation procedures. The conceptual model is obtainable from the design environment which interfaces with the implementation environment where the feature modelling is actually carried out after feature extraction activity. Chapter 5 discusses the implementation of these aspects in a greater detail.

Chapter 4

Developing the sustainability appraisal prototype

4.1 Introduction

The discussion on the implementation of the prototype is presented in three sections. These sections include the representation of the modelling framework, generation of the prototype and operation of the prototype. The first section gives a high level description of how the modelling framework is mapped to the implementation components. The composition of the components and functions are discussed in the second section while an insight into the operation of the prototype is given in the third section.

4.2 Representation of modelling framework

As illustrated in the previous chapter, the modelling framework can be sectioned into 3 parts; the Conceptual Model, Feature Extraction and Feature Modelling.

4.2.1 The conceptual model

The conceptual model refers to the digitized building model in a conventional BIM or product model format. In this implementation, the prototype is developed on the Revit® platform and so can be functional with .rvt extension BIM file. To demonstrate that the prototype has adequately considered interoperability needs and adaptability to other BIM platforms, an option for analysing conceptual design models expressed in neutral formats was also explored. The available open source neutral formats that could be used were gbXML and IFC. The use of gbXML was not suitable since it represents only information relating to building spaces and surfaces as required in green building design associated with HVAC (Dong et al., 2007; Zhang et al., 2011). On the other hand, IFC though with certain limitations relating to level of detail supported in the structural engineering domain, was found to be suitable. IFC representations capture the building's physical information and other information relating to management (planning, cost, scheduling and operation). As such building models saved as .IFC files can also be analysed by the prototype while operating within the Revit environment.

4.2.2 Feature extraction

Feature or component extraction is used to describe the linkage (interface) between the conceptual model and the feature modelling activity implemented in the C# object-oriented programming environment. It takes advantage of the fact that representations in the conceptual model observe rules and object-based modelling. As such, the associated mappings allow for the extraction of information related to structural engineering elements instantiated in the conceptual model onto the system for onward sustainability analysis.

For conceptual models in Revit Structures™, the associated mapping is shown in Figure 4.1. The feature elements such as columns, beams, floor etc considered in the prototype are mapped into the Revit Interface as RevitElement belonging to RevitAPIObject. RevitElement has three different family categories; ComponentElements, HostElement and StructureElement to which elements belong. For example, columns and beams belong to component elements on the Revit Interface and transmit as sustainability elements on the sustainability extension (feature modelling) side. The inherent possibility of this type of object mapping presents a good advantage in enhancing the feature extraction activity. This is because the mapping of objects helps to establish the process of identification and recognition of features of interest in the conceptual model. In addition, the associated mappings serve as means for transmitting abstracted information from the feature recognition activity.

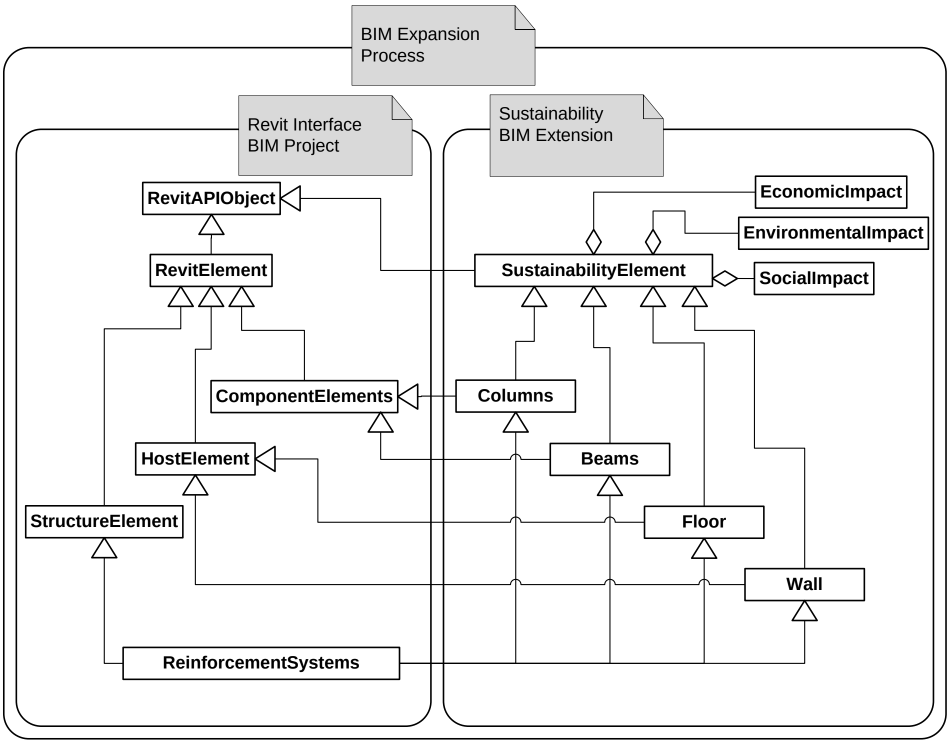


Figure 4.1: Mappings linking sustainability extension to BIM project (Revit Structures)

For conceptual models in IFC representations, the feature extraction activity is somewhat different. The .IFC file is a text based file so the feature extraction is carried out by fundamental string and character programming manipulations.

4.2.3 Feature Modelling

After extraction of the feature information into the prototype, all other follow-up actions such as interaction with the modelling database (feature library), estimation of material quantities and costs, calculation of sustainability measures and multi-criteria decision analysis all constitute aspects of feature modelling. The underlying implementation takes advantage of the object oriented paradigm to instantiate objects relating to these aspects. It has been structured according to the selected source of the conceptual model; whether manual entering of one element after the other, automatic mode of extracting features from .rvt BIM project or loading information from .IFC BIM representation. The feature extraction and subsequent modelling for sustainability are discussed in greater detail in the next section.

4.3 Generation of the Prototype

The prototype has been generated via the development of requisite use-case scenario in a conceptual structural design process. This was followed by the representation of various actions, components and associated interactions as a combination of objects, classes and events. The mappings and sequencing of the representations have been carried out in a programming environments such as the Microsoft .NET Frameworks. Also, flow charts have been useful in capturing processes and events in modelling components of the prototype. This section discusses these aspects.

4.3.1 Use case analysis

The stages of software life cycle include analysis, design, implementation, testing and debugging, deployment, maintenance and retirement. The analysis stage which can be achieved through requirement gathering, is concerned with precise problem definition; solving the problem right and solving the right problem (Deitel and Deitel, 2008). Use-case modelling diagrams provide a starting point for capturing system structure, behaviour and functions (Geyer, 2012; Geyer and Buchholz, 2012). It helps to project how a system will be used and describe the different capabilities associated with the system with respect to the actor and the various system functionalities. In this research the user is targeted to be the structural engineer. The ultimate system functionality is directed at the structural engineer becoming informed on the appraisal of the sustainability of alternative design solutions.

Figure 4.2 illustrates the UML diagram resulting from use-case elicitation of this research. The sources of information for developing the use-case process are literatures (Deitel and Deitel, 2008; Geyer, 2012; Geyer and Buchholz, 2012) and similar research work (Svanerudh, 2001; Ugwu et al., 2005; Fahdah, 2008) on the subject and refinement through regression testing of framework. This method of requirement capture has been used because the behaviour of the system and how the designer interacts with it are likely to be similar to typical sustainability related design decision support systems. Since the interaction between majority of software systems and users takes place via screens, windows, or pages, usage scenarios can be captured from existing documentations in the research area. An example of such application is the object oriented life cycle assessment framework for bridges described by Ugwu et al. (2005).

The developed use-case has been used to guide the implementation of programming direction in this work. It entails the structural engineer registering his project information and design details, and feeding in required information related to cost components, impact of elements and time. The economic and environmental appraisal could then be carried through appropriate indexing and weighting strategy from generated results on the corresponding indicators. At this stage, the onus rests on the engineer on how to combine the indicators to make a judgement vis-à-vis other factors such as prestige, future potential changes and project longevity (Bull 1993).

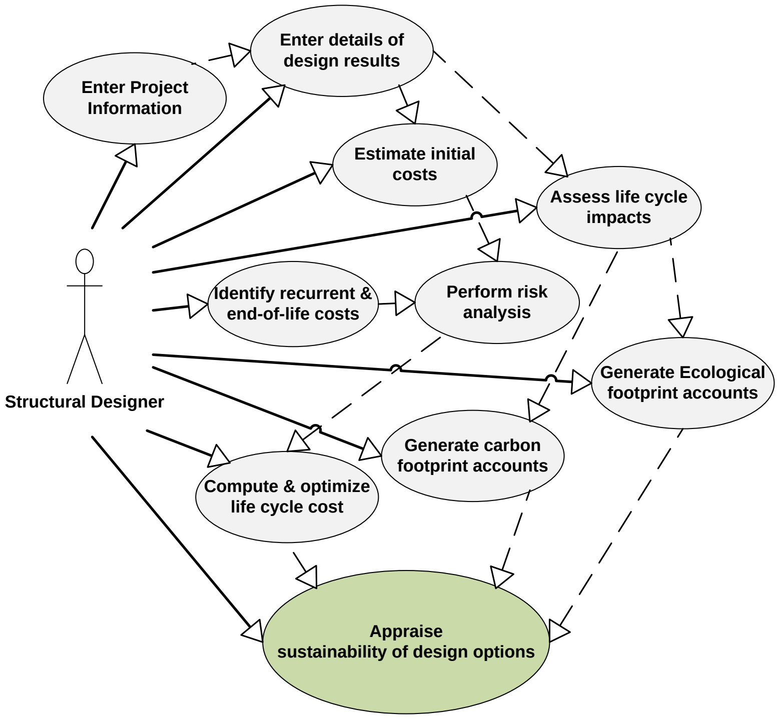


Figure 4.2: Use-case diagram

4.3.2 Implementation procedure

Flow charts constitute means for communicating steps employed in solving a problem or carrying out a task. Flow charts are commonly are usually characterized by sequence of events, decisions on alternative paths and repetition of processes. Besides the improvement of readability, flow charts have the benefit of aiding readers to understand and reproduce the functionality of implementation codes without specific knowledge about the programming language used. For implementation tasks, presentations may vary from generic/conceptual on one side of the scale to detailed presentation of programme code on the other side (Svanerudh, 2001). The flow charts illustrating the implementation aspect of this research is a hybrid of the extremes on the scale. The reason for this is to achieve a good degree of simplicity and clarity in presentation. Also, it helps to ensure that important steps are shown while imbedding details that are less important in communicating the desired flow of messages.

The implementation of the prototype in this research is represented with a main flow chart (level 0) for sustainability estimation that branches into six Level 1 charts and two Level 2 charts in order to show vital levels of detail. The Level 2 charts tend to correspond with certain entities depicted in the Use Case Diagram (Figure 4.2) such as Initial Cost Estimation, Life Cycle Cost Estimation, Carbon Footprint Measure, Ecological Footprint Measure, Multi-criteria decision making, Risk Analysis and Sensitivity Analysis.

(a) Sustainability Estimation Flow Chart

The top level (Level 0) sustainability estimation chart is given in Figure 4.3. The flow chart commences with a call to the structural sustainability estimation (SSE) programme. This can be done in a building information modelling environment such as the user interface of Revit Structures while carrying out conceptual design and modelling of a building. The next requirement in the sequence of events is to provide requisite identification for the project by registering project information and assigning design option IDs. The sequence of events then flows through a decision making process on three alternatives (Manual entry of building elements, Assess building from IFC model or Assess building from native BIM format) to extract building features for onward sustainability assessment. Once this decision is made and the relevant features are extracted, the sequence of assessment steps through the estimation of Initial Cost, Life Cycle Cost, Carbon Footprint, and Ecological Footprint which are correspondingly detailed as charts levels *1a*, *1b*, *1c* and *1d* (Figure 4.3, Figure 4.4, Figure 4.5 and Figure 4.6 respectively).

The user could explore the performance of various combinations of materials in what-if scenario situations detailed as Level *1e* chart (Figure 4.7). After saving the estimated measures of the indicators, the process can be repeated for more design options and eventually compared on multi-criteria basis of the three sustainability indicators. The process of comparison has been detailed as chart Level *1f* (Figure 4.8). The comparison then brings out the most favourable design based on the relative performance of the design options. The last event in the sequence before termination is to produce necessary reports for the assessment.

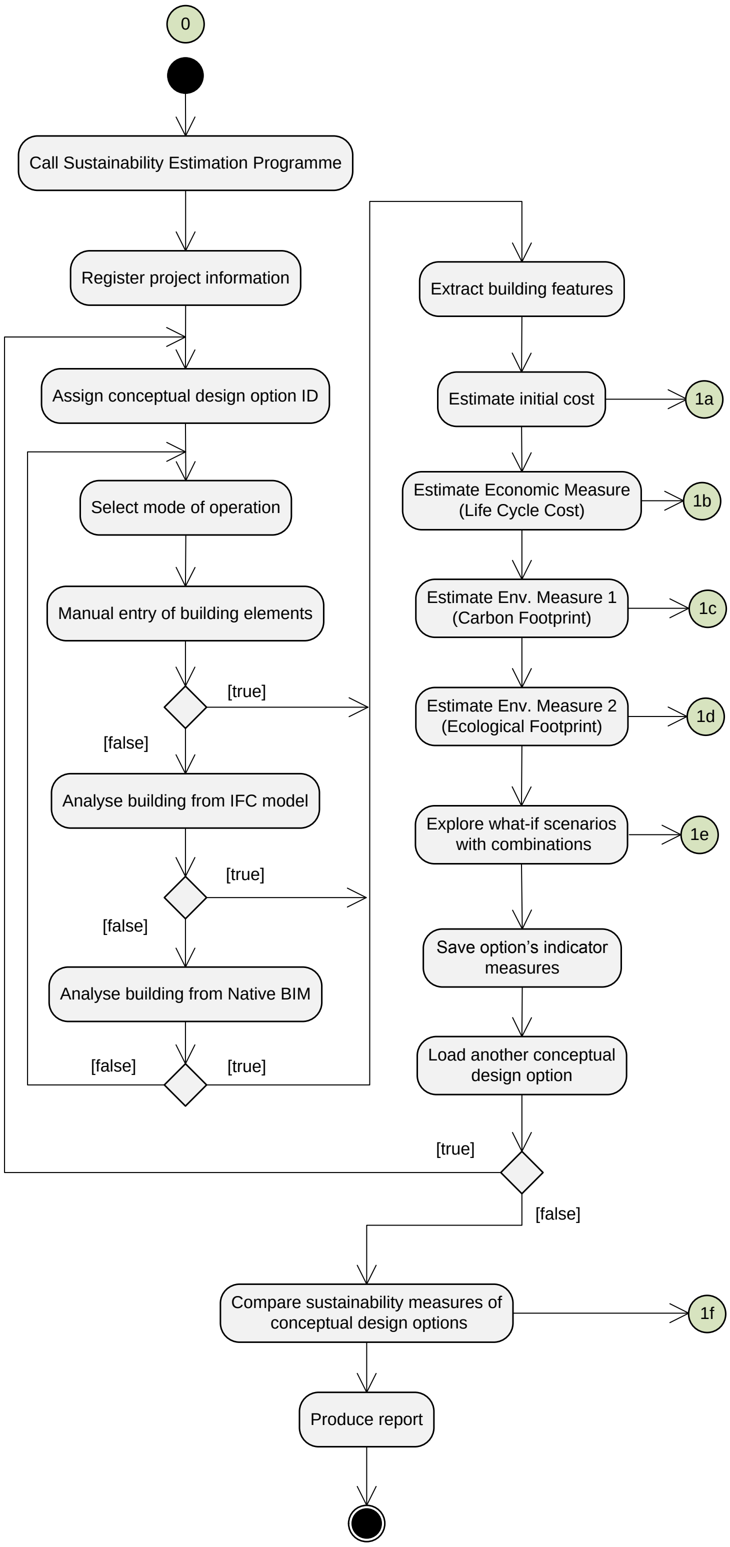


Figure 4.3 Sustainability Estimation Flow Chart (0)

(b) Initial Cost Estimation Flow Chart

In the Initial Cost Estimation Chart (Figure 4.4), extracted features and their corresponding properties and quantites are placed in tables according to component cartegories such as frame (beams and columns), floor, roof and cladding. This will allow easy interaction with a database management system to draw up corresponding cost information. It is important that information prone to changes such as cost remain in a database separate from actual programming environment because of the need to update records periodically. After the cost of all individual elements have been calculated, the sequences moves on to sum the costs according to component categories and for the overall initial cost. At this stage it is possible to perform an early check of risks of the estimation and also identify the most senitive cost component or component element cartegory. The steps involved in this process are given as chart levels *2a* and *2b*.

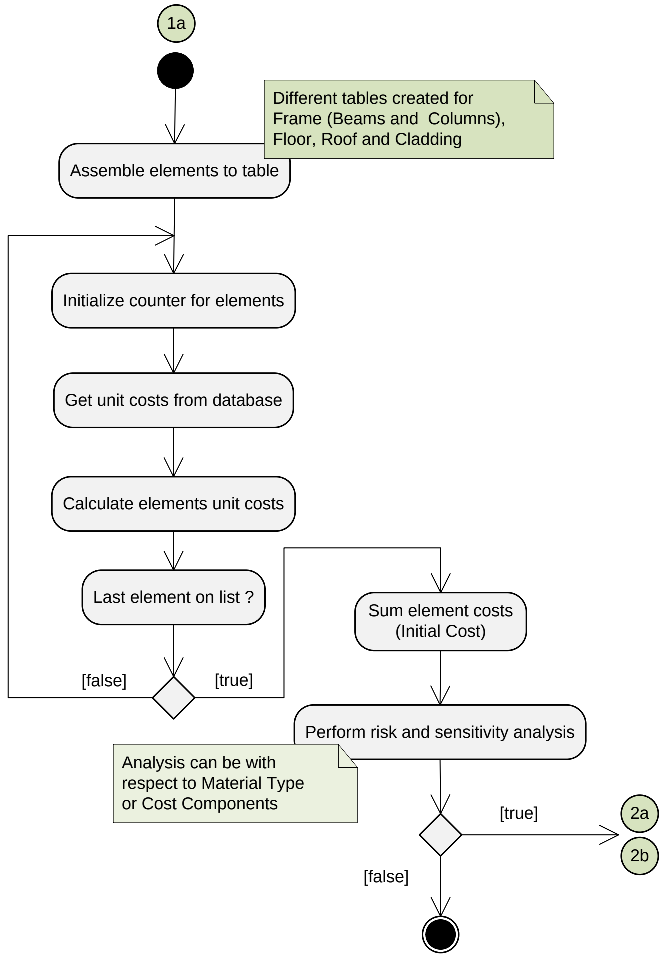


Figure 4.4: Initial Cost Estimation Flow Chart (1a)

(c) Life Cycle Cost Estimation Flow Chart

The Life Cycle Cost Estimation Flow Chart (Figure 4.5) starts by initializing the initial cost of the component element categories (Frame, Floor, Roof and Cladding). It flows through getting information such as design life and discount rates needed for the conversion of costs to present day money value. The flow chart then steps through the estimation of various cost components such as maintenance, decommissioning and residual value to aggregate the life cycle cost of components categories. This is used to obtain the overall life cycle cost. The measure of life cycle cost for design options can be further examined by the application of risk and sensitivity analysis as given by flow charts levels *2a* and *2b*.

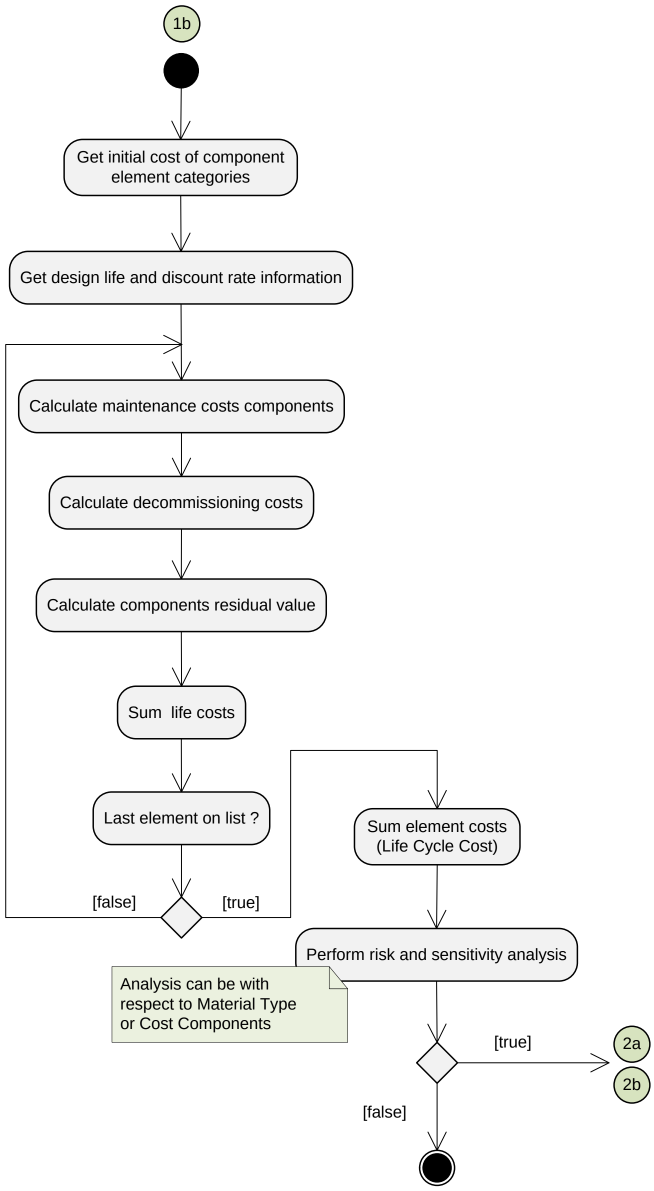


Figure 4.5: Life Cycle Cost Estimation Flow Chart (1b)

(d) Carbon and Ecological Footprint Measure Flow Charts

The environmental assessment aspect is represented by the carbon measure flow chart (1c) and ecological footprint measure charts (1d) shown in Figure 4.6.

Each of these charts has been presented in a single flow of events. While the user is required to supply options for end-of-life boundary conditions, the processes rely on the accompanying database management system to supply information on emission factors, ecology factors and embodied energy of materials. These are combined with abstracted quantities to calculate the carbon footprint and ecological footprint measures of the design options.

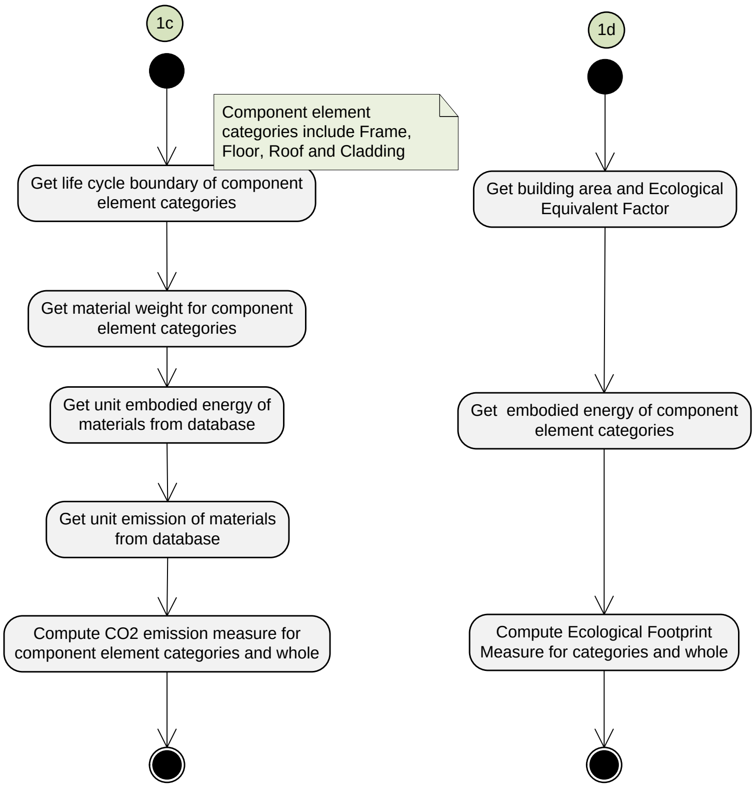


Figure 4.6: Carbon Footprint (1c) and Ecological Footprint Measure (1d) Flow Charts

(e) Flow chart for what-if scenario applications

The purpose for this chart is to make provision to check and compare the performance of combination options for other material type featuring in the prototype. This allows the user to be abreast with alternative materials to consider as substitute if the need arises. The assumption in the flow chart is that the three indicator measure for the combination option abstracted from the building model form part of the options for consideration. The early actions in this chart centres on initializing the existing material types by name, quantities and the estimation of their respective costs according to component element categories. The material types are then exclusively combined and assigned option identification (ID) numbers. Indicator measures are then produced based on these combination IDs and shown in charts for ease of reading. The flow chart further takes advantage graphical impressions to highlight combination options based on magnitude of their corresponding indicator measures or by the selection of ID numbers.

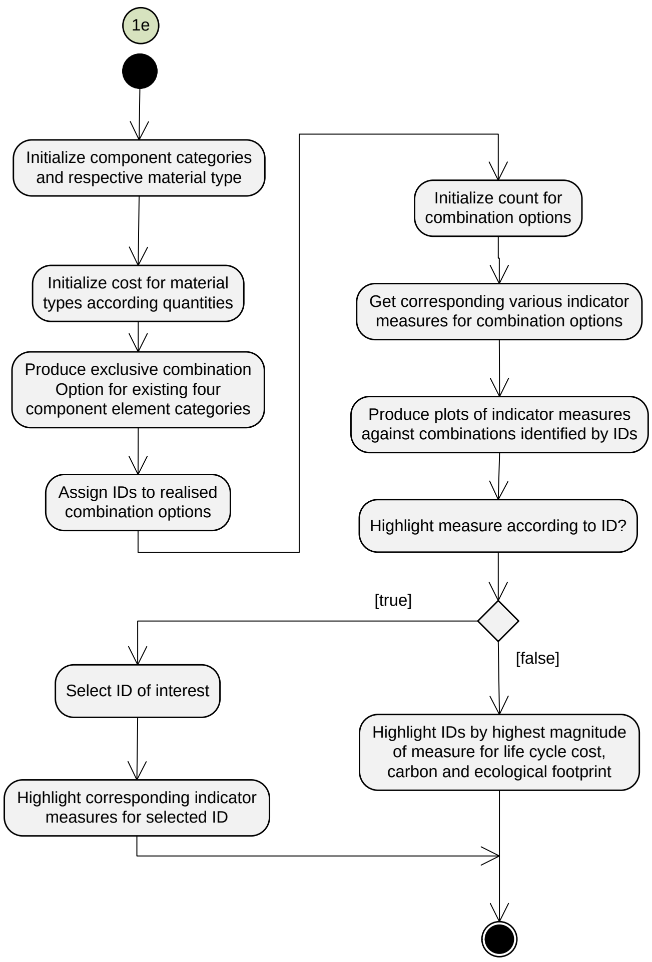


Figure 4.7: Flow chart for what-if scenarios

(f) Multi-criteria Decision Making Flow Chart

This Level 1 flow chart (Figure 4.8) compares design options based on the principle of multiple criteria decision method. It essentially combines criteria with different units by apportioning performance weightings to calculate relative score of options. The flow chart has been developed to compare two or more design options. Thus, the sequence of actions commences by loading indicator measure for more than one design option obtained from previous assessment exercise and then specifying the indicator weightings. Weightings are provided at two levels. The first level is the economic and environmental contributions. How the carbon and ecological footprint are to be combined for the environmental aspect is specified at the second level. The final action is to compute relative scores for the various design options being compared and identifying best ranked option by the magnitude of their scores.

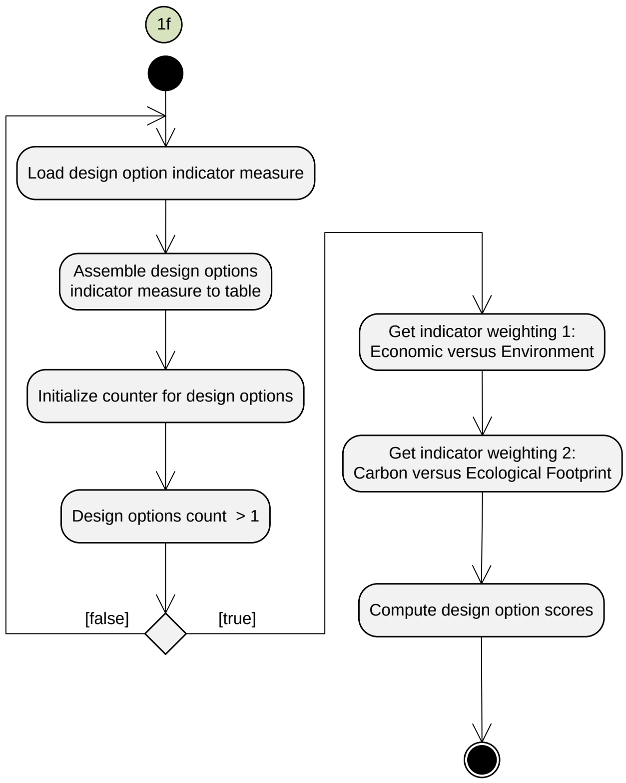


Figure 4.8: Multi-criteria Decision Making Flow Chart (1f)

(g) Risk Analysis (Monte Carlo Method) Flow Chart

Risk analysis can be performed for the initial cost and the life cycle cost of the structure in this implementation of the research. The same flow chart (Figure 4.9) is valid for either case. This level 2 chart commences by initializing the cost information for cost component items (Initial Cost, Maintenance, Decommissioning and Residual Value) or the component element categories (Frame, Floor, Roof and Cladding). The next action is to specify the number of trials or seed and to set the number of bands for apportioning frequency of occurrence. The range of the sets of bands fluctuates around the various initialized cost information of components in the previous step. After the number of trial runs attains the seed on performing a simulation, the band with the highest frequency is identified as the most probable outcome from the analysis. The knowledge of this value can be used as a basis for re-assessing the desirability score of design options and in making final decisions.

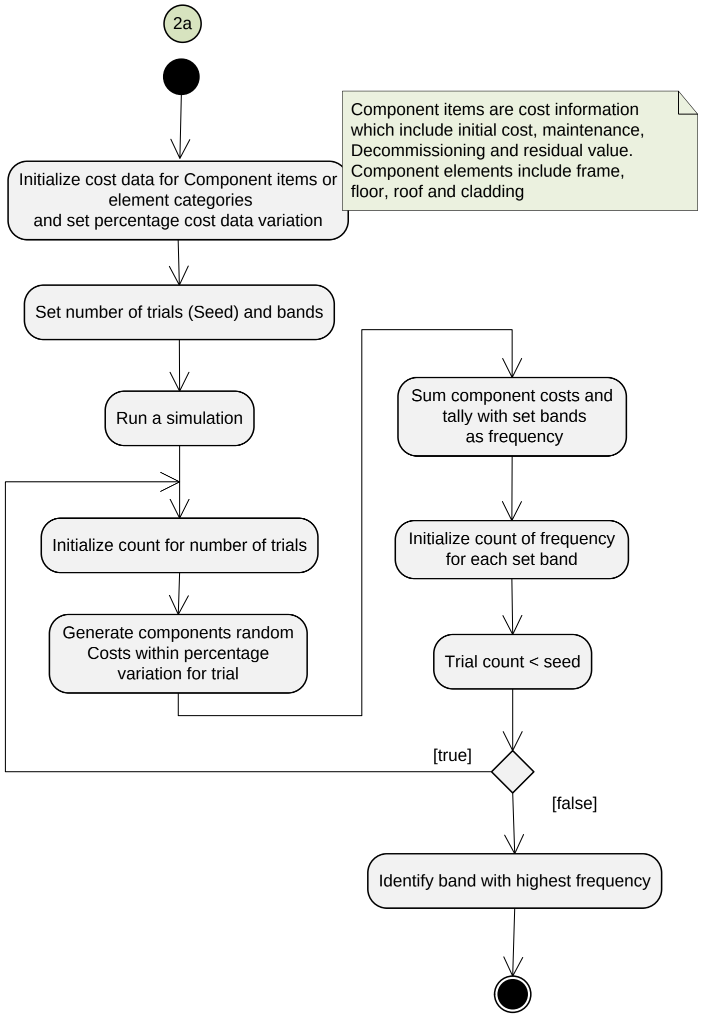


Figure 4.9: Risk Analysis (Monte Carlo Method) Flow Chart (2a)

(h) Components Sensitivity Flow Chart

Like the Risk Analysis Flow Chart, the Components Sensitivity Flow Chart (Figure 4.10) can consider cost component items or component element categories. The first action is the initialization of the cost data and then specifying the control percentage variations for components. The next step is to run a simulation which alternates the control variation for the cost of the various components to generate sets of pairs of cost data which can be plotted to graphically identify the most sensitive components.

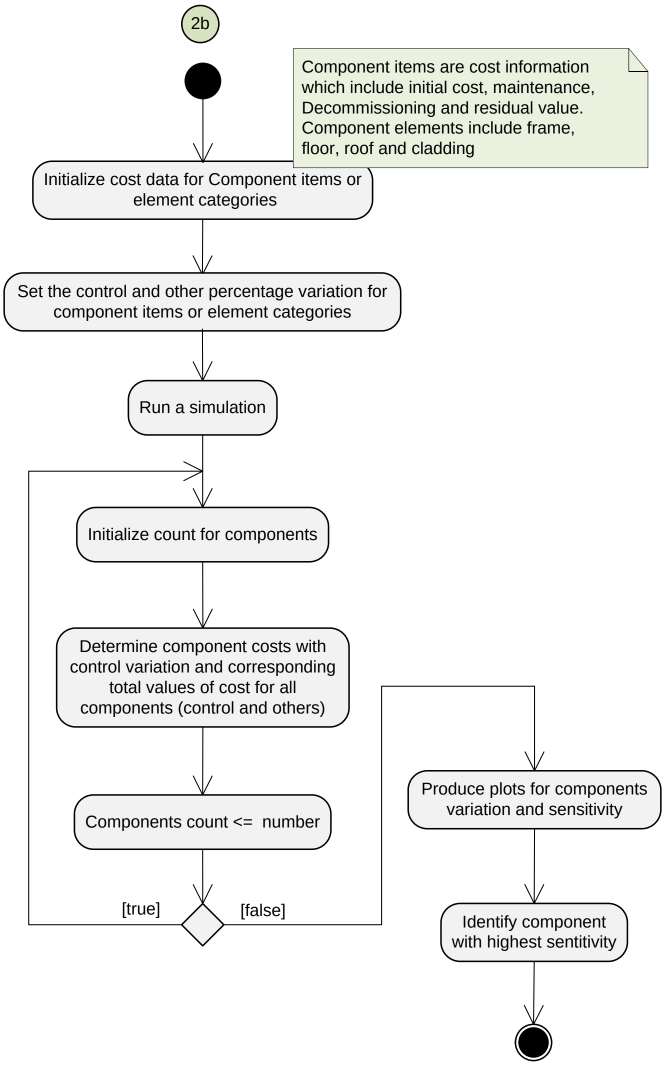


Figure 4.10: Component Sensitivity Flow Chart (2b)

4.3.3 Object representation and database formulation

Another vital aspect of prototype implementation requires the mapping of frameworks, architectures, flow charts and entities to objects and rules for initialization and instantiation as programmable codes. This requires knowledge both in the construction domain and a computer programming language. In many cases, it is easier and more practicable for objects and rule representation to reflect existing knowledge and principle in the application domain. In this way, written codes can easily be read and understood by others. The implementation aspect of this research applied this premise in the representation of objects in the programming environment and database management system of the prototype.

(a) Object representation

Figure 4.11 shows some examples of objects featured in the prototype. The main objects include COMPONENT, FRAME, FLOOR, ROOF CLADDING, COST, INDICATORS etc. These main objects are decomposed down to child objects. For example, FLOOR has child objects as types of floors such as in-situ concrete, precast – on steel beams, and metal decking. Also the main-objects SECTION and CONNECTION give rise to child-objects such as universal beam (UB) and universal column (UC) as SECTION types, characterized by Plate, End Plate, Haunch etc. as associated CONNECTION. Similar reasoning have been observed in representing other main-objects working together and governed by object-rules and relationships. These objects have been correspondingly represented in a database system to store object properties and information liable to change with time.

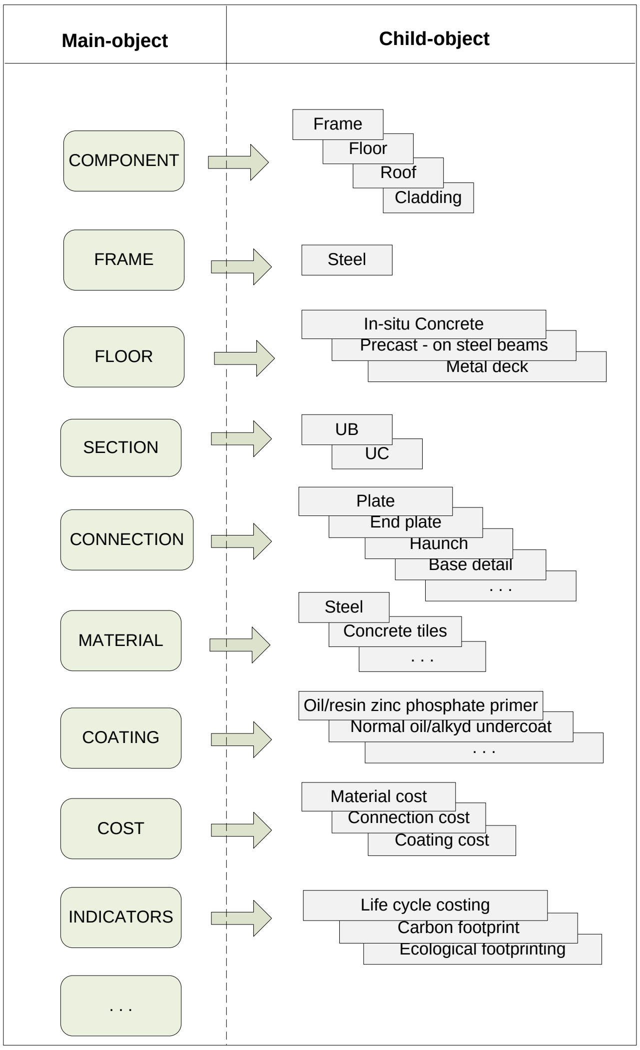


Figure 4.11: Implementation Object Representation

(b) Prototype database

The prototype database is a vital component of the sustainability framework implemented in SQL database management system. The database is relational and holds information on properties, costs, carbon emission values, embodied energy values, end-of-life boundary conditions etc. related to objects. Figure 4.12 shows the tables for the four component elements (Frame, floor, Roof and cladding) featured in the implementation of the prototype. The AllSectionsData Table (Frame) contains properties of both universal beams (UB) and universal columns (UC) as well as cost details of sections and associated connections. Also, the other tables for floor, roof and cladding hold the various components IDs and components types (e.g. FloorType) the category for child-object (in-situ, metal decking). Corresponding values of unit primary (embodied) energy and carbon values are included in the tables. These values have been sourced from existing information as discussed in Section 3.7.

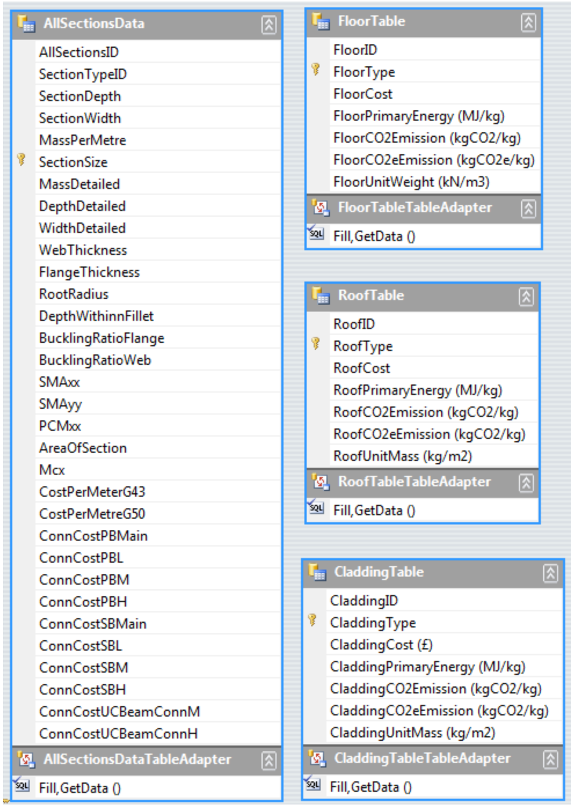


Figure 4.12: Main components database tables

Figure 4.13 shows further detail of the tables associated with Frame Object. Primary key relationships are used to establish communication within the database and with the programming environment. The Frame Object database generally consists of two central tables, the AllSectionData and the SectionType tables are shared between two groups of tables for universal columns and universal beams. Information is extracted from the database into the programming environment by means of requisite connection string via the allocated primary keys.

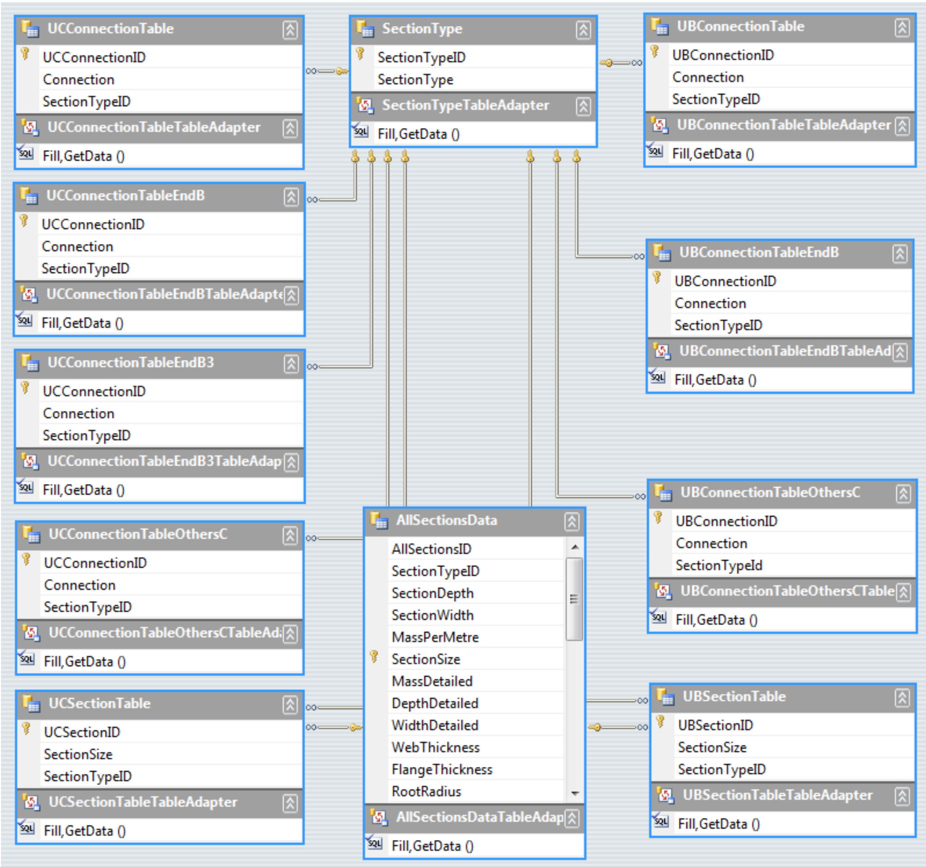


Figure 4.13: Frame component relational database

4.3.4 Components description

The feature extraction part and the modelling aspect constitute the main components of the implementation in the programming environment (see Figure 4.14). The Command Class, assisted by the GeomHelper and GeomUtil, combines with the OperationMode Class to extract information from building models. Extracted information are passed unto the sustainabilityEstimator Class to perform the required sustainability analysis. The sustainabilityEstimator communicates with the modelling database to draw up corresponding information on cost and life cycle information to carry out typical sustainability analysis.

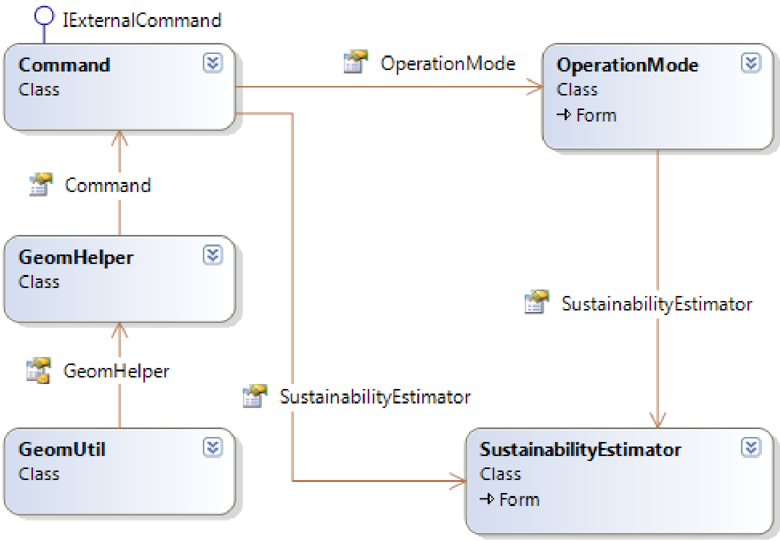


Figure 4.14: Static structure of prototype main implementation components

(a) Feature extraction components

The Command, GeomHelper, GeomUtil and OperationMode classes work together to transfer extracted feature information from conceptual building model to the feature modelling component (Figure 4.15). For .rvt-based conceptual models, the Command Class holds the link (IExternalCommand) to external programme, in this case Revit Structures^{TM}. The GeomUtil contains geometric-related functions that assist the GeomHelper in obtaining geometric properties of feature when called by the Command Class. Information extracted in this mode is usually passed via the OperationMode, a derived class of windows form, to the modelling component. The Command, GeomHelper and GeomUtil have been developed and modified based on RevitAPI-assisted programming guidance (Autodesk, 2010).

In the case of IFC model, extraction of feature information is performed independently by the OperationMode class, programmed to open and iterated through a .IFC file to identify required information. A .IFC file (STEP physical file) is in the text format defined by ISO 10303-21, where each line typically consists of a single object record in a compact and readable form. This type of IFC file format can be seen to contain information expressed in regular representation pattern when opened in text-based programme such as Notepad (given in Appendix 1). The prototype therefore takes advantage of the fundamental string and character programming manipulations existing in C# to extract required feature information. The system reads the IFC file to identify prescribed lines and particular information satisfying specified conditions dictated by the feature element characteristics. On the aspect of manual input of information on building elements, the prototype accepts information within the modelling component interface discussed next.

(b) The feature modelling components

The modelling database and the sustainabilityEstimator comprise the main feature modelling components (Figure 4.16). The modelling database has been tagged SteelSectionsDataSet, a derived Dataset Class containing information on materials, costs, lifecycle information about building elements. It is a relational database implemented in MS SQL and linked through requisites connection string within the C# environment. It is possible to update the database where necessary to keep abreast with contemporary information and emerging changes in costs. In course of the implementation, the author discovered that to get the conceptual modelling environment configured to using the database after been added to the programming environment, copies of the database primary file and transaction log file must be added to the Program Directory of the installation folder of the BIM platform, Autodesk in the Computer's programs file. This action need to be performed for synchronisation each time the database is updated.

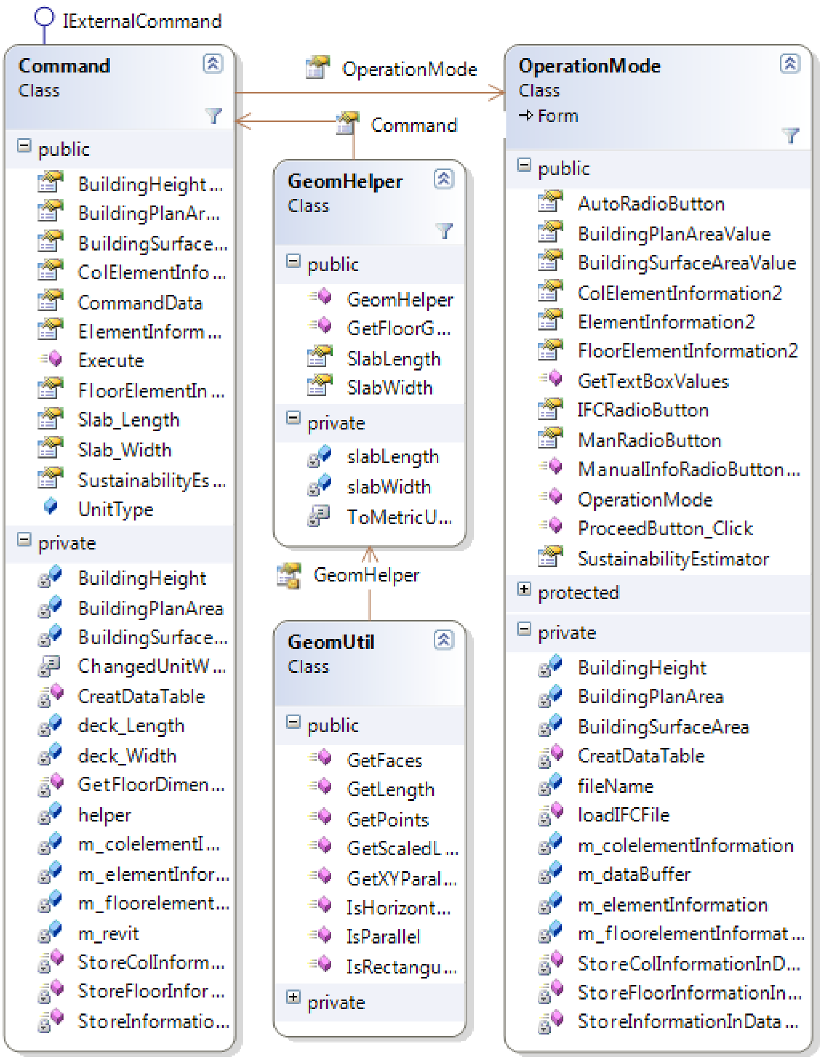


Figure 4.15: Components of feature extraction implementation

The sustainabilityEstimator is a windows form-based class embedded with series of programming methods and event handlers that work together in the analysis process. It is also associated with a number of form-based classes performing various functions as seen in the figure. The key methods can be grouped into seven, according to their functions. The report presents a more detail description of these groups in the next section.

(i). Provision of information on elements extracted from the conceptual model
(ii). Performance of the sequential transfer of element information into tables
(iii). Processing of element information to obtain material quantities and initial costs
(iv). The estimation of corresponding sustainability indicator measures
(v). Risk and sensitivity analysis to optimize estimated life cycle cost and the influence of associated components.
(vi). Calculation of desirability score through multi-criteria decision analysis
(vii). Production of reports through implemented reporting service

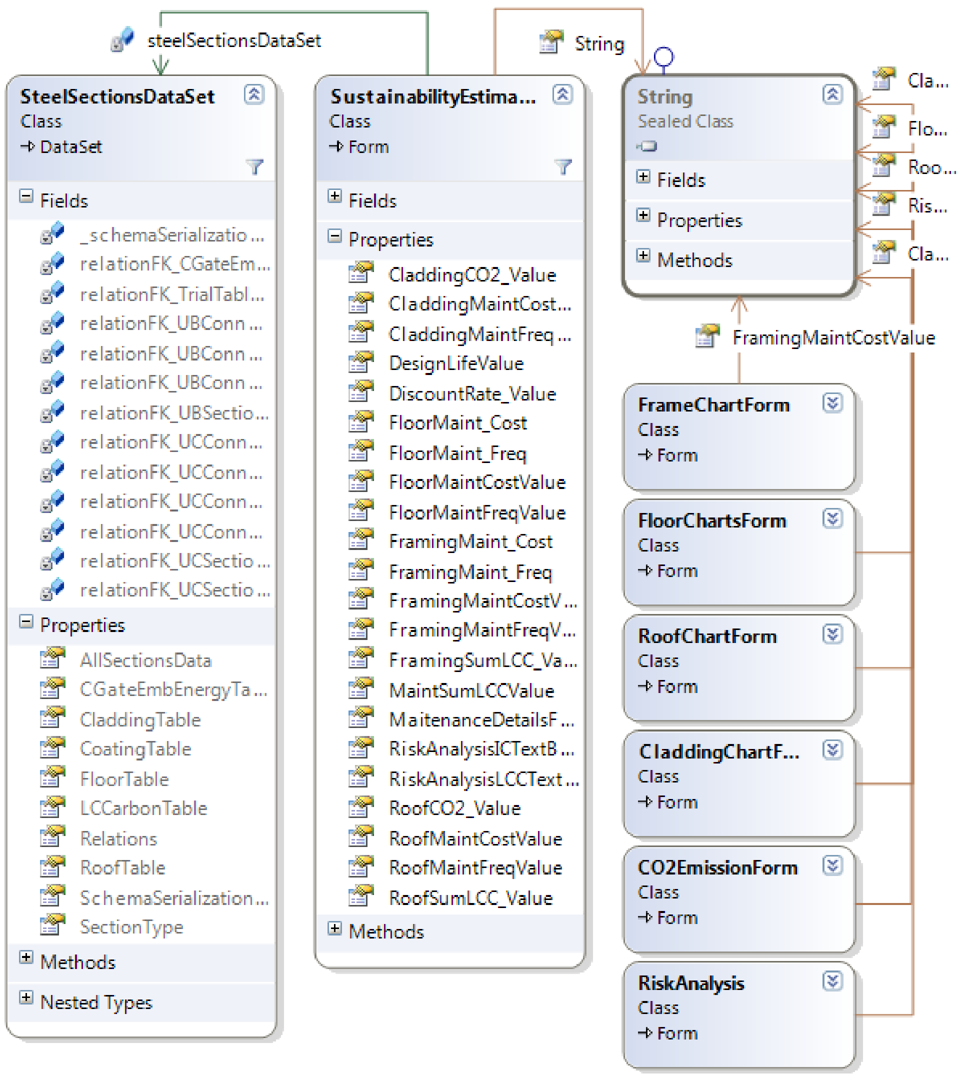


Figure 4.16: Components of feature modelling implementation

4.3.5 *Functional description of core modelling events*

The discussion of the functional description of the core modelling events featured in the prototype is categorised into seven aspects as presented below.

(a) Provision of information on elements extracted from the conceptual model.

The methods responsible for receiving element information include Elements_AutoMode, Elements_IFCModel and Elements_ManMode. The

Elements_AutoMode is responsible for the extraction of information from Revit BIM model, IFC model is handled by Elements_IFCModel while the Elements_ManMode deals with information from manual input. Typical information handled by these group of functions include element names and types, element identification numbers such as Universal Identification (UID) tags, elements dimensions, connection details and number of element. They also interact with the modelling database to provide corresponding elements costs.

(b) Sequential transfer of element information into tables

Information from elements describe in (a) are collated based on transaction with three dataTables; ElementInfo, ColElementInfo and FloorElementInfo, and transferred to three corresponding dataGridViews for beams, columns and a combination of floor, roof and cladding. This collation allows for inspection of abstracted information, possible modifications, and for easy manipulation by subsequent functions.

(c) Processing of element information to obtain material quantities and initial costs.

The Methods, CalculateTotalCostWt and CalInitialCost are both responsible for selecting quantities of various materials and the aggregation of their initial costs. The total weight of sections and initial cost are calculated based on information stored in the datagridViews discussed in (b).

(d) The estimation of corresponding sustainability indicator measures

Special form classes that interact with the SustainabilityEstimator class were designed to execute this task. These classes include the FrameChartForm, FloorChartForm, RoofChartForm, CladdingChartForm and CO2EmissionForm

(Figure 4.17). The first four classes respectively produce the lifecycle cost of frame, floor, roof and cladding elements. Risk analysis, detailed in the next subsection, can be performed on the estimated total life cycle cost of the frame. The designer has the option of using either the optimized value or un-optimized value to carry on the sustainability analysis. The CO2EmisionForm combines all the elements to estimate the structural carbon footprint and ecological footprint. These classes receive input information from the SustainabilityEstimator and return estimated measures back to it. An additional function attached to the classes is the production of corresponding individual charts.

(e) Risk analysis to optimize estimated life cycle cost

Section 4.7 outlines the statistical theory applied in the risk analysis method employed in this research. It has been implemented in the RiskAnalyis Form Class (See Figure 4.18). This class is called through PerfRiskAnalysisButton_Click event in the SustainabilityEstimator Form Class. The RiskAnalaysis Class has been developed based on Monte Carlo Method. It contains methods that use React.NET Reference to generate random values in a Normal Distribution regime around the estimated life cycle cost of the structure. An optimized value of the estimated life cycle cost is generated from this analysis which is passed on to the SustainabilityEstimator Class. In the aspects of sensitivity, statistical algorithm has been implemented to check the components (items costs or elements costs) of the estimation to show the degree of their respective influence on life cycle cost.

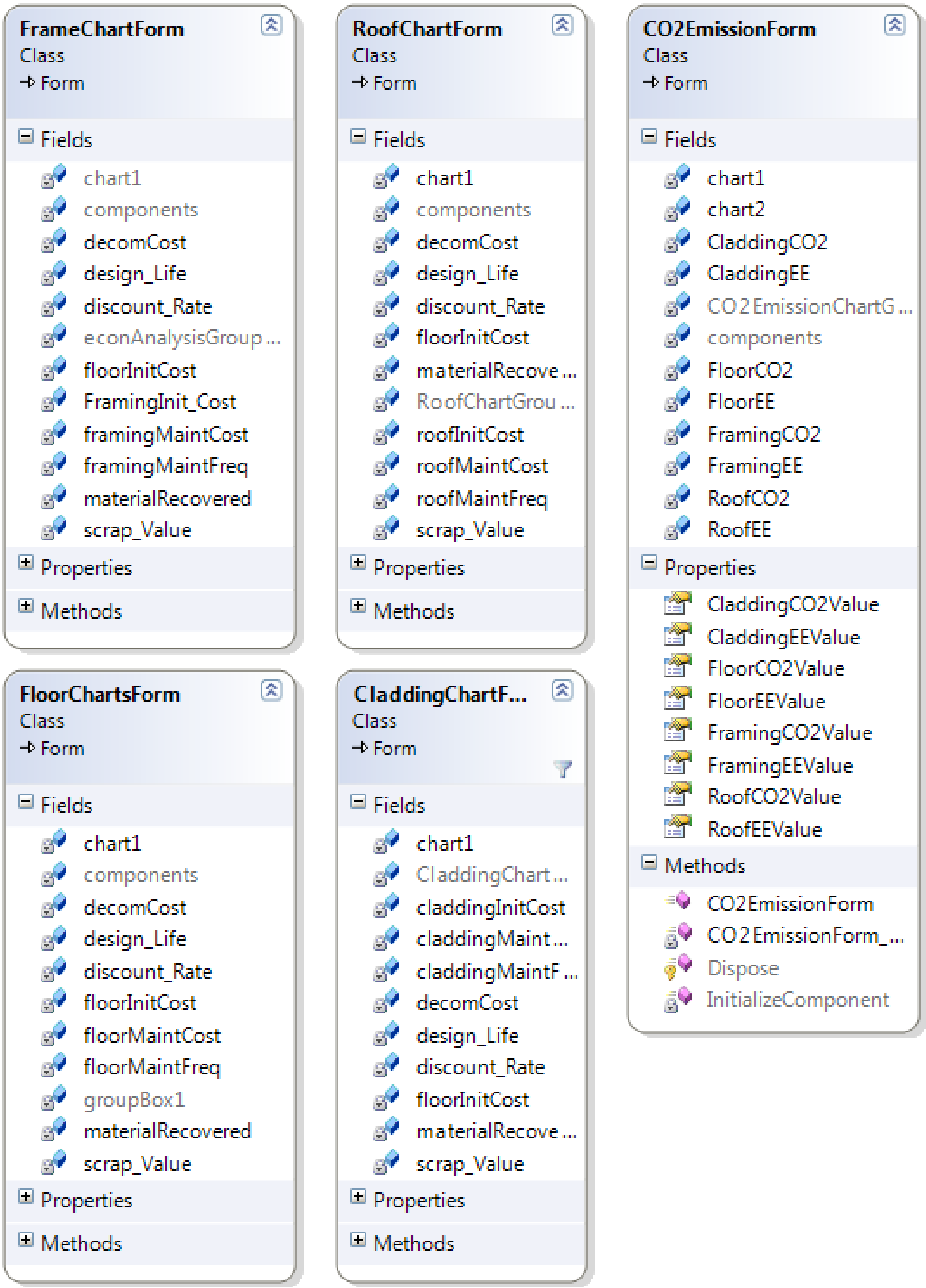


Figure 4.17: Components of sustainability indicators measure implementation

(f) Calculation of desirability score through multi-criteria decision analysis

This function is handled mainly by the LoadCurrentButton_Click, LoadAlternativeButton_Click and the OptionsScore_Click events. The first two event-handlers execute aspects pertaining listing sustainability indicator measures of design options in a table (dataGridView) in preparation for multi-criteria comparison. The OptionsScore_Click carries out the multi-criteria decision analysis and produces a corresponding chart. The implementation ensured that the number of options comparable at any point in time is scalable.

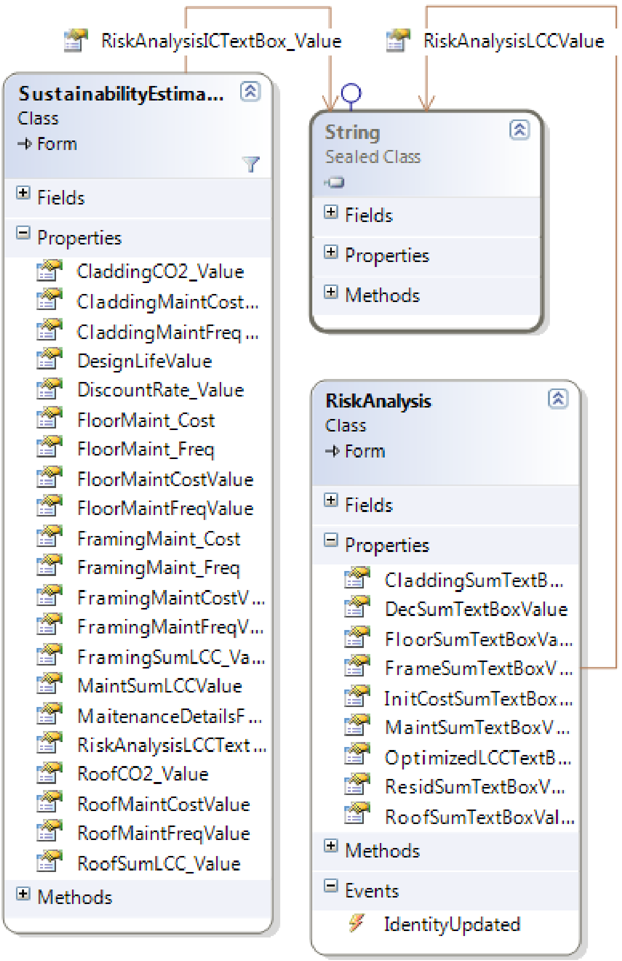


Figure 4.18: RiskAnalysis class and related event handlers

(g) System reporting service

This is the concluding part of the modelling events; intended for the production of desired reports for record purposes and further analysis. To accomplish this aspect, internal methods within the SustainabilityEstimator class were combined with external classes in the implementation. The key internal methods include runRptViewer, RptGetDatasetElem and RptGetDatasetInd. The runRptViewer initiates the command to bring up reports. The Latter two directs this command to report on information concerning input elements and indicator measures respectively. On the interim, reports can be executed for one design option at a time but can be improved to a greater level of sophistication. The external supporting classes are depicted in Figure 4.19. They assist in the production of dynamic reports through the generation of the requisite report definition language (RDL). The TableRdlGenerator creates tables in RDL format while the RdlGenerator supplies and serializes the data into the created table. This information is then communicated to the SustainabilityEstimator for output on the screen. RDL is a Microsoft proposed standard for defining reports and uses XML schema applications with SQL Server reporting services. The version used in this work has been generated in accordance with the 2005 Definition Standard, 2.0.50727.42 XSD Tool Runtime Version (Gotreportviewer, 2010).

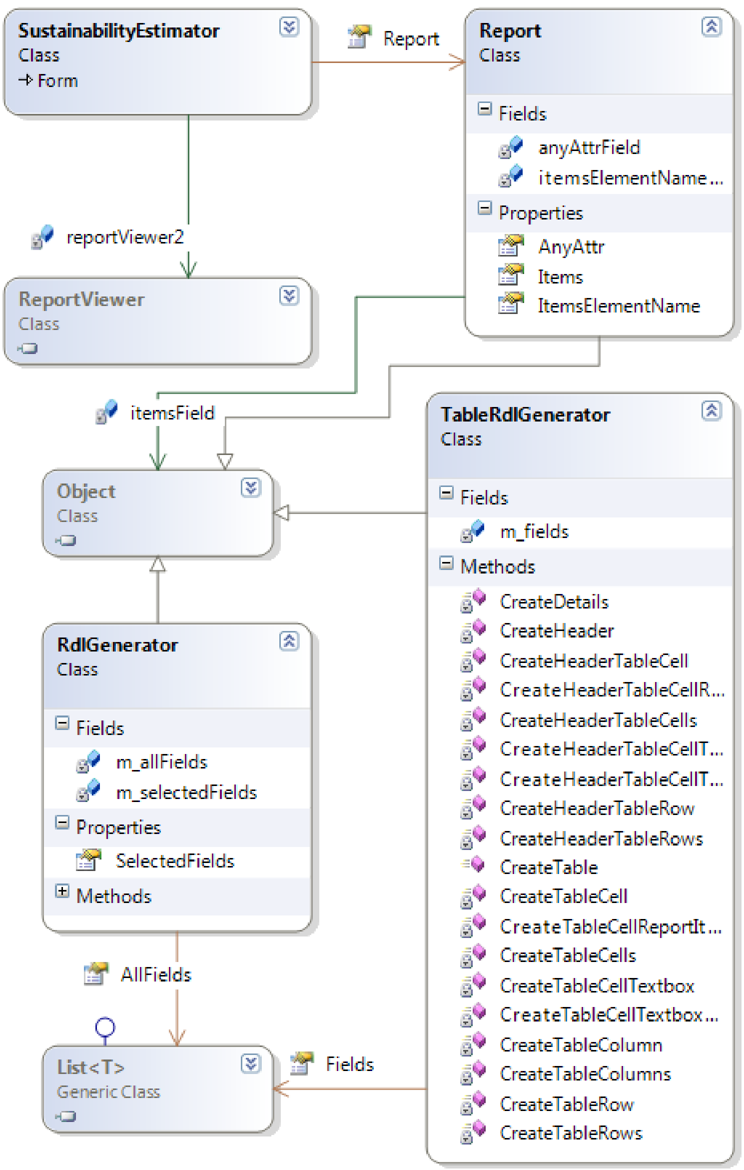


Figure 4.19: External components of reporting service

4.4 Operation of prototype

Discussions in this section commences with the various programming namespaces pulled together to achieve the prototype functionalities. Other aspects covered include description of the prototype operation sequences and the associated outputs.

4.4.1 Prototype namespaces and dependencies

The prototype consists of both generic and external implementation protocols in interaction with five inter-dependent implementation namespaces (Figure 4.20). These namespaces include AnalyticalSupportData_info, DynamicTable, Rdl, RevitSDKSample.AnalyticalSupportData_info.CS and SampleRDLSchema.

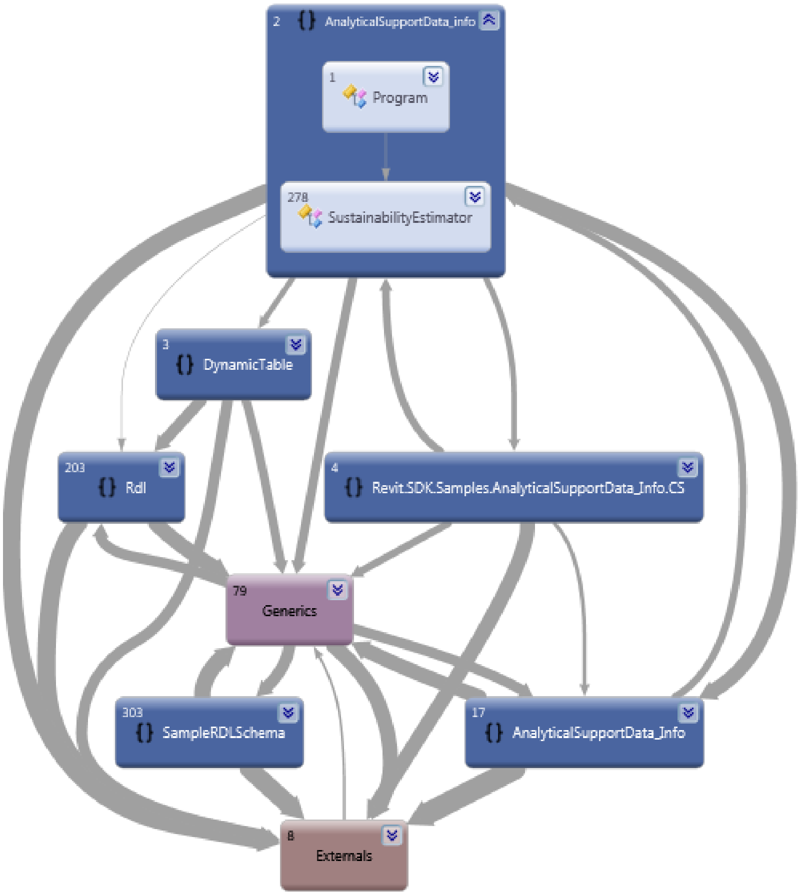


Figure 4.20: Prototype dependencies by implementation namespace

The implementations under AnalyticalSupportData_info namespace are in two parts. One is the SustainabilityEstimator and the other part includes the group of library-based and form-based classes interacting with the SustainabilityEstimator. Some of the classes in the second are the SteelSectionDataSet, RiskAnalysis, FrameChartForm, FloorChartForm, RoofChartForm and CladdingChartForm. These implementations constitute core of the prototype where the main feature modeling activities of input, analysis and output of information take place.

The RevitSDKSample.AnalyticalSupportData_info.CS is the namespace (Figure 4.21) under which classes are implemented for feature extraction from the building model. The Command Class, assisted by the GeomHelper and GeomUtil communicates with the building model to extract structural information from a BIM environment or BIM-based file. These information are passed via the OperationMode to the SustainabilityEstimator. The DynamicTable, Rdl and SampleRDLSchema all combine to make the reporting system implemented in the SustainabilityEstimator functional. The external namespaces include Revit API-related, windows system-based, Microsoft WinForms Reporting and React.Net references. The React.Net reference is statistic-related and constitutes a key reference for the implementation of risk analysis.

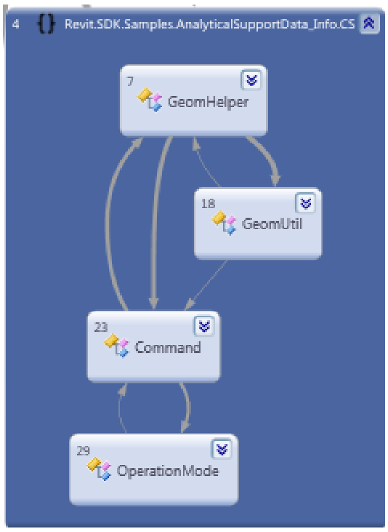


Figure 4.21: The feature extraction namespace

4.4.2 Description of prototype operation sequence

The prototype has been interfaced with Revit Structures 2011 to run as an add-in tool. The programme can be called by the designer during a building's structural modelling activity through the external link embedded in the Revit Structures. Figure 4.22 shows the implementation sequence diagram describing the flow of information in the prototype. The diagram has been simplified to show four major objects; the User (Designer), User Interface, OperationMode and SustainabilityEstimator.

The User Interface is the BIM-enable environment of Revit Structures™. The OperationMode is the first point of call when the prototype is loading. Here, the designer is able to register project information details and to choose the desired operation mode. The operations modes are either manual, automatic or IFC File options. The manual mode is rather a cumbersome option of allowing a designer to enter individual elements one at a time whereas the automatic mode employs feature extraction technique to abstract all the associated elements from the structural model developed in Revit Structures. The third option presents the opportunity of abstracting relevant structural information from a project saved in IFC open file format. This latter option also demonstrates that the prototype could actually be adapted to any BIM-enabled platform that supports object-oriented mapping of building data. The designer while interacting with the user interface within the Revit Structures environment calls the structural sustainability estimation programme. Any one of these options, when selected, links the SustainabilityEstimator where the main sustainability programming objects and component are embedded. The SustainabilityEstimator is configured according to the chosen mode of operation and serves as the interface where the designer supplies information such as discount rate, maintenance requirements, lifecycle boundary and weighting factors used for generating the various indicator measures.

4.4.3 Description of outputs from prototype operation

The following subsections give descriptions of the various steps for the operation of the prototype. They are presented in the flow order of the prototype operation.

(a) Calling of the sustainability programme from Revit

The programme is called from Revit Structures modelling environment through the link for external tools housed in the Add-Ins Tab. This activates a command on the active Revit Application Document (uiDoc) where the building model has been created. This action brings up the OperationMode form (Figure 4.23) to receive project details and the intended mode of operation. Manual input mode, if chosen, is programmed to be carried out on a second form, SustainabilityEstimator, called from the Operation Mode. For the Automatic mode, the building model need to be selected (highlighted) in Revit Structures modelling environment. This is a condition for the Automatic Mode to be configured while loading the SustainabilityEstimator. The third option, IFC mode, requires loading of an IFC model from a file. The system flags different advice instructions for each of these modes when selected.

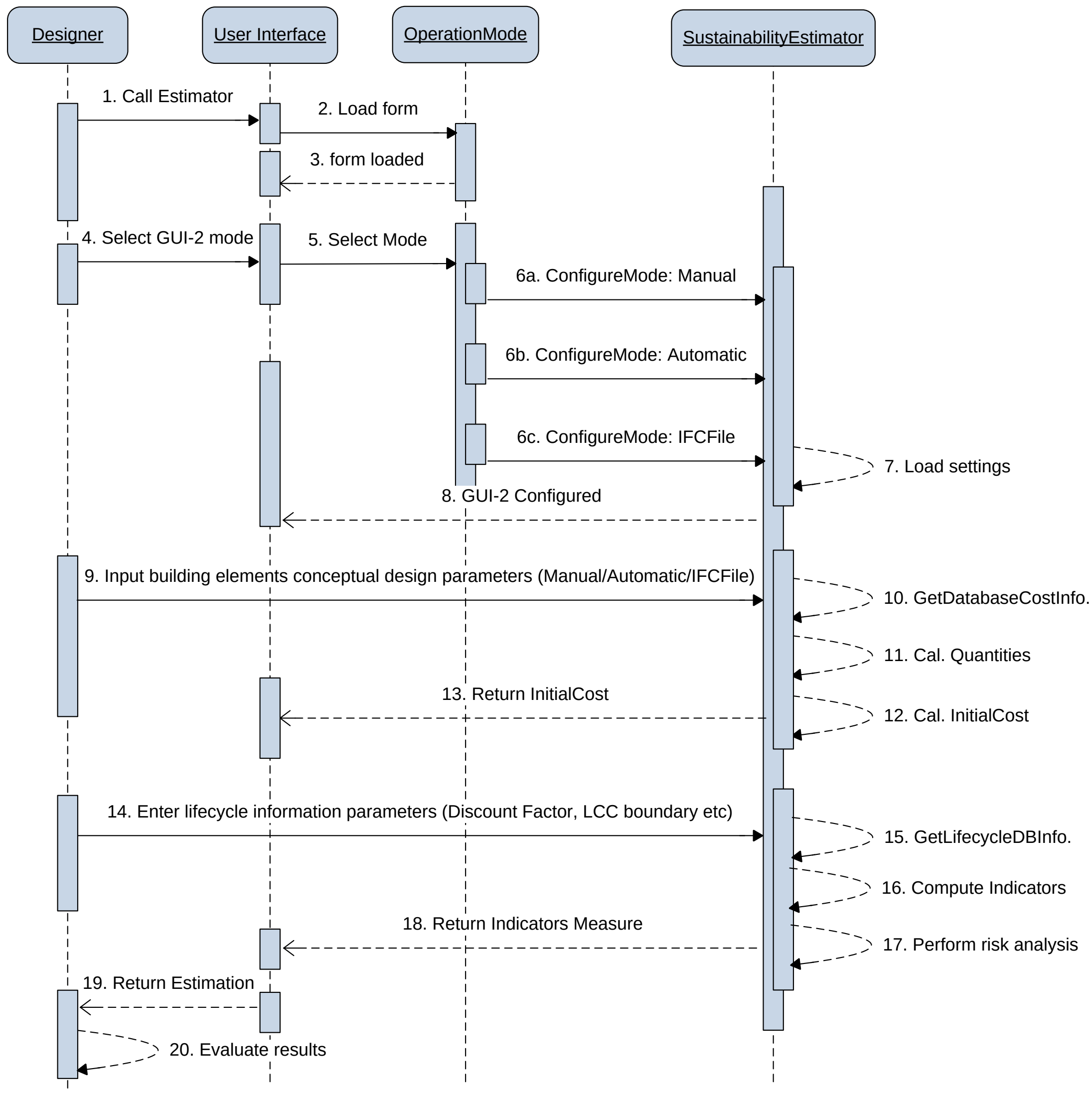


Figure 4.22: Implementation sequence diagram

Figure 4.23: Operation Mode

(b) Initial Cost, Material Records Information and Cost Summary

The first tab, material selection – meant for manual input is disabled on running other modes. The automatic mode and IFC file options begins from the second tab, Initial Cost (Figure 4.24). Here, coating and cladding details are finalised for onward transfer to tables. The tables can be viewed on the Materials Record Tab. This tab page provides the opportunity to inspect information on building features and make possible modifications if necessary. A summary of the sequence of the main actions carried out on these pages are shown on Figure 4.25. Programming functions in the Initial Cost and Materials Record Tab communicate with the system database to draw up required material information. The next tab page, Cost Summary, gives an overview of the total initial costs of each category of elements after which input on the sustainability indicator commences. The Cost Summary tab page provides the first opportunity to view the curve showing the performance of the various material combinations. Also on this tab, the user has the opportunity to identify the option with the minimum cost combination.

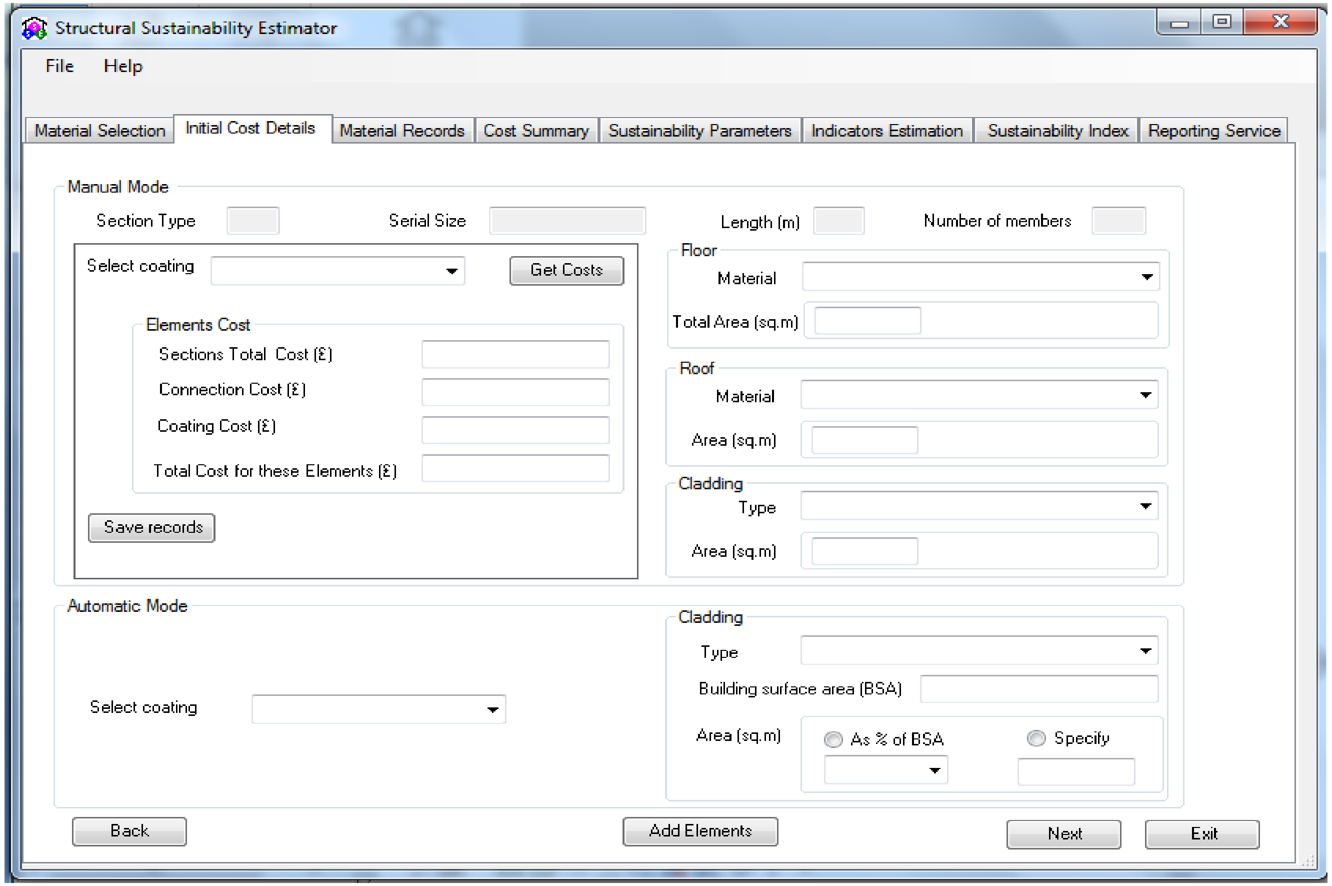


Figure 4.24: The Initial Cost Details tab of the SustainabilityEstimator

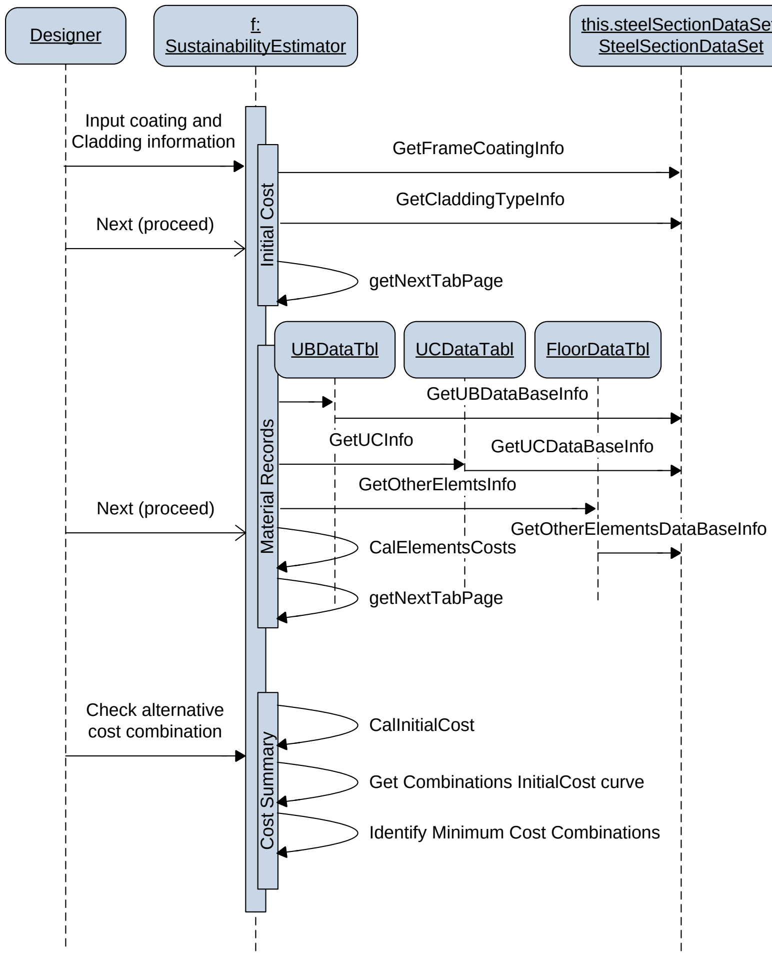


Figure 4.25: Sequence for obtaining Material Records and Initial Cost Summary

(c) Sustainability Parameters and Indicator Estimation tabs

In the sustainability Parameters tab (Figure 4.26), the user is required to confirm or enter the building design life, discount rate, maintenance frequency and envisaged maintenance costs. Also required is the option of decommissioning, whether demolition or dismantling. These information are essential for the life cycle cost calculations. Also, risk and sensitivity analysis to optimize the estimated life cycle cost can be performed from this tab page. On the aspect of the environmental indicators, life cycle boundaries, embodied energy values of material and equivalence factors are supplied. The equivalence factor is necessary for the calculation of ecological footprint. On completion of information on this tab page, the prototype is ready to carry out indicator estimation. The results of estimations are shown on the next tab page, Indicator Estimation. They have been arranged according to the various components and sustainability pillars. It is also on this page that information for different options can be saved to a CSV file. Later in the programme, information from different options can be loaded from this saved file for comparison with other options.

(d) Sustainability Index and the Reporting Service

The Sustainability Index Tab (Figure 4.26) is where the performance of the conceptual design options can be seen. The tab provides the function to load sustainability indicators information of various design options and display them in a table. The user can then proceed to specify the various weightings for the carbon and ecological footprint in the environment and also weightings on combining environment and economic pillar for the sustainability performance of the building. The result of the analysis is obtained via the principles of multi-criteria decision analysis. It is expressed in a chart, which shows the sustainability score of the various options. The option with the highest score is the favoured one in terms of sustainability. Information on elements and sustainability indicators of options can be printed through the Reporting Service Tab. This can be done by exporting information generated to a Word file, Excel file or PDF file for onward printing or record purposes.

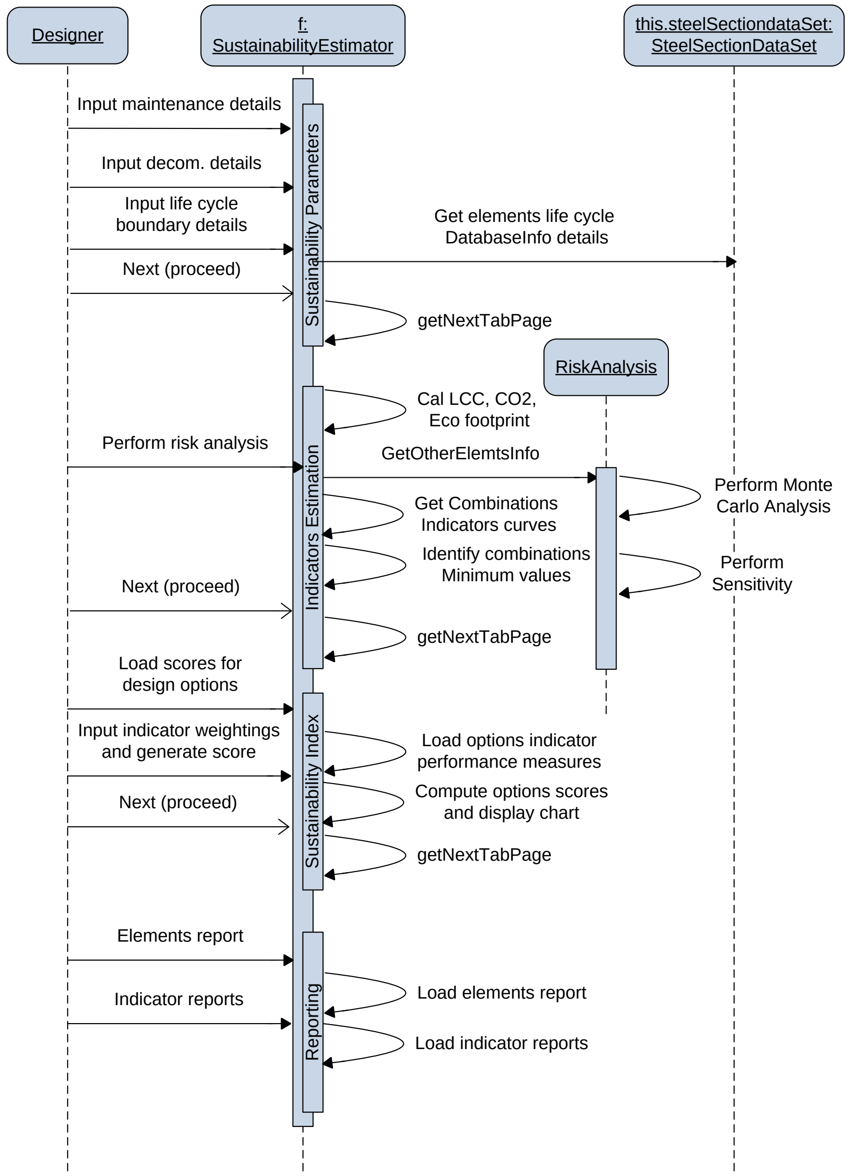


Figure 4.26: Sequence for obtaining option's sustainability performance

4.5 Summary

The implementation of the modelling framework in the form of a prototype was discussed in this chapter. It covered high level description of how the modelling framework transforms to the implementation components. The composition and functions of components were also examined and a description of the prototype operation presented. The representations used in the implementation entailed a combination of classes, interaction of several programming methods and series of event handlers working together. A case illustration is presented in the next chapter to further explain the working of the prototype.

Chapter 5

Example case study - using the prototype

5.1 Introduction

In this chapter, the use of the proposed prototype system is demonstrated in a typical design activity. The intention is to illustrate the usefulness of the system in informing the conceptual design process of steel-framed structures. A case study based on three design options of a three storey office building, is examined here. In addition, aspects of using the prototype to explore what-if scenario is demonstrated with analysis of an IFC model. Figure 5.1 illustrates the scope of the case study. Aspects relating to BIM-enabled software other than Revit Structures^{TM} are beyond the scope of this work and could be covered by future expansion of the SSE. The rational for the case study, its implementation, outputs and related implications are discussed.

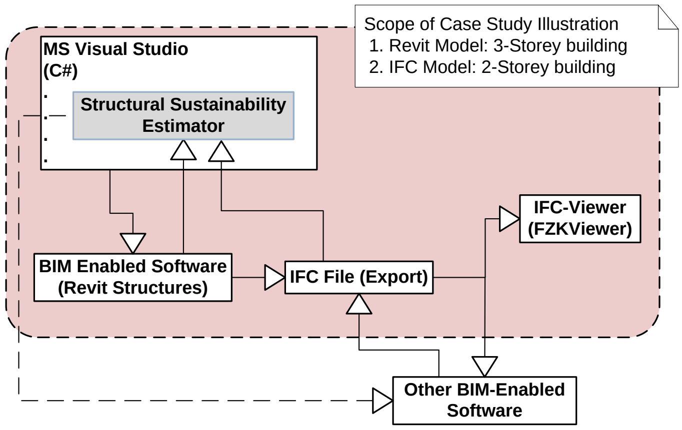


Figure 5.1: Scope of case study

5.2 Rationale and goal of the case study

Researchers appear to be in consensus that a case study is an empirical method aimed at investigating a contemporary phenomenon in a special setting or context (Benbasat et al., 1987; Eisenhardt, 1989; Runeson and Höst, 2009). Runeson and Höst, argue that many research questions in software engineering are suitable for case study research investigation because of the seemingly unclear boundaries between phenomena and their contexts. It is such unclear boundaries that requirement engineering, the key preliminary aspect of software development, seeks to understand. Case studies have been identified as one of the contributing methods to problem solving in requirement engineering. This entails applying a proposed solution to a substantial example for the purposes of providing important evidence which can be further substantiated by an evaluation (Zave, 1997). The case study in this research follows this line of discourse. The prototype has been used to analyse typical conceptual design examples in preparation for evaluation presented in the next chapter.

The implementation of the prototype system has gone through conventional iterative software development cycle based on the Rapid Application

Development (RAD) model. This entailed continuous testing of system components and incorporation of feedback analysis to improve the system to maturity. The case study is therefore designed to illustrate the overall functionality of the system. This will help to create the opportunity to examine how the sustainability modelling requirements and framework have been correctly implemented in accordance with Objective 5 of this work. The goal of the case study is to investigate the contributions of the prototype to informing designers on the sustainability of alternative conceptual design solutions. This chapter discusses the efficacy of the proposed sustainability modelling framework in assisting designers to evaluate the sustainability score of conceptual design options based on life cycle costing as the economic indicator, and environmental impacts relating to the atmosphere and biosphere. This creates the basis for favouring a design solution above alternatives when selecting preferred options during design iterations.

5.3 Case study implementation

To adequately describe the various aspects of case study implementation, the rationale underlying project formulation, a description of the alternative design solution to be analysed, the data input processes and analysis of the output of the SSE are presented here. Attempt has been made to also describe the operation of the prototype with the aid of corresponding screenshots at various stages.

5.3.1 Project formulation

In pursuing the development of guidance on the design and construction of sustainable, low carbon and zero carbon buildings in the UK, five different building types were selected. These are schools, warehouses, offices and mixed-use-buildings (TARGETZERO.INFO, 2012). Out of these, office building category has been chosen for the demonstration of this work. This is because they are common and can be found amongst other categories. Also, office buildings vary in sizes, from small to very large - typically rectangular in plan shape. These peculiarities make office building especially appropriate for the prototype demonstration.

In typical design project settings, the architect and the client commences work with the development of the building concept (Tizani et al., 2002; Ruikar, 2005). The architect transforms the client brief into design concepts characterized by total space requirements, positioning of rooms, floor layouts etc. The conceptual design are usually developed to conform to relevant standards and passed to the structural engineer for his designs. The structural designer is expected to confine his design within the limits of the architectural concepts in terms of space and positioning of structural members. Hence in this case study, the options of conceptual structural solutions developed for the office building project are assumed to be identical in space and number of floors.

5.3.2 Description of project options and input data

The project used for the case illustration is a hypothetical 3-storey office building framed in structural steel. The height of the structure is 12 m from foundation to the soffit of the roof. It is 3.5 m between floors (to allow excess space for services and circulation of air) and having a plan area of 30 x 18 m. The respective conceptual design options for the sustainability appraisal are shown in Figure 5.2. The options have similar input data on items such as; design life of structure; the building footprint or floor area; building surface area for cladding purposes, maintenance frequency for the various key elements; and discount rate for calculating corresponding net present values. However, the options vary in framing pattern (positioning of grids), floor type, type of cladding and material used for roofing. Table 5.1 gives the details of the input data relating to the similarities and differences between the design options. The building footprint area has been kept equal for the alternative design solutions since structural framing options rarely change a building plan area which is usually dictated by the architect's design. In this illustration, openings in the floors such as for staircases have been ignored based on considerations that they will be similar for all options and therefore do not have any significant effect on the final output.

5.3.3 Data input process and operation screens

The process of feeding information into prototype and checking corresponding output results goes through seven operation screens. These operation screens have been developed based on ensuing implementation tasks during the research work. The prototype considers only the superstructure of a building for sustainability analysis since maintenance issues are not often associated with the substructure after construction is completed. The criteria used for sustainability evaluation are life cycle costing, carbon footprint and ecological footprint. The components of the life cycle cost include the initial cost, maintenance, decommissioning cost and residual value. Carbon footprint is currently calculated based on the embodied energy of the materials. Ecological footprint combines the measure of the Built-up Land and the Energy Land (equivalent land value of the embodied energy of building materials) of the structure. The operation screens therefore reflect these aspects.

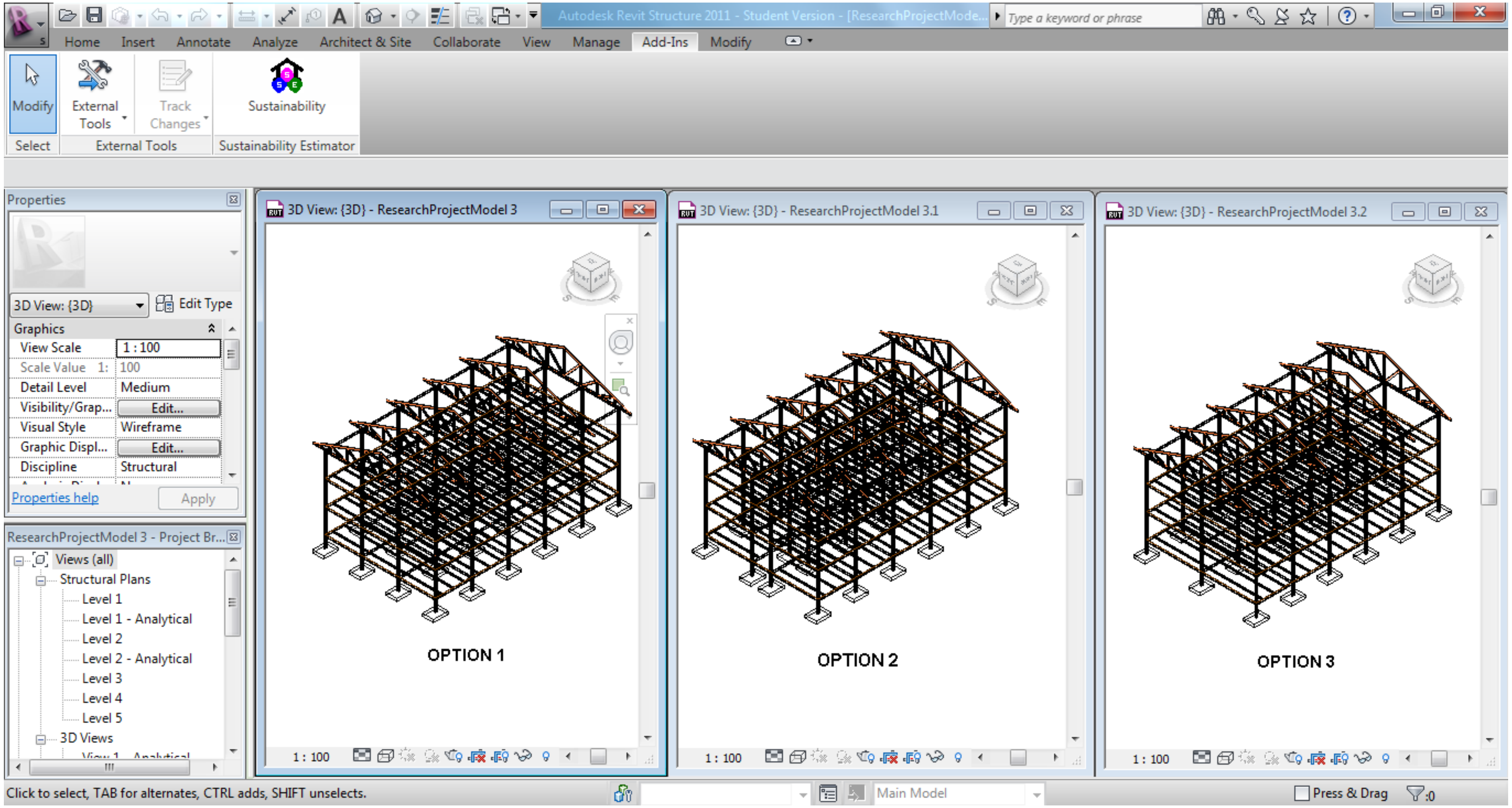


Figure 5.2: 3D Models of the three design solutions

Table 5.1: Input data for design options

Description	Option 1	Option 2	Option 3
Design life	80.00	80.00	80.00
Building floor area	540.00	540.00	540.00
Building surface area (m^2)	1344.00	1344.00	1344.00
Cladding area (m^2)	1008.00	1008.00	1008.00
Maintenance frequency (Yrs.)	10	10	10
Discount rate (%)	2	2	2
Framing weight (t)	86.84	82.47	74.00
Floor Type	Metal decking (composite)	In situ - concrete	Precast concrete on steel beams
Cladding Type	Metal - aluminium	Metal-steel	Fibre cement
Roof Material	Metal (aluminium)	Clay tiles	Concrete tiles
Key difference in grid spacing	Grid spacing @ 6m centres (3 bays)	Grid spacing @ 7.5m, 3m, 7.5m (3 bays)	Grid spacing @ 9m centres (2 bays)

(a) Initial Cost of Structure

Figure 5.3 shows the first screen, the Operation Mode window, when the prototype is called from Revit Structures™. For this case study, the Automatic Mode is the appropriate option, so it has been selected since Design Option 3 has been highlighted prior to the calling of the SSE prototype. It also means that Option 3 is being analysed in this current operation. Options 1 and 2 have been analysed earlier with their respective indicator measures saved-up in two different files. Later on, these files are to be loaded into the prototype for comparison with the results obtained for Option 3. In the next screen (Figure 5.4), the user provides some essential information that are difficult to capture from the building model in Revit Structures. These include types of coating for the steel work, types of cladding and their estimated areas. They are required for estimating the initial cost of the structural framing. When this is done, the prototype lists, in a table, all the elements and corresponding essential attributes extracted from the building model (Figure 5.5).

On the material Records page, the user is able to carry out visual inspection and make modifications where necessary. For example in this case study, the prototype identifies the first Universal Beam Element as having an ElementID of 168468, Section size of UB305x302x25, 9m length etc. If the outcome of the inspection is satisfactory, the total initial cost can then be viewed next (Figure 5.6). Thus for design Option 3, the initial cost of the structure is £671,568. This value may vary in the range of ±12% as obtained from the SPON's cost estimates (Langdon, 2012) (extracts given in Appendix 2). The initial cost includes cost of structural steel sections and joint fabrication (frame), coating, structural floor, roof and cladding. The user can then proceed to obtain the measures of the sustainability indicators from here.

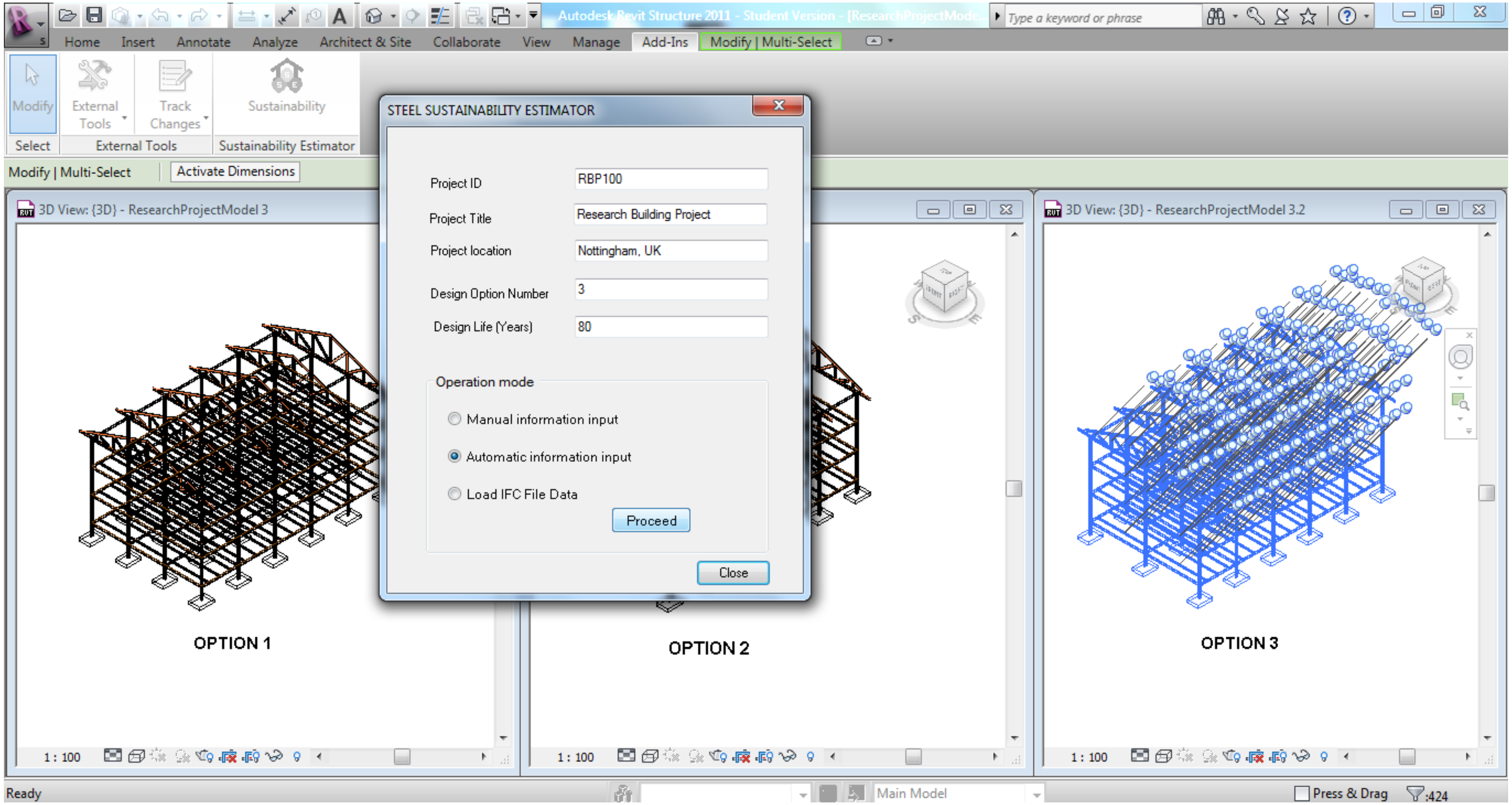


Figure 5.3: Supply of Project Information and selection of input mode

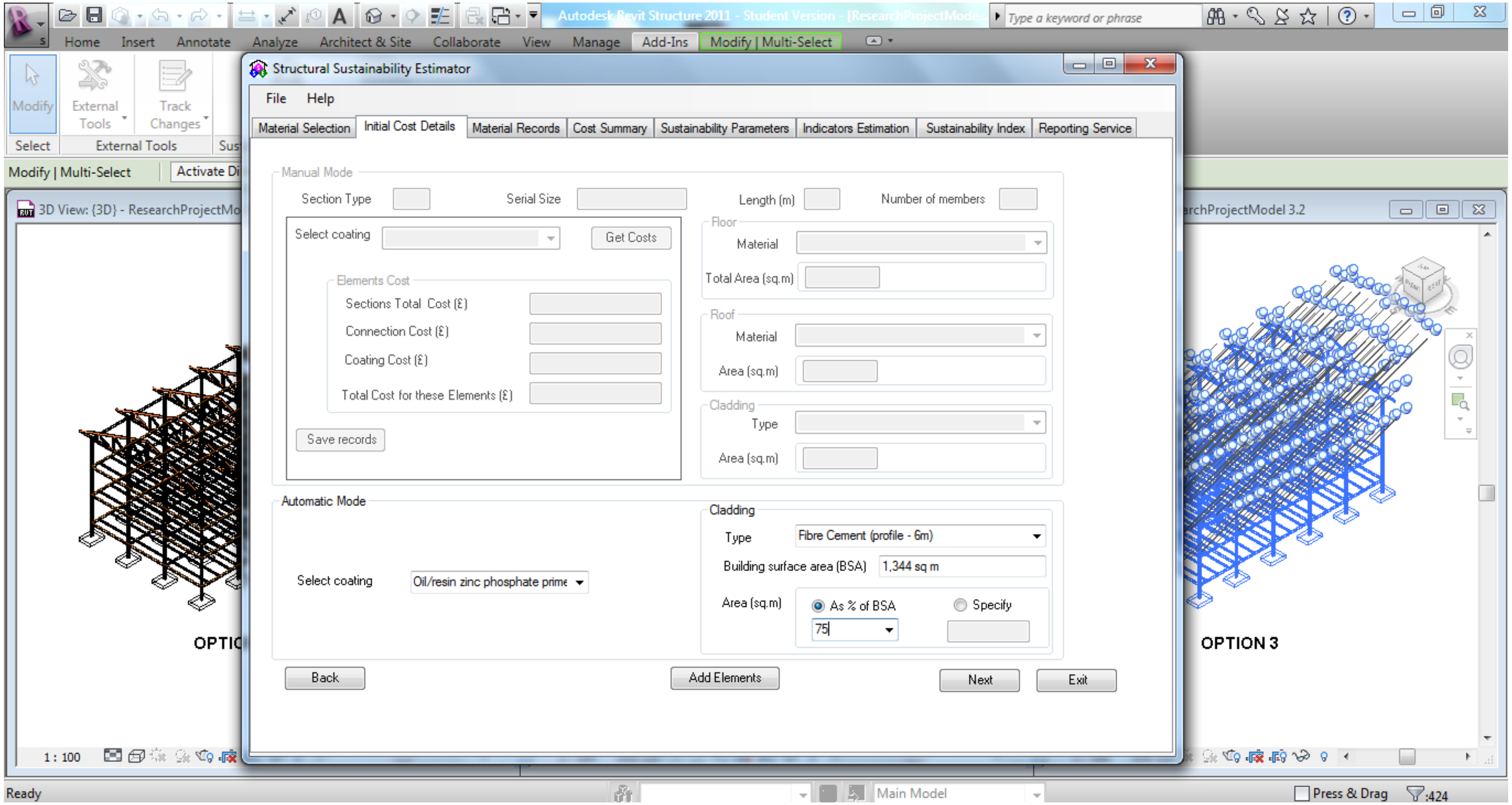


Figure 5.4: Providing additional information for calculating initial cost

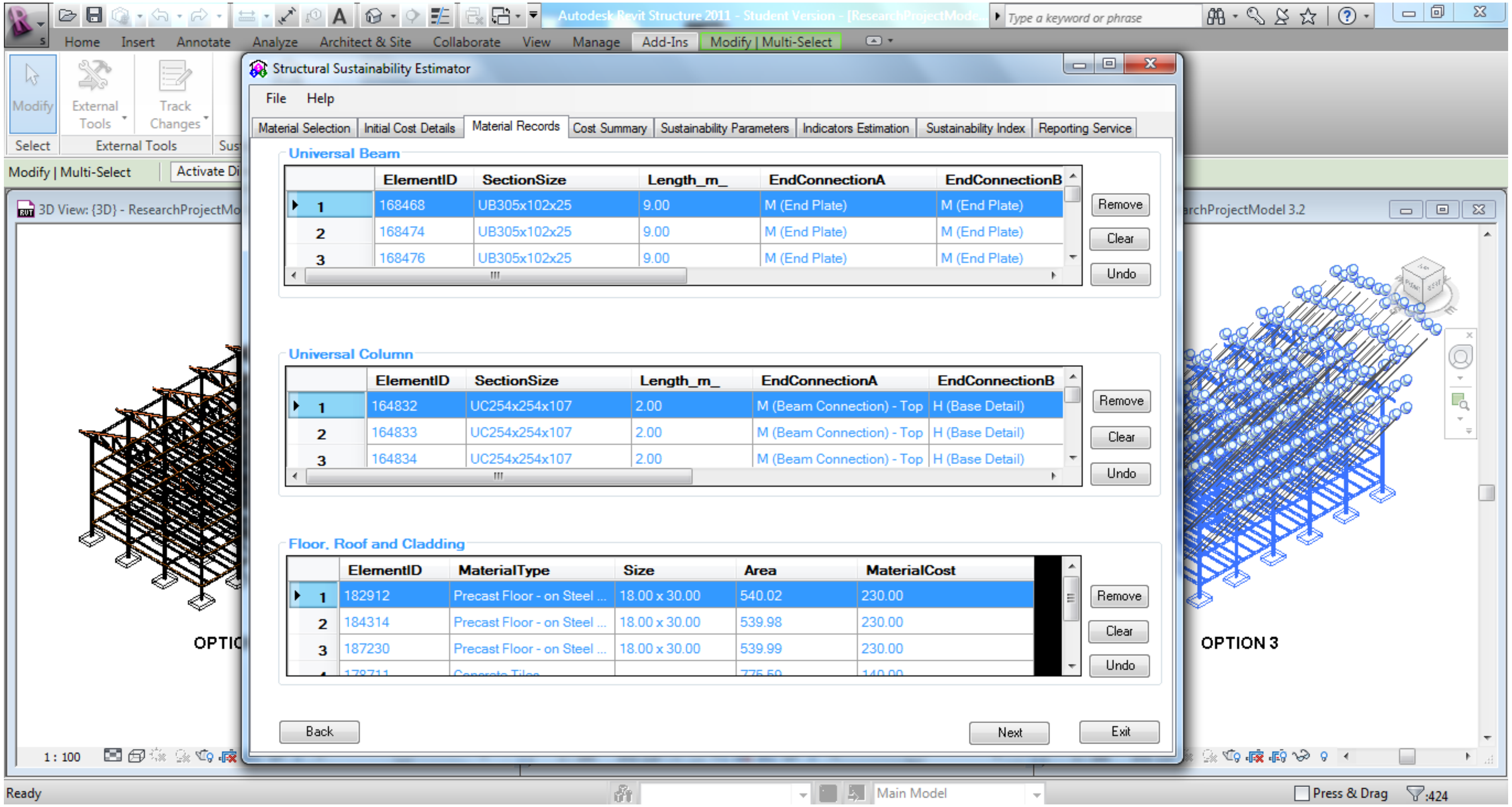


Figure 5.5: List of elements information from extraction activity

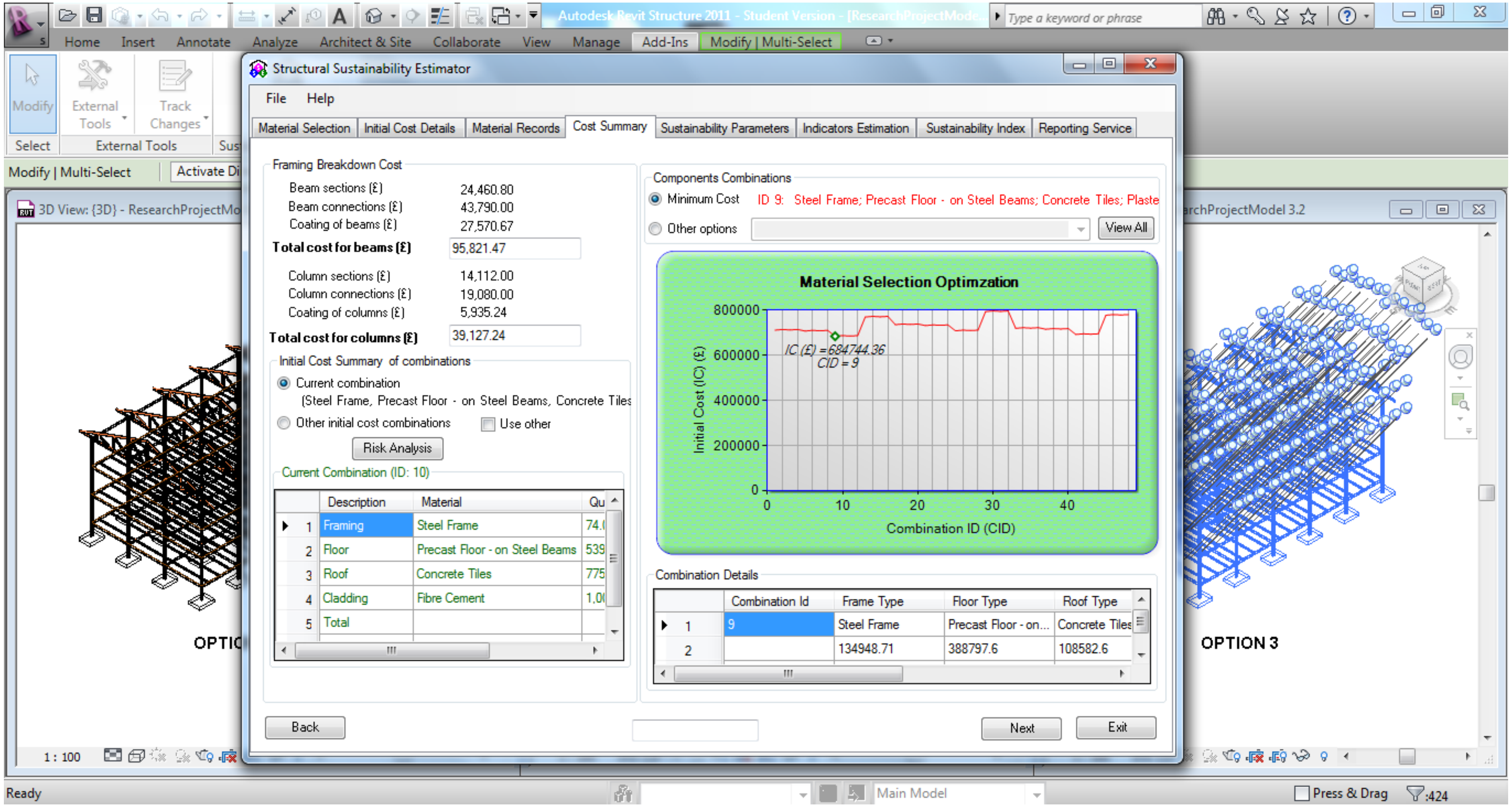


Figure 5.6: Summary of initial cost components

(b) Sustainability indicators measures of structure

This aspect of the prototype operation is divided into two parts: supply of economic-related variables and providing information for environmental-related estimations. It commences with the confirmation or modification of the building design life (Figure 5.7). The user also decides on the discount rate for calculating the net present value of estimated costs, maintenance conditions/costs and the decommission option for the structure. A building design life of 80 years and a 2% discount rate are adopted for this case study. The end-of-life option for decommissioning the structure is considered to be deconstruction which allows for steel material recovery rate of 90% (Gardner et al., 2007).

For the carbon footprint measure of the environmental aspect, the life cycle boundary and recycled content for steel have been specified to be cradle-to-gate and UK/EU average respectively. The building area (540 m^2) and the equivalent factor (2.51) are required for ecological footprint calculations. In the course of this research, information on recycled contents were not found for materials used for floor, roof and cladding of buildings. However, the prototype is flexible enough to be updated with this information when they become available from research.

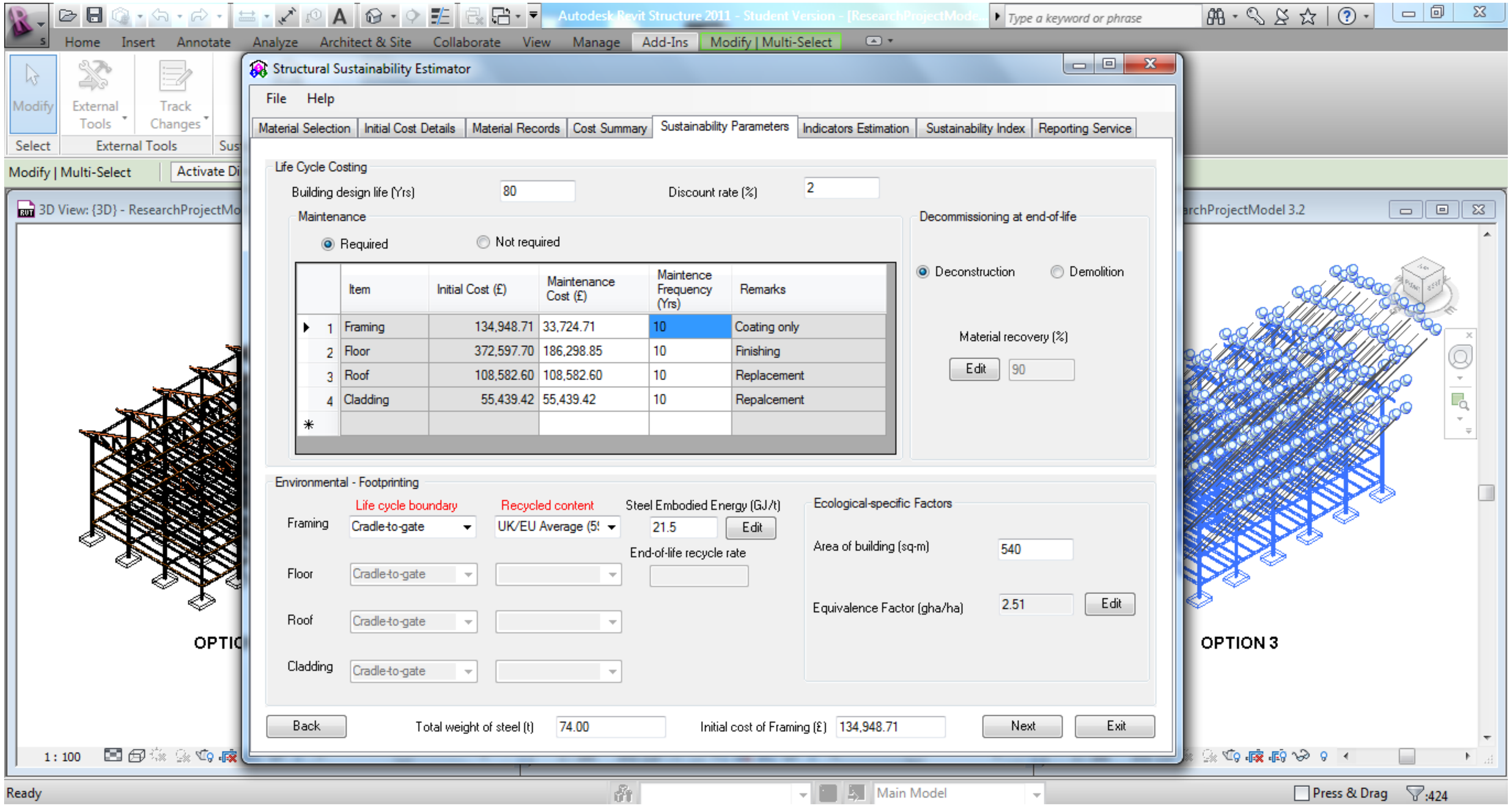


Figure 5.7: Providing required information for sustainability indicator estimation

The estimated measures of the indicators are displayed next (Figure 5.8). The user is able to view charts for life cycle cost for framing, floor, roof and cladding system of the structure. Risk analysis can also be performed at this juncture to optimize the life cycle cost of the structure based on Monte Carlo Simulations. The net present value of life cycle cost of Option 3 is £1,996,022 for this case study. It is also possible to view the pie chart of the various contributions of the component building systems to the overall structure's embodied energy and carbon emission. These have been estimated to be 2,162 GJ and 113,558 $kgCO_2$ respectively. For ecological footprint, the equivalent of agricultural fertile land used up is estimated at 22.5 gha. In a similar manner, these indicator measures were obtained for design options 1 and 2; and saved to a CSV file which can be uploaded in the next screen for onward analysis.

5.3.4 Options' sustainability scores and analysis

Figure 5.9 shows the sample output (Sustainability Index tab page) for the comparison of the three conceptual design options. Typically on the Sustainability Index tab page, the user loads the sustainability indicator measures of the various alternative design solutions (three options in this case) and moves on to specify the respective weightings for combining the environmental performance indicators, carbon footprint and ecological footprint. The next set of weightings to specify is for economic and environment analysis. In both cases the default weightings have been set to 50%:50%. The final event on this tab page is to click on the specified button to generate a chart showing the sustainability score of the various options.

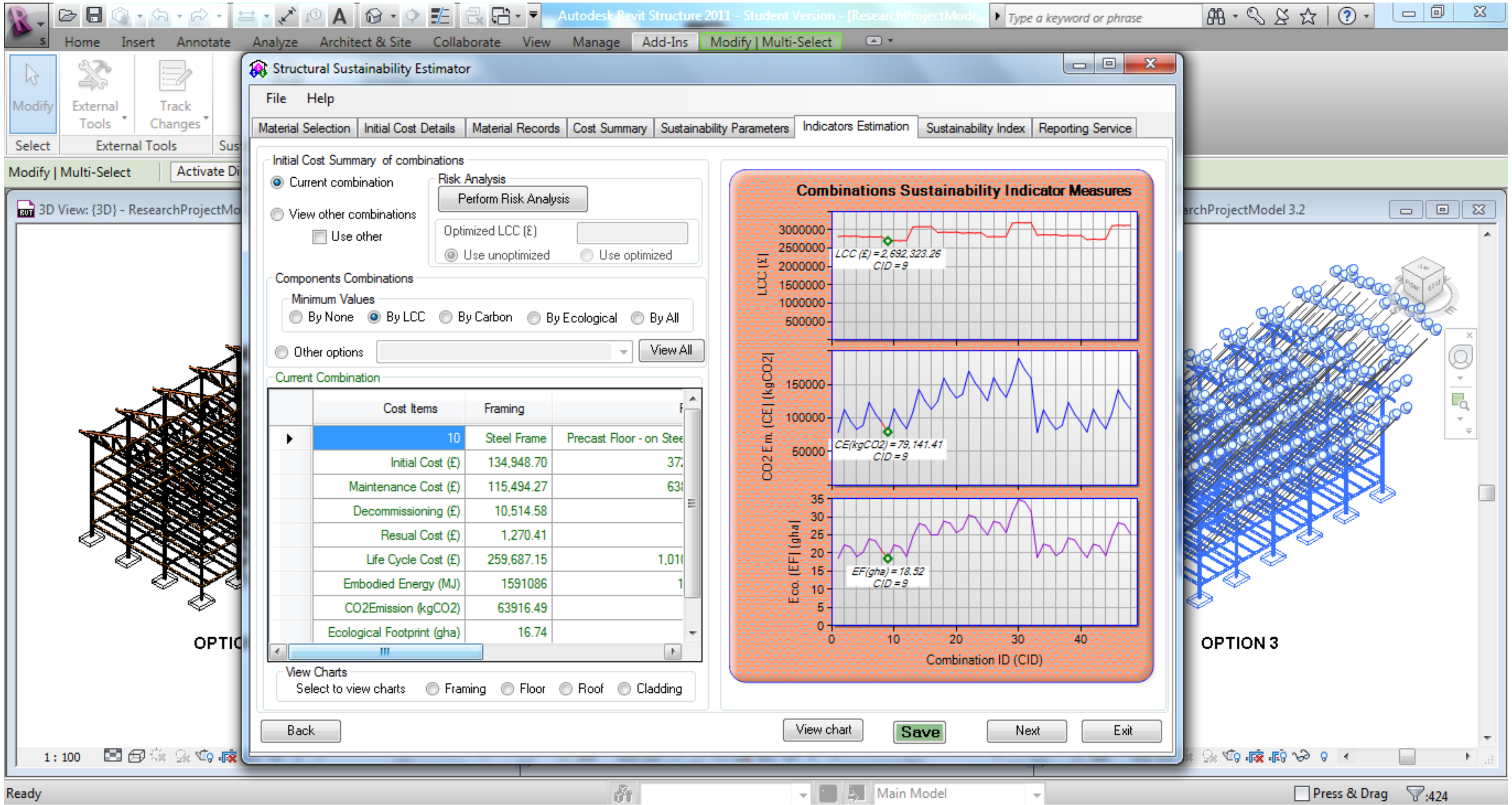


Figure 5.8: Saving up indicator estimation results for analysis

The sustainability score for options being compared is relative and is given in the range of '0–1', with '0' and '1' respectively depicting the least and most favourable sides of the scale. As seen from the chart the sustainability (desirability) scores are 0.27, 0.38 and 0.35 for options 1, 2 and 3 respectively. This is obtained from applying the default weightings to the normalised values of the respective indicator measures based on principles of MCDA. Table 5.2 gives more details on the values of the indicators making up these scores. It is worth mentioning that cost estimates shown on the table may vary in the range of ±12% (Langdon, 2012). The steps adopted in calculating the desirability scores as implemented in computer programming manipulations are further shown in Table 5.4. The table has been presented in four sections, including Options, Economic, Environment and Desirability score calculation for clarity and ease of understanding.

With respect to the MCDA principle, the ranking of the three options is: Option 2 > Option 3 > Option 1. That is, Option 2 has the highest sustainability score of 0.38 and it is therefore the preferred option in terms of sustainability of structural steel framing system. As evident in Table 5.2, within the scope of the prototype, Option 3 is closely ranked to Option 2. In the aspect of environmental sustainability, Option 3 is more favoured as it has the least measures of embodied energy, carbon footprint and ecological footprint while Option 2 is better in terms of the economic indicator of life cycle cost. On combining the economic and environmental aspects, Option 2 emerges as the most sustainable option when equal weightings of these measures are considered; however this situation might change if the ratios of the different sets of weightings are altered.

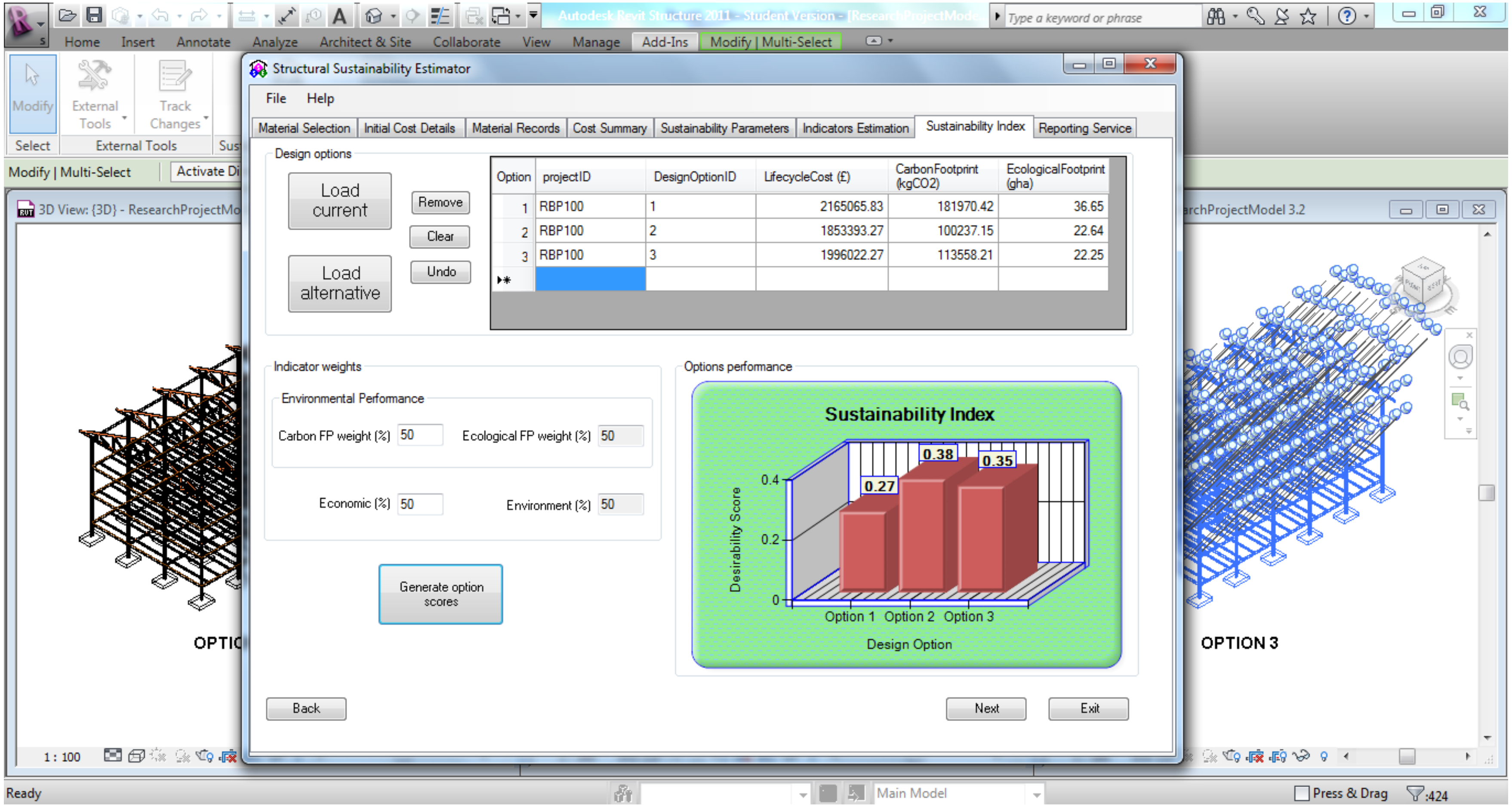


Figure 5.9: Output of sustainability analysis of design options

Since the indicators relate to economics and the environment, the author is of the opinion that options with higher desirability score will perform better among other options if rated with tools such as BREEAM. This is because they all share the same ideals of protecting the environment at minimal cost possible. However, BREEAM which produces single overall score of Pass (≥30%), Good (≥45%), Very Good (≥55%), Excellent (≥70%) and Outstanding (≥85%), covers more scope in categories of sustainability assessment. It is therefore useful to consider the particular categories that are of direct relevance to the SSE prototype.

Table 5.2: Components of the sustainability analysis output for design options

Description	**Option 1**	**Option 2**	**Option 3**
Economic			
Initial Cost (£)	827,056	744,867	671,568
Maintenance cost (£)	1,328,750	1,115,625	1,315,210
Decommissioning cost (£)	10,733	10,671	10,514
Residual value (£)	1,474	1,416	1,270
Life cycle cost (£)	2,165,066	1,869,747	1,996,022
Environmental			
Embodied energy (GJ)	3,662	2,191	2,162
Carbon footprint ($kgCO^2$)	181,970	100,849	113, 558
Ecological footprint (gha)	37.7	22.7	22.6
Sustainability Score	**0.27**	**0.38**	**0.35**

It is worth mentioning that it is practically difficult to use BREEAM to directly assess the design options considered in the example case study for the purpose of comparison. This is because of the difference in basis of operation and the overall content of assessment. However, similar aspects in the assessment systems have been examined to establish the relevance of the SSE outputs.

BREEAM scheme covers 10 categories of sustainability (BRE, 2012) including management, Health and wellbeing, Energy, Transport, Water, Material Waste, Land Use and Ecology, Pollution and Innovation (Table 5.3). Three out of these 10 categories can be said to be directly related to the sustainability assessment proposed in this research. They include Energy (CO_2 emissions), Materials (Embodied life cycle impact, Materials re-use) and Land Use and Ecology (Protection of ecological features, Mitigation/enhancement of ecological features). There are other main issues besides the ones listed in the brackets that are considered in these categories. Weightings in the form of credits have also been assigned to the various issues considered in these three and the other seven categories. The table gives the corresponding credits assigned by BREEAM to the main issues listed in the three categories of interest. The credits for these issues are combined based on percentage weightings to obtain the proportion of relevance to the SSE prototype. It can be seen from the table that sustainability indicators considered in the SSE can contribute to about 26.02% of BREEAM overall ratings. That is to say, a design option with the best sustainability ranking assessed by the SSE is likely to score a high proportion of 26.02% of BREEAM rating. If such design option eventually performs well in the remaining 73.98% of BREEAM ratings, it is most likely that the BREEAM overall score will not fall below the "Good" classification.

Table 5.3: BREEAM ratings and relevance to SSE

BREEAM Section	Main Issues (credits)	Weighting	Weighting (%)	Relevance to SSE (%)
Management	Commissioning	0.120	10.91	
	Construction site impacts			
	Security			
Health & Wellbeing	Daylight, Lighting	0.150	13.64	
	Occupant thermal comfort			
	Acoustics			
	Indoor air and water quality			
Energy	CO_2 emissions (15)	0.190	17.27	10.80
	Low or zero carbon technologies (3)			
	Energy sub metering (2)			
	Energy efficient building systems (4)			
Transport	Public transport network connectivity	0.080	7.27	
	Pedestrian and Cyclist facilities			
	Access to amenities			
	Travel Plans			
Water	Water consumption	0.060	5.45	
	Leak detection			
	Water re-use and recycling			
Materials	Embodied life cycle impact - materials (4)	0.125	11.36	7.95
	Materials re-use, landscape protection (3)			
	Responsible sourcing & Insulation (5)			
	Robustness (1)			
Waste	Construction waste	0.075	6.82	
	Recycled aggregates			
	Recycling facilities			
Land Use & Ecology	Site Selection (2)	0.100	9.09	7.27
	Protection of ecological features (1)			
	Mitigation/ enhancement of eco. value (6)			
	Long term Biodiversity (2)			
Pollution	Refrigerant use and leakage	0.100	9.09	
	flood risk			
	NO_x emissions			
	Watercourse pollution			
	External light and noise pollution			
Innovation	Exemplary performance levels	0.100	9.09	
	Use of BREEAM Accredited Professionals			
	New Tech. and building processes			
TOTAL		**1.10**	**100**	**26.02**

To a large extent, specifying weightings of the various indicators rest in the hand of the designer or user which is influenced by his/her perception of the likely degree of impact associated with the various indicators. However, it is possible to create some uniformity in the application of these weightings if standardization is initiated by concerned institutions. The ideal practice that allocation of weighting to criterion in decision frameworks should reflect preferences of the concerned decision makers has been highlighted by Gühnemann et al. (2012). This is potentially a source of contention especially where there is no standard institutional guide for combining indicators in decision making. For the indicators used in this research, such guides have not been found and therefore constitute a gap that needs to be tackled in sustainability research. The prototype in this research was developed on the default basis of equal weightings of the indicators and sub-indicator categories. Although most composite indicators rely on equal weightings (Giovannini, 2008), there is some empirical basis for doing so in this research. The environment, carbon footprint and ecological footprint sub-indicators are complementary and measure two distinct important aspects of the environment: atmosphere and biosphere, respectively. These aspects are considered equally important in terms of impact. A correlation of carbon exists in the two indicators (Galli et al., 2012) but this does not affect the prototype results as the same condition is applied for all the considered design options. At the main indicator level, economy and environment also constitute two out of the three key (equally important) pillars of sustainable development. This is also reflected in the Building for Environmental and Economic Sustainability (BEES) approach in combining environment and economy to select cost-effective green products (Lippiatt and Boyles, 2001).

5.3.5 Development of the MCDA and sustainability scores

The theory and equation for the multi-criteria decision analysis have been discussed in Section 3.9. This section gives an insight on how it was developed with respect to the example case study examined in this chapter.

Table 5.4 outlines the steps employed in applying the MCDA for the example case study. Analysis implemented in the SSE basically considers the sustainability indicators of the design options to be compared. In this case: Option 1, Option 2 and Option 3. The values of indicators presented under the Economic and environment headings of the table. Columns 'A', 'D' and 'G' are the respective indicator measures for LCC, Ecological Footprint and Carbon Footprint. The reciprocal of these indicator measures (Columns 'B', 'E' and 'H') are divided with the sum of the reciprocals in the individual columns to produce values in Column 'C, 'F' and 'I''. For example, the dimensionless value 0.3571 in Column 'C' for Option 2 is obtained from dividing 5.35 x 10^{-07} by 1.50 x 10^{-06}. Column 'C' is further multiplied by the respective specified weightings, 'w' for a single indicator that represents a sustainability dimension (i.e. economic) or 'ww' for more than one indicator that represent a sustainability dimension (i.e. environment). The weighting for economic and environment is assumed to be 50% each. The weightings of carbon footprint and ecological footprint are also 50% each of the environment making an overall 25% for each when combined with the economic weighting. The product of this multiplication is given by Columns 'J', 'K' and 'L'. The weightings produce the ratios used in combining the indicators measures irrespective of their different units to yield the sustainability scores. This (Column 'M') is obtained by simply adding values in Columns 'J', 'K' and 'L' for the respective design options. The option with highest score value is the most favourable which is Option 2 in this case.

Table 5.4: Calculation of design options sustainability scores

OPTIONS	ECONOMIC			ENVIRONMENT						DESIRABILITY SCORE CALCULATION			
				CARBON FOOTPRINT			ECOLOGICAL FOOTPRINT			w = 0.5	ww= 0.25	ww = 0.25	SCORE
	A	B	C	D	E	F	G	H	I	J	K	L	M
	(LCC (£))	= 1/A	= B/∑B	(CF (kgCO2))	= 1/D	= E/∑E	(EF (gha))	= 1/G	= H/∑H	= w * C	= ww * F	= ww * I	= J + K + L
OPTION 1	2,165,066	4.62E-07	3.08E-01	181,970	5.50E-06	0.2269	37.7	0.0265	0.2310	0.15	0.06	0.06	**0.27**
OPTION 2	1,869,747	5.35E-07	0.3571	100,849	9.92E-06	0.4095	22.7	0.0441	0.3836	0.18	0.10	0.10	**0.38**
OPTION 3	1,996,022	5.01E-07	0.3345	113,558	8.81E-06	0.3636	22.6	0.0442	0.3853	0.17	0.09	0.10	**0.35**
TOTAL (∑)	6,030,835	1.50E-06		396,377	2.42E-05		83	0.11483					1

5.4 Feature extraction from IFC model and what-if scenario

IFC has been a promising advance for tackling interoperability challenges in the AEC industry. As an open format for building planning, design, construction and management; many design and modelling tools have incorporated implementations to communicate with IFC models. This has mostly been in the form of importing from or exporting to IFC file format. For example, Revit Structures has a facility for exporting to an IFC file. However, the extent of structural information that can be exported is limited to major structural elements such as beams, columns and slabs. This section illustrates how the prototype extracts relevant structural information from an IFC model for sustainability analysis. The intention is to demonstrate that the prototype implementation has made consideration for interoperability issues. It also implies that the prototype is flexible and can be modified to operate in any BIM-enable modelling platform that supports interfacing with OOP tools. Figure 5.10 shows the FZKViewer version of the structure used for this demonstration. FZKViewer is a free application for viewing/displaying semantic data models such as IFC and CityGML (KIT, 2013). The structure is simple 2-story steel framed building with a plan area of 240 m^2.

The screenshot for using the prototype to access an IFC file is given Figure 5.11. The operation involves calling up Windows Open-dialog to select the .IFC extension file and iterating through the contained IFC model to extract all relevant structural information. Once this is completed, the operation of the prototype follows the described steps detailed in sections 4.4.3, 5.3.3 and 5.3.4.

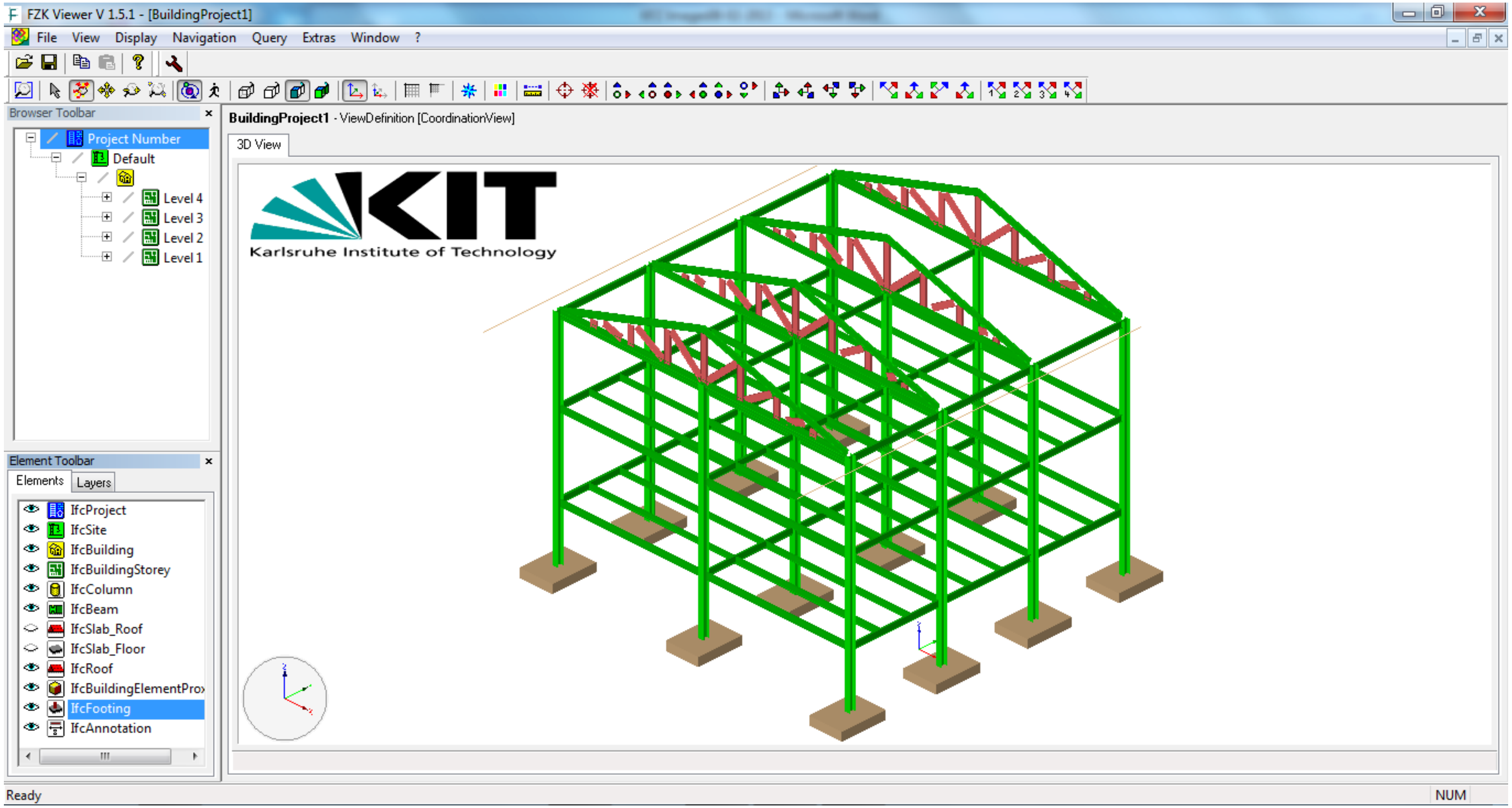


Figure 5.10: IFC-based building model displayed in FZKViewer IFC viewer

The prototype can further be used to explore situations of what-if-scenarios with component cost items or structural elements of a design option. This is illustrated with information extracted from the IFC model. In Figure 5.12, the ComboBox drop-down list displays the various combination options of the what-if cases of the various components. The options are identified by identification numbers. The performance of the options can be viewed on the adjourning chart which gives a curve of the three (LCC, Carbon Footprint and Ecological Footprint) indicators measures for the available component combinations. The value of the indicator measure for each selected option is displayed on the chart. Also, the best ranked combination can be identified based on either of the three indicator measures. This provides useful information for users to select and combine elements during conceptual design activity to achieve improved sustainability ranking.

Furthermore, the risk and sensitivity of selected options can also be examined as shown in Figure 5.13. Two options of analysis have been implemented. The first option displays the result for analysing the components cost items such as initial cost, maintenance cost, decommissioning cost and residual value. The components elements (framing, floor, roof and cladding) are displayed when the second option of analysis is chosen. The charts include probability density function (PDF) and cumulative density function (CDF) for risk analysis; and sensitivity charts showing components curves and bar proportions of influence on the life cycle cost. The PDF and the CDF charts give the value with the most frequent occurrence and its probability of occurrence respectively.

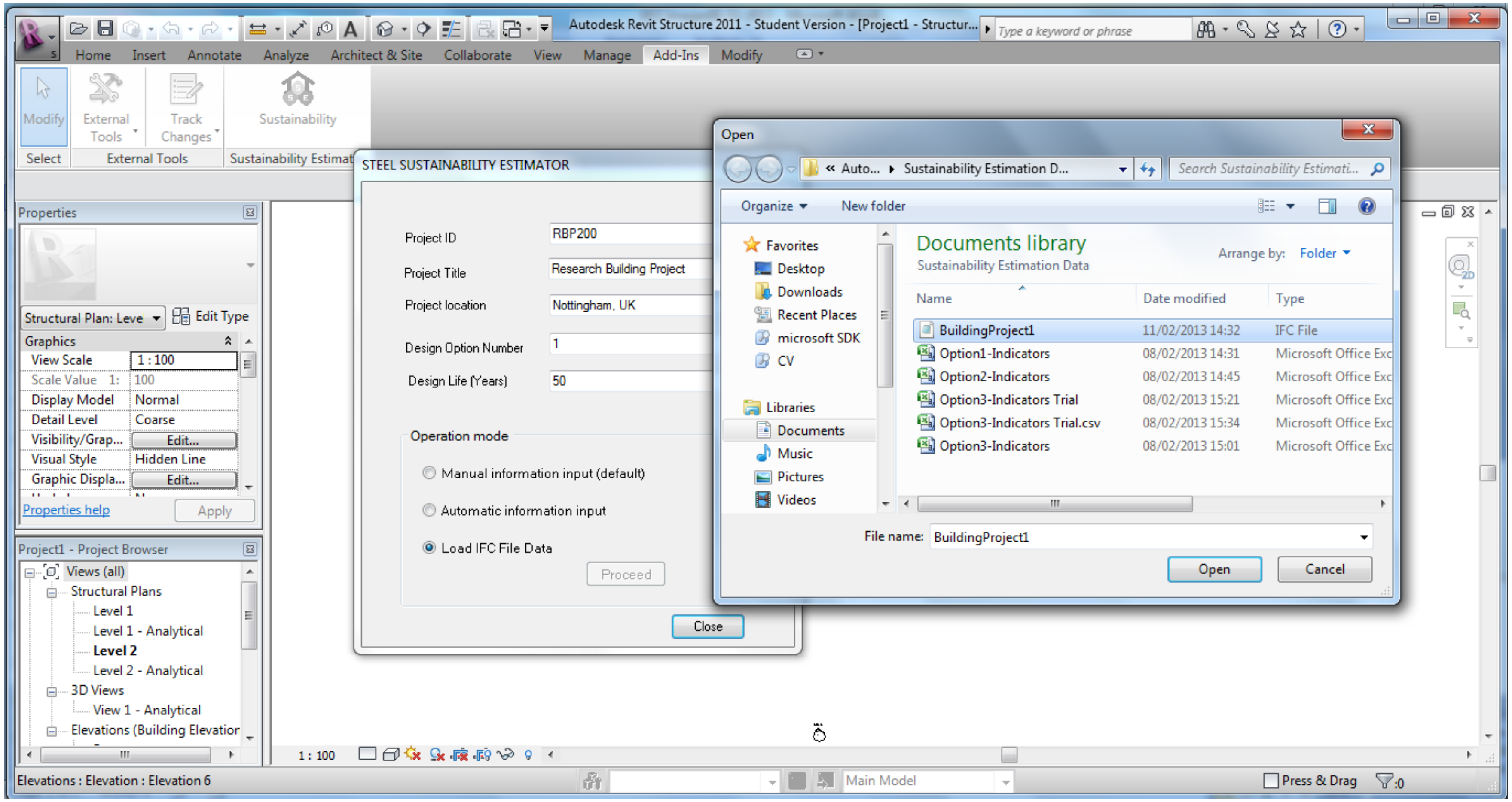


Figure 5.11: Loading .IFC file for extraction of features

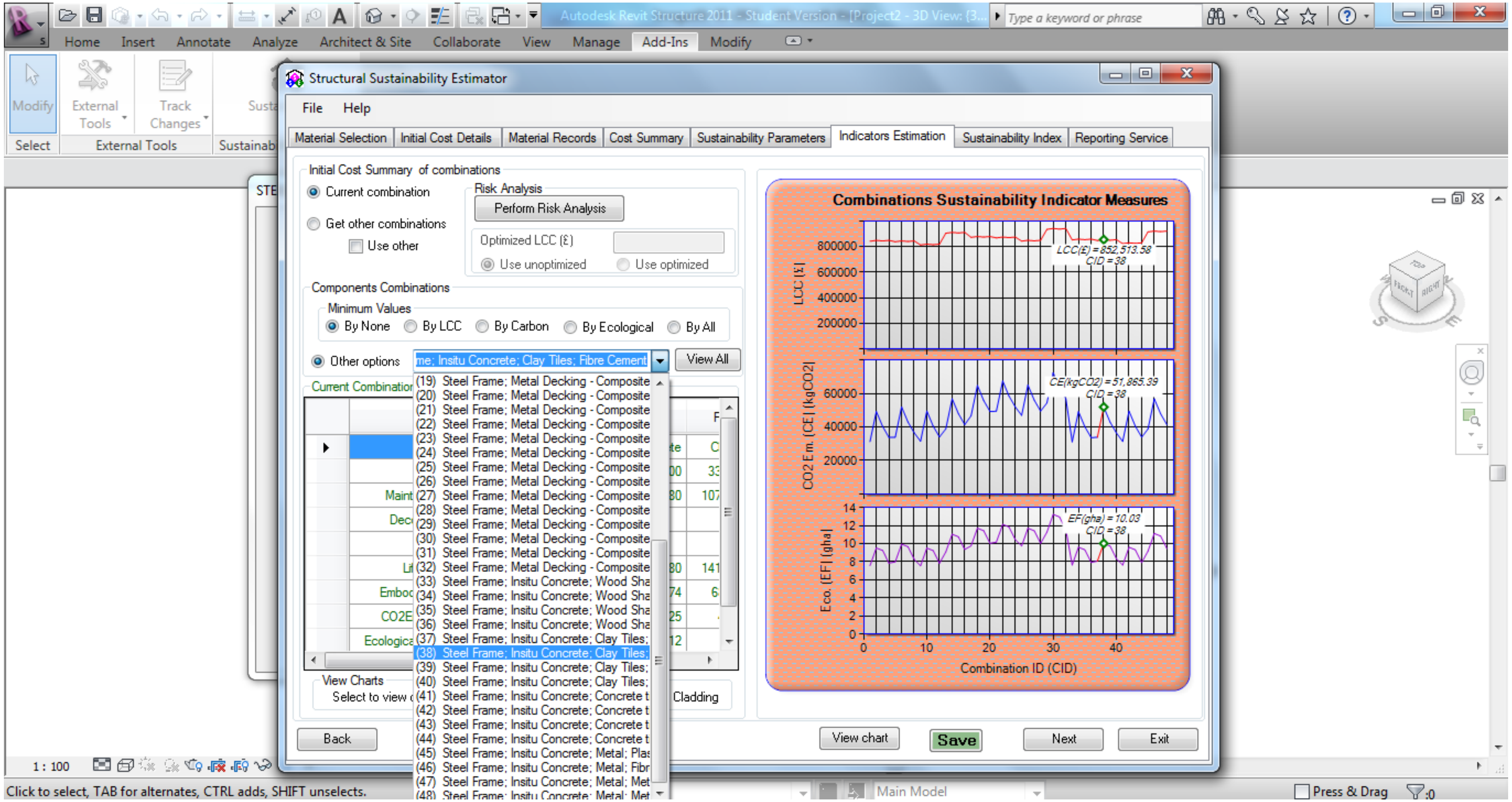


Figure 5.12: What-if scenarios showing components performances

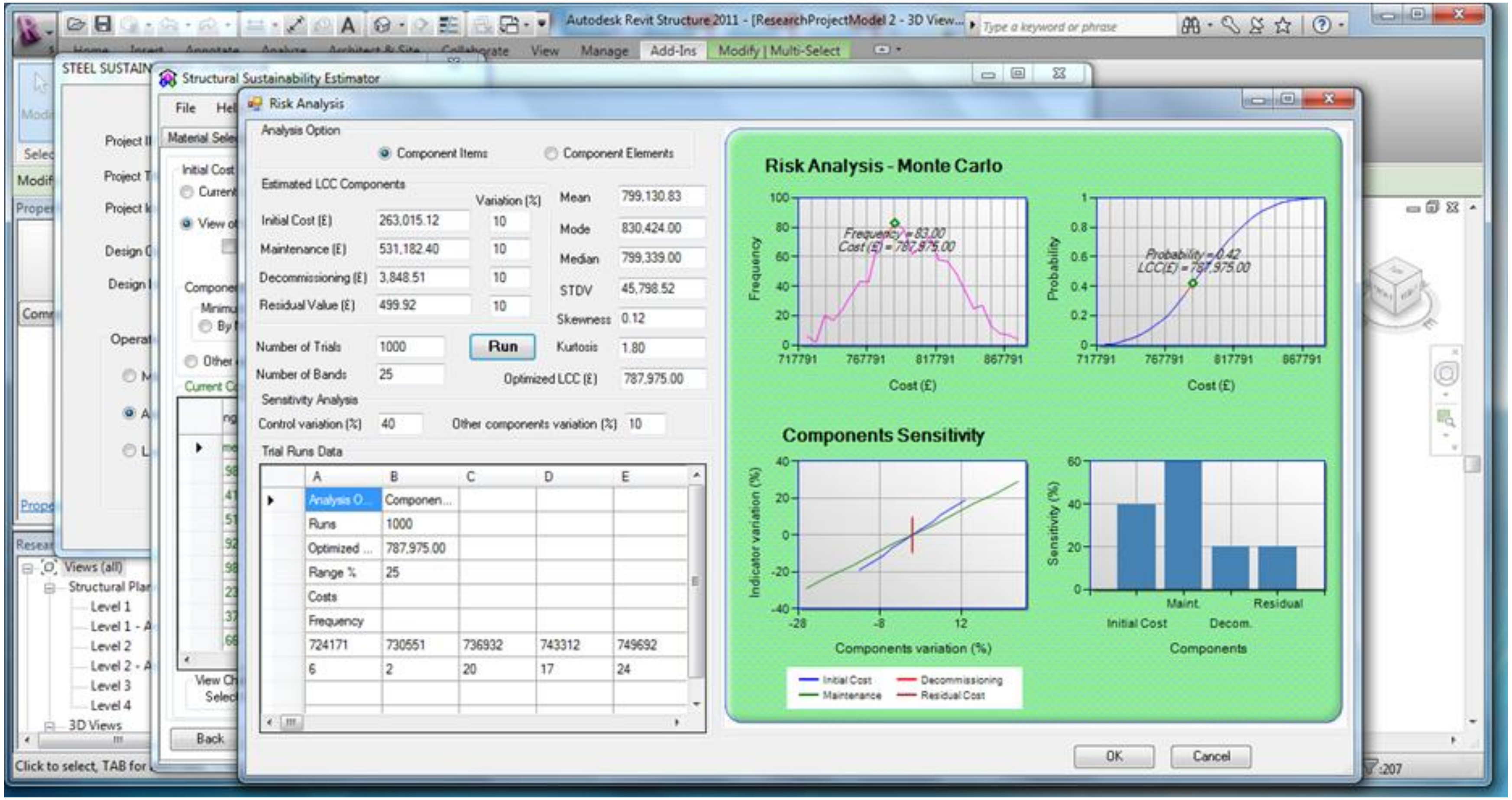


Figure 5.13: Risk and sensitivity analysis on combination option

In this risk analysis example (Figure 5.10 and Figure 5.13), the estimated life cycle cost from the first instance of the analysis using the SSE is £79,1916.94 (Table 5.5). The table gives details of initial cost and maintenance information. It also shows the breakdown of the cost with respect to the component cost items such as initial cost, maintenance, decommissioning and residual cost. The breakdown can also be viewed with respect to the component elements. These values have been generated via processes already described in sections 4.4.3, 5.3.3 and 5.3.4. The key steps include extraction of elements from the building model, abstraction of material cost from the database and the estimation of initial costs of materials.

The associated risk analysis can be performed based on the breakdown of component cost items or component elements. The system therefore allows simulation runs to be carried in order to obtain LCC values with highest frequency based on the specified number of runs. Figure 5.14 shows the charts developed from the various simulation runs employed in estimating the life cycle cost. The calculations for verifying the output of one of the runs is given in the Appendix 3. The charts corroborate the fact that the higher the number of runs the smoother the curve. This also makes the highest frequency value of the LCC obtained from the process of risk analysis more salient for identification. The LCC values are shown in Figure 5.15 for the two options of components cost items and elements. It can be inferred from the chart that LCC has a high risk of fluctuating between £794500 and £808000 for the structure within the limits of the risk analysis implemented in the SSE.

Table 5.5: Sustainability indicator measures for 2 storey building

(a) Component elements quantities and initial cost

Description	Material	Quantity	Cost
Framing	Steel Frame	29.12 t	69088.98
Floor	In situ Concrete	240.00 sq. m	104400.00
Roof	Clay Tiles	401.80 sq. m	62279.00
Cladding	Metal-Aluminium	530.10 sq. m	25974.90
Total			261,742.88

(b) Maintenance information

Item	Initial Cost	Maintenance	Maintenance	Remarks
Framing	69088.98	13380.88	10	Coating only
Floor	104400.00	52200.00	10	Finishing
Roof	62279.00	62279.00	10	Replacement
Cladding	25974.90	25974.90	10	Replacement
Project ID	RBP100			
Design Option No.	1			
Design Life	80 years			
Discount Rate	2 %			

(c) Components indicator output information

	FRAME	FLOOR	ROOF	CLADDING	
Combination ID 38	**Steel Frame**	**In situ Concrete**	**Clay Tiles**	**Metal-Aluminium**	**Total**
Initial Cost (£)	69088.98	104400.00	62279.00	25974.90	261742.88
Maintenance Cost (£)	45824.41	178765.10	213281.83	88954.13	526825.46
Decommissioning (£)	3848.51				3848.51
Residual Cost (£)	499.92				499.92
Life Cycle Cost (£)	118261.98	283165.10	275560.83	114929.03	**791916.94**
Embodied Energy (MJ)	626123	2729.83	138211.16	213630.3	980694.29
CO2Emission (kgCO2)	25152.37	405.5	9568.47	11356.86	46483.2
Ecological Footprint (gha)	6.66	0.08	1.34	2.07	10.15

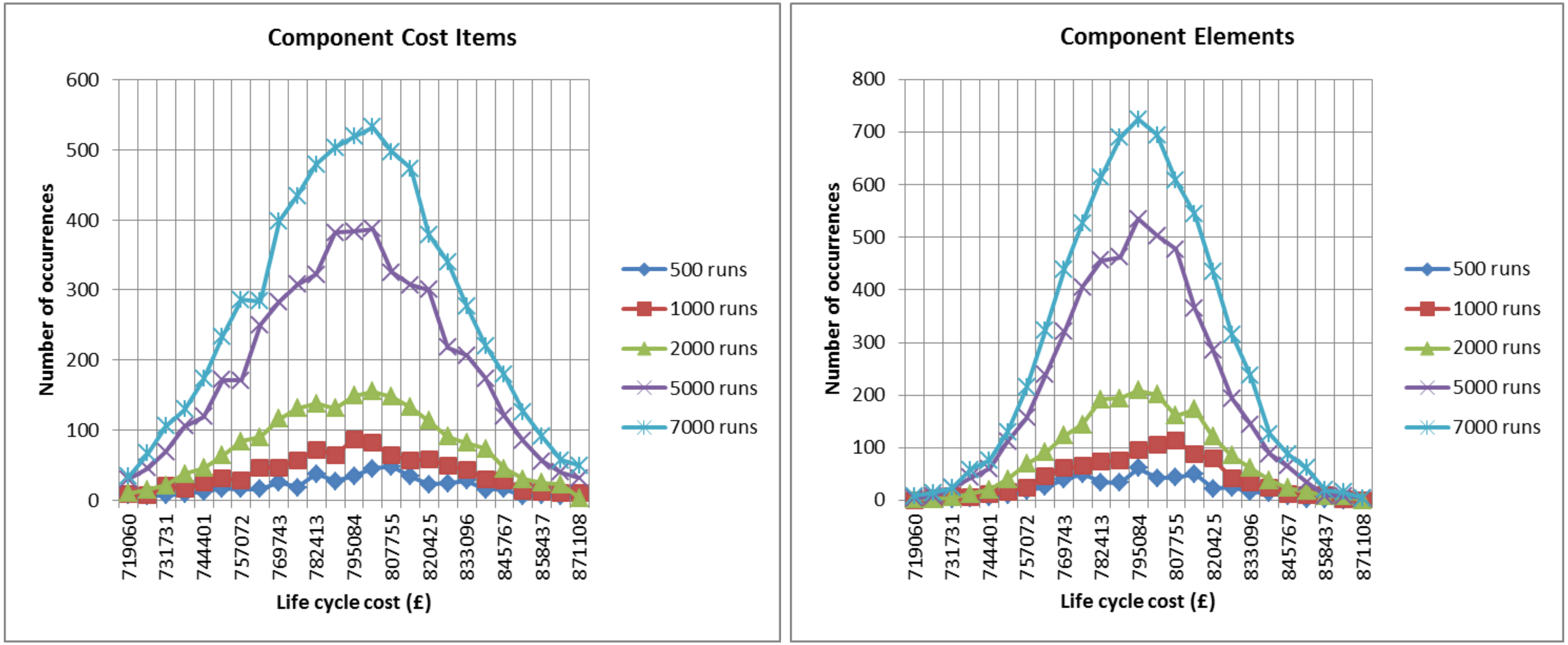


Figure 5.14: Monte Carlo simulation frequency distribution of life cycle cost for component items and elements.

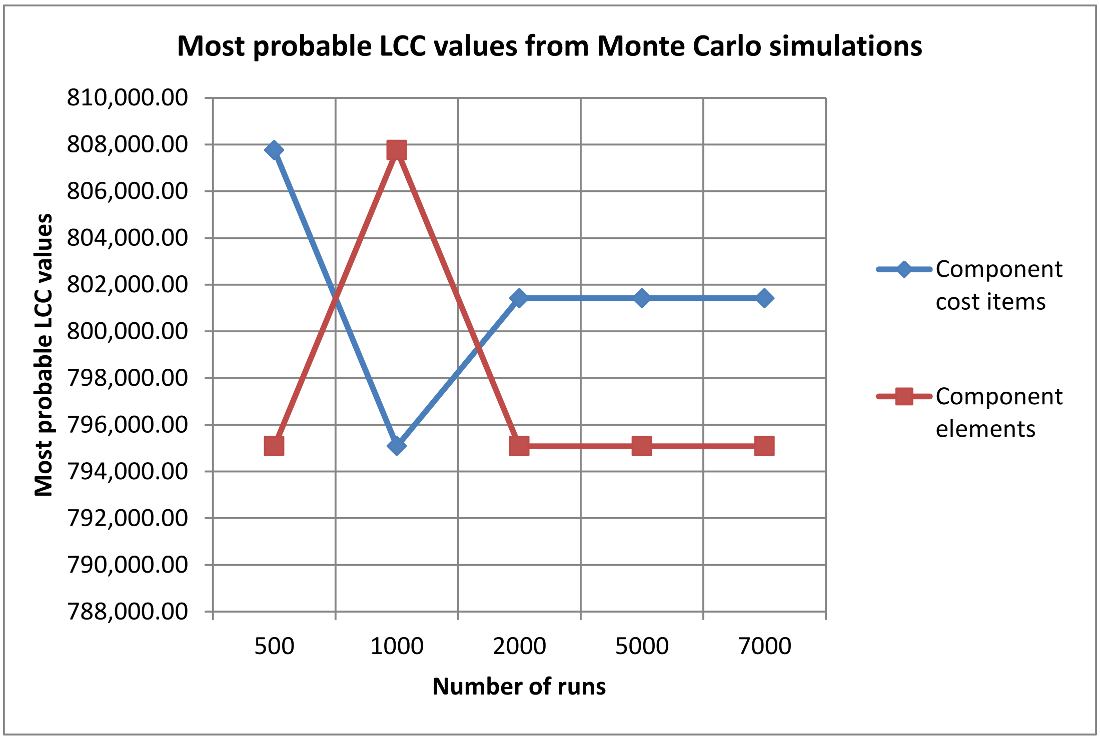


Figure 5.15: Distribution of modified LCC values from the process of risk analysis.

5.5 Discussion and inferences

The case illustration and associated descriptions presented in the previous section give the key steps in the operation of the sustainability model. The prototype has been developed to fulfil the implementation requirements of being generic, formal, flexible, scalable, and time-efficient. It is generic in terms of the fact that primary structural framing elements such as columns and beams; and also floor and cladding systems have been considered. Sustainability related concepts and information associated with the use of these generic elements in early design iterations have been represented in a structured and formal manner to achieve appreciable degree of automation using feature extraction and object-oriented programming techniques in interacting with building product model.

Currently the prototype is implemented on the Revit Structures platform and flexible enough to carry analysis on a product model saved in IFC file format. It is also possible to use the prototype with other BIM-enable software tool that supports OOP with little adaptations and changes in configuration. Analysis can be done on a single member, a group of members or the whole framing of a building. The prototype also allows for scalability in terms of variations in sizes and number of floors of buildings; and the number of conceptual design options to be analysed.

The analysis of options is limited to economic and environmental aspects of sustainability since the methods of accounting for the social pillar is still in infancy. Also, it has relatively insignificant influence on decisions of structural modelling. The indicators used to depict the two sustainability aspects include lifecycle cost, carbon and ecological footprint. These indicators are able to capture the vital aspects of building performance (BIM-IWG, 2011) in terms of structural sustainability. They constitute easily quantifiable measure of the effect of decisions made around the key variable components that can have significant impact on building sustainability. These indicators already have existing information on established theories and procedures that aid their application in various scenarios; however the synthesis and management of such information to guide decisions such as in early building design stages has not been sufficiently explored. It is essential to mine information but what is even more essential is the utilization of the mined information. This work is targeted at putting the information on these key sustainability indicators to work for the structural engineers in their design iterations. It has been pursued through the modelling and mapping of information surrounding decisions and processes connecting objects such as materials, construction methods, costs etc.

Though objects such as cost may vary with time and market forces, these can always be updated in the appropriate prototype databases. Thus the most important aspect of the prototype is the modelling and mapping of synthesised information to inform the structural engineer's design decisions in contemporary IT application such as BIM in the construction sector. This research therefore demonstrates that with the emerging contemporary BIM technology, building professionals such as the structural engineer can incorporate sustainability criteria into early design iterations to guide decisions on selecting best ranked design solutions for detailed design and onward construction.

5.6 Summary

This chapter presented a case study to demonstrate the use of the proposed prototype system in a typical design activity. It examined three design options of a three storey office building in order to illustrate the usefulness of the system in informing the conceptual design process of steel-framed structures. The intention of this aspect of the research is to apply the prototype on a case study as an evidence of its efficacy for further substantiation through an evaluation process. The evaluation aspect is presented in chapter 7.

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Chapter 6

Evaluation

6.1 Introduction

This chapter presents the evaluation methodology employed in the research. The intention of this research aspect is to assess if the implemented prototype adequately represents the modelling framework. It covers evaluation of the prototype on informing the conceptual design activity of structural engineers about sustainability of alternative solutions. The goal, procedure, results and accompanying discussions of the evaluation are presented.

6.2 Evaluation Goal and methodology

The evaluation methodology is used as part of the methods in this research to achieve the research objectives. The evaluation goal is to assess the prototype on whether it reflects developed sustainability modelling framework. It is intended that feedback from the evaluation process will provide information on appropriateness, suitability, applicability, and ease of use of the prototype.

Evaluation remains one of the dimensions of contributing to the solutions to software requirements engineering (Zave, 1997). It is possible to apply evaluation to a single solution or a comparison of several solutions. There exist several evaluation techniques suitable for different research fields and purposes. In software requirement engineering, it is recommended that evaluation should be implemented on real world-applications or industry settings to assess systems on scalability, practicality, and ease of use (Cheng and Atlee, 2007). Hence in this research, the evaluation is based on the application of the prototype on real-world conceptual structural design scenario using BIM-enabled software, Revit Structures^{TM}. Sample population of evaluators has been targeted to be a mixture of academics and industry personnel. At this juncture, it is worth mentioning that the prototype is a demonstration of concept and has scope limitations in application of typical real-world design scenarios.

The research adopted questionnaire survey as a key tool in this methodology. This has been found to be appropriate since the goal and intended questions are clear, new information will be generated about the prototype, the target sample population (civil and structural engineers) is known, and feedback could be generalised as well as used to improve the system (Buckingham and Suanders, 2004)

6.3 The evaluation process

The prototype software was presented to a group of civil engineering personnel. Their responses were gauged by the means of a questionnaire. The intention is to obtain feedback from both peer and group review. The principal drawback of this methodology is the direct presentation of the work by the author. It is also possible that one-to-one semi-structured interviews could easily introduce bias into the results because of familiarity or other social factors. To minimize these effects, the presentation was carried out as objectively as possible and participants were also encouraged to be objective in their responses.

The procedure for the evaluation is as follows.

- A presentation to explain the working of the prototype at a theoretical level was made before the evaluators. The presentation covered how the prototype has been designed to achieve the target of informing the conceptual structural design process on the sustainability of alternative design solutions based on building life cycle information.
- The evaluators were shown a case study to demonstrate how the prototype could be used to carry out sustainability analysis of a typical steel-framed building, including implications associated with outputs of the prototype.
- Questionnaires (see Appendix 4) were given to the evaluators to assess the system. The questionnaire contains ten quantitative and six qualitative questions. The intention of the quantitative questions is to gauge (using Likert scale) the general opinion of evaluators towards the research. On the other hand, the qualitative questions are semi structured and aimed at capturing important generic factors that interviewees feel may have been missed out or ignored in the implementation. This qualitative part also allows the free expression of opinions that would have been difficult to capture with the Likert scale.

6.4 Evaluation results

The evaluation result presents issues relating to the selection of sample size, response rate and the discussion of the responses from the interviewees.

6.4.1 Selection of Sample size

The evaluators consisted of a group of civil engineering practitioners totalling 9 in number. A description of the disciplines of the evaluators is given in Table 6.1. Four out of the nine evaluators have industry experience and worked as designers. The other five structural engineers from the academic background have knowledge/experience of software programmes operation, decisions support tools and sustainability issues.

Although the sample size may not adequately represent the number of civil engineering practitioners in the industry, the response from the evaluators is the key required information to assess the system. On the interim, the information gathered from the group of evaluators is adequate to improve the system since it is developed at a prototype level. In conditions of more extensive time and budget limits, a larger sample size and zonal surveys in various civil engineering institutions of the a country such as the UK will be useful for gathering responses.

Table 6.1: Evaluators background and experience

Evaluators	**Number**
Design and Industry Experience	4
Structural engineer - Academic	5

6.4.2 Response rate

The response rate for the evaluation is 89%. Eight out of 9 questionnaires were returned with responses. Among the eight returned questionnaires, one was partially filled; leaving out some responses in the quantitative part and providing no comment on the qualitative part.

6.4.3 Analysis of responses

The responses for the quantitative questions are given in Figure 6.1. The figure shows the difference in judgemental responses of the interviewees. The difference in opinions have been reflected in the use of descriptive terms such as 'most of', 'few of' etc. to capture varying opinions of the interviewees. It is worth mentioning that whether opinions are in the majority or minority, careful consideration is still given to how such opinions may contribute to improving the system.

The quantitative responses generally indicate the interviewees had positive opinions about the SSE. The responses for the ten quantitative questions on general impression, sustainability appraisal issues and implementation requirements were all the good side of the Likert scale. The responses were either "agree" or "strongly agree". A few responses were "neutral" on issues of the adequacy of the number of sustainability indicators used in the prototype.

Most of the responses from the interviewees suggest that the SSE was easy to use and that the steps have been presented logically. There is a good agreement that SSE is capable of informing structural engineers on the sustainability implications of their design solutions. This is especially important for creating awareness among designers in the emerging use of BIM in the AEC industry.

Another interesting point is most of the interviewees agreeing that the number surprising as many sustainability appraisal schemes usually consider numerous indicators for assessments. Although for the purpose of decision making during conceptual design; LCC, Carbon footprint and ecological footprint measures seem adequate to rank options. This has been shown by the prototype. Most of the interviewees also share the opinion that key elements in structural framing systems have been considered and the prototype show a good degree of flexibility and scalability with building's size and number of floors. The time taken to get analysis results out the prototype is not unnecessarily long.

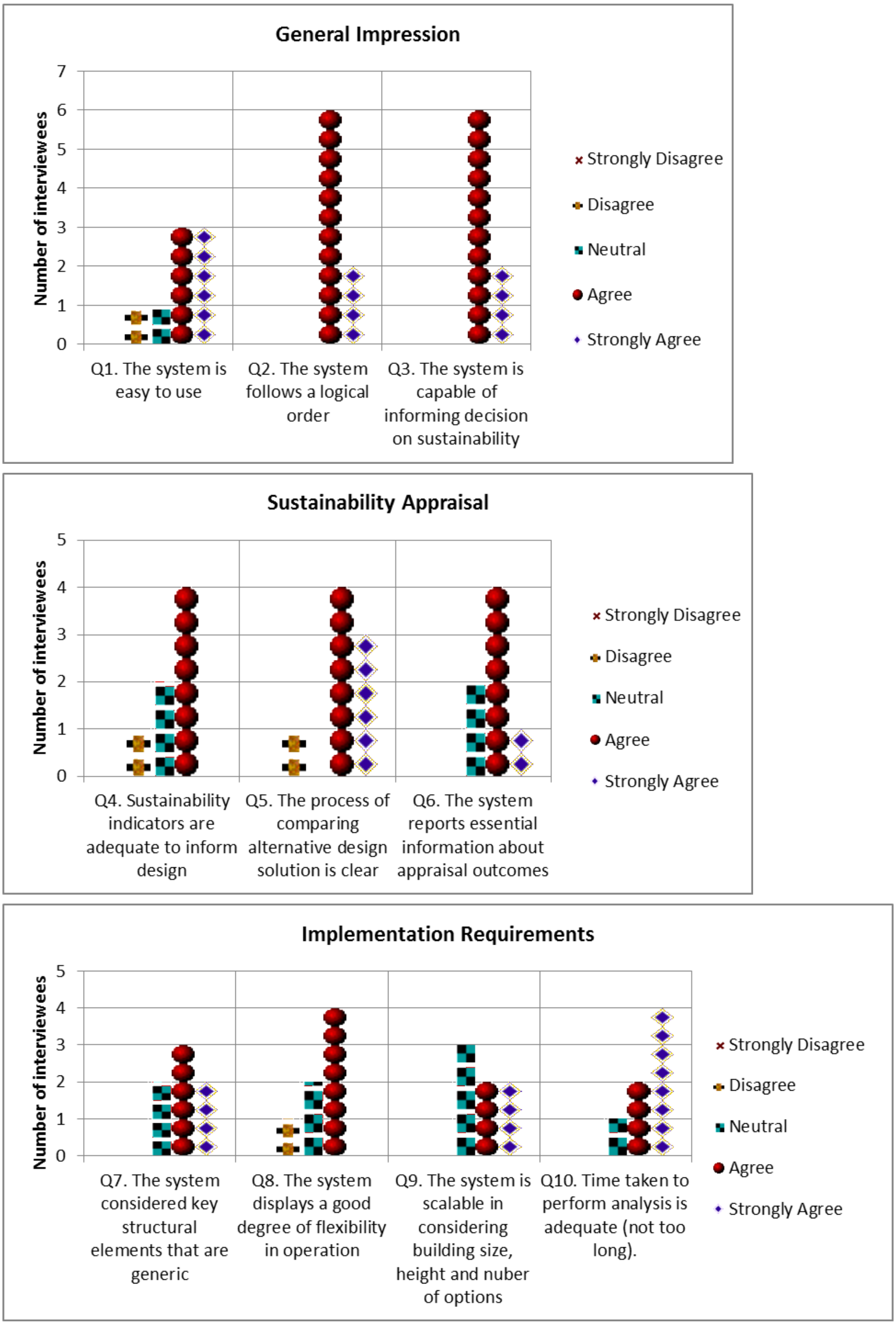

Figure 6.1: Response from evaluators for quantitative questions

The responses on the qualitative part provided a good deal of inferences for evaluating the research as much as the quantitative aspect of the questionnaire. It is not feasible for interviewees to give detail comments on specific aspects of the SSE because of complexity of the prototype, the relative level of its completeness and the convenience of space and time. Some of the qualitative responses may require that interviewees actually use and familiarize themselves with the prototype. The qualitative questions were therefore drawn at high level, though careful enough to cover significant issues that interviewers feel could enhance the overall research.

Discussed next are the six qualitative questions and the corresponding responses from the interviewees. The discussion also includes a summary of the inferences deduced from the evaluation.

Q11. Is the system capable of creating awareness and application of sustainability measures in early design iteration?

> The interviewees were generally of the opinion that the prototype can help to create awareness on sustainability issues among structural designers. They were also happy with the fact that, beyond awareness, designers will also become able to analyse the sustainability of their design solutions at an early stage of design. This is particularly useful with the emergence of parametric modelling systems were building elements are being represented by intelligent objects in digitized form.

Q12. Is the system likely to create positive impact on sustainable construction?

The interviewers were affirmative that the system can contribute positively to the ideals of sustainable construction. Although views on what constitute sustainable development vary, they are built on the economic, environmental and social well-being of the present and future generations. As such sustainable construction seeks to promote economic, environmental and social sustainability in the sector's activities. Ironically, the sector is noted for heavy consumption of natural resources. This makes the sector's sustainability promotion efforts important. Environmental sustainability may be achieved through the protection of the ecosystem and efficient use of resources. Long-term resource productivity and low use cost can contribute to the economic aspects. These are the overall goals the prototype aims to achieve by using the key indicator measures of life cycle costing, carbon and ecological footprint to rank structural design and framing options early in the design stage.

Q13. Which parts or features of the system did you find particularly useful?

The intention for this question is to gather information on the features that interviewees find generally more useful in the building sustainability appraisal process. This will help in the event of possible improvement of the prototype and recommendation for further implementation refinement. The useful features mentioned include the risk analysis tool (using Monte Carlo Method) and the aspect that deals with selection of options (using multi-criteria decision analysis). They were also impressed with the level of automation in the extraction of elements from the building model. This is really useful in saving time in that designers do not have to manually enter one element after the other to carry out analysis. Also, the ability of the prototype to carry out analysis on IFC building model makes it useful for interoperability purposes. This is an important feature that also implies that the prototype can be adapted to any OOP-based parametric modelling platform apart from Revit Structures. Conforming to conventional Microsoft Windows screen presentation pattern was also pointed out to be useful for easy familiarity with prototype.

Q14. What are the likely barriers to adopting such systems to inform conceptual design scenarios?

Awareness of the existence of such programme in the structural engineering field among practitioners will go a long way to encourage its use. However a typical barrier will be the level of confidence users can bestow on the programme and output result. This is typical of new systems which can be overcome by continuous use and practice. Another issue is acceptability and recognition in the sector of the industry for which it has been developed. This also depends on the level of integration and adaptability that can be achieved with other structural design tools. To a large extent, good publicity and advertisements through demonstrations in workshops and conferences alike, new programmes such as the SSE may become widely familiar and acceptable.

Q15. What additional features or requirements of the system will you recommend?

Aspects on expansion and improvement of the prototype were mentioned as desired additional features. These include increasing the library of materials and elements, combining of charts for individual elements and means to show the significance of the difference in desirability scores from the comparison of design options.

More specifically, the interviewees pointed out that it will be useful to have standardized weighting for combining the environmental and economic sustainability indicators used in the prototype. This is an important aspect in sustainability analysis as designers, based on orientation and background, could have varied opinions about the proportion of the overall impact associated with the respective indicators. Standardization of indicator weightings for sustainability is beyond the scope of this research and lies in the hands of the construction sector as a whole. However, a good degree of flexibility has been incorporated in the implementation of the prototype so that users can vary weighting to whatever standardization they may be working with.

It was also suggested that another good additional feature for the prototype to perform would be to export results generated by the prototype back to the building model in Revit Structures. This is an aspect that need further research and would require permission or collaboration with proprietary owners of the BIM enable platforms. The reason being that proprietary building modelling programmes such as Revit Structures remains locked to other programmes while running and active. Another suggestion is to create IFC compatible data structure that could store results generated by the prototype which in this case can be accessible by BIM-enable platforms compatible with IFC schema.

Q16. Any additional comments

The interviewees added that it is an interesting area of research and commercialisation of the prototype is worth considering once it can be applied on actual design options of buildings about to be built or already built.

6.5 Result discussion and implications

In general, the interviewees were of the opinion that in the future the structural designers will become more sustainability-aware and they are likely to conduct early appraisals of their designs for the purposes of selecting best ranked options. The interviewees are optimistic that the research successfully addresses this aspect. They also felt that this will be useful when the industry develops to the point of structural sustainability design labelling as it is now obtainable in energy labelling of products.

Interestingly, the idea including sustainability assessment of structural components of the building to conceptual structural design was noted by several interviewees to be thoughtful. They believed this will help the structural engineer to check the sustainability credential of alternative solutions as design progresses. As such engineers can make informed decision on materials to be used or substituted to achieve better sustainability performance.

The evaluators' recommendations are summarized in Figure 6.2. It depicts issues to address for contemporary IT implementations to successfully consider sustainability issues in the design process. Conventionally, clients require their projects delivered at minimum cost which unfortunately makes sustainability less palatable for the fear of increase in project cost. However, it is becoming clear that a sustainable design will not only favour future generations but also has the advantage of saving costs on the long run. The interviewees appear to have a consensus on this premise and therefore suggest the need for defining industry-wide accepted sustainability indicators with standardized weighting ratios and developing extensive database of life cycle information of building materials on the sustainability side. This prototype can benefit from the existence of such information for further improvement. Such improvement will be on extending the prototype to consider other structural materials and extensive life cycle information. It was also suggested that future implementation of the design side could be improvement on consideration of different building shapes, increased level of automation and operation in other existing BIM-enabled platforms.

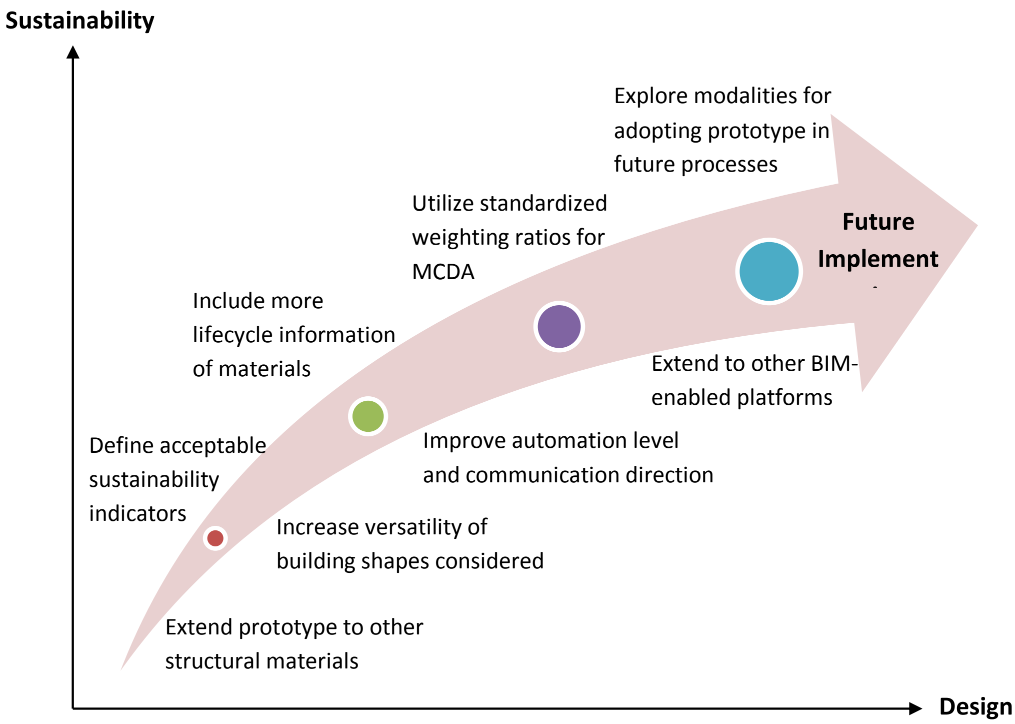

Figure 6.2: Evaluators recommendation

6.6 Summary

This chapter presented the evaluation of the prototype system in accordance with the last objective of the research. The intention for the evaluation is to assess whether the implementation of the prototype fulfilled requisite modelling requirements. Ultimately, it is aimed at assessing the prototype to know how it has improved the process of informing conceptual structural design decisions on the sustainability of alternative design solutions. The evaluation results show that this is not only affirmative but that it can go beyond creating awareness to encouraging structural engineers to start assessing their designs from the conceptual modelling stage, and assist them to declare such assessment results on completion. Future improvements were also recommended for the prototype.

Chapter 7

Conclusion and recommendations

7.1 Introduction

This chapter gives a recap of the research objectives and a summary of how they have been realised in the course of this research. It also summarizes the research findings, contributions, recommendation for further work and lists the interim dissemination realised in the research work.

7.1.1 A recap of aim and objectives of the research

The research aim was to investigate how the use of building information modelling technology can influence conceptual design decisions based on the life cycle information and the sustainability of alternative design solutions. This is targeted at quantifying the sustainability of design solutions to inform conceptual design decisions as an integral part of building information modelling (BIM). To achieve the overall aim of the research, the set objectives were as follows.

Objective 1. Ascertain the challenges associated with contemporary building information modelling and decision-support tools in building design and construction

Objective 2. Identify requirements for modelling sustainability implications of alternative design solutions for the building product.

Objective 3. Establish a modelling framework capturing relationships amongst various factors influencing design decisions based on sustainability.

Objective 4. Implement a sustainability design-decision-support prototype system based on established framework.

Objective 5. Validate the system for the suitability of the framework implementation from the point of view of typical design environments for steel structures.

Objective 6. Evaluate the system on its effectiveness in improving the sustainability appraisal of conceptual design.

7.1.2 Realisations of objectives

Objective 1:

Sustainable construction is one of the key contributors to achieving sustainable development through appropriate and efficient material use to enhance reduction of costs and emissions. Decisions-support tools in construction remain an identifiable promoter of sustainability goals that can significantly influence the early stages of planning and design of projects. However, even with the advancements in IT, this has not been sufficiently explored to the benefit of building professionals, especially the structural engineer. This gap also exists with BIM, the recent focus of IT in the Construction Industry.

Objective 2:

The design process of buildings is iterative and usually ends up with options. It is possible to include sustainability as one of the factors to guide the selection of options from conceptual design activity. This entails adding sustainability implications into the building modelling process. This research revealed that requirements that guide such modelling activity are in two parts; the first aspect is concerned with sustainability appraisal and the second, software implementation needs. For building sustainability appraisal; system boundary, component and process flows, functional units and time dimension were identified to be important. Generality, formality, flexibility, ease-of-use, scalability and time-efficient are the requirements for software implementation.

Objective 3:

A modelling framework is desirable for the purpose of evaluating options to ease decision-making. For buildings, the key performance variables that influence sustainability are related to economy and environment. Life cycle cost was identified as the best indicator for economy whereas carbon footprint and ecological footprint measures are combined to respectively account for the atmosphere and biosphere of the environment. The framework is developed taking advantage of a database of construction information, object-based programming technology and tools for scoring options based on multiple criteria.

Objective 4:

The compatibility of object-oriented programming in .NET environment with object-based parametric modelling is a panacea for BIM extensions and interfacing with external plug-in tools. This allowed for appropriate object mappings based on feature extraction activity from conceptual design model. The inherent object oriented properties of polymorphism, encapsulation and inheritance have been useful in implementing the prototype.

Objective 5:

The prototype was used on a case study to examine results against the sustainability modelling framework. The system is capable of not only enhancing the awareness of sustainability among professionals such as the structural engineer but also give the opportunity of declaring the sustainability of their designs. The prototype was found to be suitable in terms of logical flow and scales the desirability of design solutions based on the indicators considered.

Objective 6:

Survey results show that the system is logical and relatively easy to use as it follows conventional windows-based interface design. It was also established that it could be useful to inform designers on sustainability in the construction industry and help in prioritization of the use of construction materials and structural frames.

7.2 Research findings

The research identified a number of challenges associated with incorporating sustainability decision support systems to inform design decision. These challenges have been found to be critical in integration of sustainability assessment tools to the deployment of BIM for construction transaction. They include:

(i). Current sustainability assessment programmes focus mainly on existing buildings.
(ii). Projects are evaluated at relatively late cycle stages when it is too difficult to incorporate changes.
(iii). Evaluations of projects are still at high level and too general to trace proportion of impacts associated with elements.
(iv). The financial aspect in sustainability evaluation frameworks is often not reflected
(v). Building assessment tools are yet to be fully integrated into BIM
(vi). Current sustainability analysis tools are services oriented and require the exchange of data to carry out analysis.
(vii). Lack of dynamic parametric modelling of transactions between BIM and sustainability assessment tools.

The summary of specific aspects of research associated with resolving the above challenges are:

(i). Integrate sustainability assessment into early project stages such as early design, to have greater influence on impacts.
(ii). Inclusion of sustainability issues into early project cycle stages has greater influence on reducing negative impacts.
(iii). Sustainability evaluation at profession-specific level will create awareness and promote sustainability ideals to manage elements and materials more consciously.

(iv). Sustainability assessment should reflect both economic and environmental evaluations as a minimum for sustainable development ideals

(v). Object oriented programming technology presents opportunity for feature extraction through feature modelling to implement integration of building assessment tools with BIM

(vi). Sustainability assessment and related tools are also relevant to the structural engineer and the architect as much as it is recognised for services engineer.

(vii). Parametric modelling transaction is possible between BIM and sustainability assessment tools acting as plug-ins. Two-way information updating and modification will become possible from adequate collaboration with proprietary owners of BIM-enabled tools.

7.3 Contributions

The novelty in this work is the proposal of a BIM-based prototype system for selecting best ranked structural solution among alternatives - based on their estimated sustainability measures. The ensuing contributions to this area of research include the following.

- This research identified the need for profession–specific sustainability pursuance for holistic sustainable construction in the AEC Industry.
- It systematically categorized key IT requirements to guide conceptual design decision-support tools based on thorough review of literatures and experiences from the framework implementation.

- The research demonstrated a possible application of BIM in sustainability analysis of conceptual design options through feature mapping and modelling technology.
- The research produced a framework embodying a tacit simplification of sustainability implications and building lifecycle processes that eased modelling and quantification to inform building designers.
- The research established information modelling representations - in the form of a process model, implementation algorithms and object-based instantiations (capturing the components of building sustainability and associated processes, decision support system including aspects of risk and sensitivity analysis, what-if scenario applications and mapping of database information) to inform design decision.

7.4 Recommendations and future work

The construction sector has been recognised to have a substantial influence on sustainable development both in terms of positive and negative impacts. The growing concerns to reduce the negative impacts have been a driver in sustainability research innovations. One of such research areas has been the development and optimization of decision support systems to aid professionals. The goal is to assist professionals in making better informed decisions while and when it matters most in terms of time to effect changes. Hence, this work targeted the conceptual design stage and structural steel framing systems. Further area of work will be to extend the prototype to other structural framing systems such as reinforced concrete and to be able to consider different shapes of building geometry. Modalities for extension to other BIM platforms remain another interesting area for further investigation.

7.5 Research dissemination

The following papers have been published in relation to this research.

- Oti, A.H. and W. Tizani. *Developing incentives for collaboration in the AEC industry*. in *Proceedings of the International Conference on Computing in Civil and Building Engineering*. 2010. Nottingham: University of Nottingham Press.

- Oti, A.H. and W. Tizani. *A Sustainability Appraisal Framework for the Design of Steel-Framed Buildings*. in *Proceedings of the Thirteenth International Conference on Civil, Structural and Environmental Engineering Computing*. 2011. Crete, Greece: Civil-Comp Press, Stirlingshire, United Kingdom.

- Oti, A.H. and W. Tizani. *Building information modelling for sustainability appraisal of conceptual design of steel-framed buildings* in *14th International Conference on Computing in Civil and Building Engineering (14th ICCCBE)*. 2012. Moscow State University of Civil Engineering (National Research University), Moscow: Publishing House "ASV".

- Oti, A.H. and W. Tizani. *A sustainability extension for building information modelling* in *Proceedings of the CIB W78 2012: 29th International Conference –Beirut, Lebanon, 17-19 October*. 2012. Beirut, Lebanon: CIB MENA.

7.6 Summary

This research investigated how the utilization of current process and data modelling techniques can be employed to model sustainability related information to inform decisions right from the early stages of structural design. Sustainability requirements in construction have warranted the need for structural engineers to become better informed on the best ranked design solution, in terms of sustainability, among alternatives. BIM presents opportunities for integrating the modelling of sustainability performance into the early stages of building design. This thesis outlined the research work on a proposed integrated framework, based on the feature modelling technique to depict the sustainability of the structural engineer's conceptual design of steel-framed building. The framework combines three key sustainability indicators, life cycle costing, carbon footprint and ecological footprint measures for the assessment of sustainability. LCC accounts for economic sustainability while carbon footprint and ecological footprint give a measure of the impact on the atmosphere and biosphere, respectively, of the environment.

The basic programming representations of the implementation of the computer-integrated sustainability framework in the form of a prototype system were presented. The goal of this investigation is to establish an information model that captures data and process needs of the designer in considering sustainability issues at the early design stage. The implementation of the prototype tool is based on a significant amount of data that was collected from existing life cycle process inventories and cost databases associated with construction methods and materials. The management of this data has been implemented in Microsoft SQL within the integrated C# object-oriented environment of Visual Studio .NET Framework. Currently, the prototype targets structural steel framing systems with various floor and cladding systems. A case illustration and evaluation of the prototype were presented to demonstrate the usefulness of the tool in assessing the performance of alternative design solutions. The prototype ranks design alternatives based on the principle of Multi-criteria Criteria Decision Analysis. It has brought out the need for institutional standardization of the process of specifying sustainability indicator weightings to avoid issues with subjectivity from users. This aspect is outside the scope of this research. Thus, with adequate maturity of this demonstrated concept, structural engineers will become better informed on the sustainability of their alternative design solutions.

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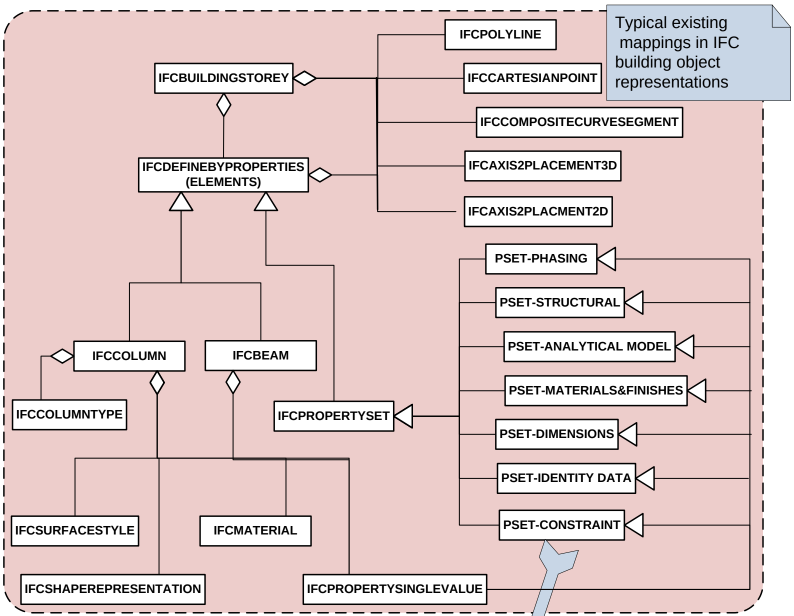
Appendices

APPENDIX 1

Snippet for feature extraction from IFC file




```
#160=IFCPROPERTYSINGLEVALUE('Column Location Mark',$,IFC
#175=IFCPROPERTYSINGLEVALUE('Base Level',$,IFCLABEL('Lev
#176=IFCPROPERTYSINGLEVALUE('Base Offset',$,IFCLENGTHMEA
#177=IFCPROPERTYSINGLEVALUE('Top Level',$,IFCLABEL('Level 3'),$);
#178=IFCPROPERTYSINGLEVALUE('Top Offset',$,IFCLENGTHMEASURE(0.),$);
#179=IFCPROPERTYSINGLEVALUE('Column Style',$,IFCINTEGER(0),$);
```

Extract of column element PropertySet of .IFC file syntax

```
else if (line.Contains("IFCCOLUMN") && line.Contains("UC-Universal"))
{
    sitStart = line.IndexOf("=");
    sitEnd = line.IndexOf(",", sitStart + 3);
    sitValue = line.Substring(1, sitStart - 1);
    ColNum = Convert.ToInt32(sitValue);
    Col_Num = ColNum;
    ColStart = line.IndexOf("$");
    ColEnd = line.IndexOf("'", ColStart + 3);
    type_Name = line.Substring(ColStart + 3, ColEnd - ColStart - 3);
    ColTypeName = type_Name;
    ColStart = line.IndexOf("'", ColEnd + 3);
    ColEnd = line.IndexOf("'", ColStart + 3);
    readValue = line.Substring(ColStart + 1, ColEnd - ColStart - 1);
    ColIdValue = readValue;
    if (ColNum > LenNum)
    {
        ColElementLength = Col_Value.ToString("n");
    }
}
else  if (line.Contains("Base Connection") && line.Contains("IFCLABEL"))
{
        sitStart = line.IndexOf("=");
        tempValue = line.Substring(1, sitStart - 1);
        LenNum = Convert.ToInt32(tempValue);
        ColEnd = line.IndexOf("IFCLABEL");
        sitStart = line.IndexOf("'", ColEnd);
        sitEnd = line.IndexOf("'", sitStart + 2);
        sitValueCol = line.Substring(sitStart + 1, sitEnd - sitStart - 1);
        double Num;
        bool isNum = double.TryParse(sitValue, out Num);
        if (!isNum)
        {
           if (LenNum > Col_Num)
            {
                ColConnectionA = sitValueCol;
            }
        }
        else
        {
            continue;
        }
  }
```

C# programming snippet for iterating through .IFC file to extract features

APPENDIX 2

Approximate Estimate Rates (Extract from SPON's)

Item	Unit	Range	
2A FRAME AND "B UPPER FLOORS			
Reinforced concrete floors: no frame			
Suspended slab; no coverings or finishes; per m^2 of floor area			
2.75m span; 8 kN/m^2 loading	m^2	58.00	74.00
3.35m span; 8 kN/m^2 loading	m^2	66.00	84.00
4.25m span; 8 kN/m^2 loading	m^2	82.00	105.00
Suspended slab; no coverings or finishes; per m2 of floor area			
150mm thick	m^2	78.00	100.00
225mm thick	m^2	120.00	155.00
Reinforced Concrete floor and frame			
Suspended slab; average depth; no coverings or finishes; per m2 of upper floor area			
up to six storeys	m^2	150.00	190.00
wide span suspended slab with frame; per m^2 ...			
up to six storeys	m^2	170.00	215.00
Reinforced Concrete floor; Steel Frame			
Suspended slab; average depth; 'Hollow rib' permanent steel shuttering; protected steel frame; no covering or finishes; per m^2 of upper floor area			
up to six storey	m^2	200.00	255.00
Extra for spans 7.5 to 15m	m^2	23.00	29.00
Suspended slab; average depth; protected steel frame; no covering or finishes; per m^2 of upper floor area	m^2		
up to six storey	m^2	190.00	245.00
Suspended slab; 75mm screed; no covering or finishes; per m^2 of upper floor area			
3m span; 8.50 kN/m2 loading	m^2	62.00	79.00
6m span; 8.50 kN/m2 loading	m^2	66.00	84.00
7.5m span; 8.50 kN/m2 loading	m^2	69.00	88.00
3m span; 12.50 kN/m2 loading	m^2	74.00	95.00
6m span; 12.50 kN/m2 loading	m^2	61.00	78.00
Precast Concrete floor steel frame			

Suspended slab; average depth; protected steel frame; no covering or finishes; per m^2 of upper floor area		180.00	230.00
Extra per m2 of upper floor area for	m^2		
wrought formwork	m^2	4.20	5.35
sound reducing quilt in screed	m^2	4.45	5.75
insulation to avoid cold bridging	m^2	7.95	10.20

2C ROOF

Softwood trussed pitched roofs

Structure only comprising 100 x 38mm Fink Trusses @ 600mm centres(measured on plan); per m^2 of roof plan area			
30^o pitch	m^2	25.00	30.00
35^o pitch	m^2	25.00	31.00
40^o pitch	m^2	28.00	34.00
	m^2		
Fink roof trusses; narrow span; 100mm insulation; PVC rainwater goods; plasterboard; skim and emulsion per m2 or roof plan area			
concrete interlocking tile coverings	m^2	96.00	120.00
clay pan tile coverings	m^2	105.00	130.00
composition slate coverings	m^2	110.00	130.00
plain clay tile coverings	m^2	130.00	160.00
natural slate covering	m^2	140.00	170.00
reconstruction stone coverings	m^2	110.00	140.00
Mono-pitch roof trusses; 100mm insulation; PVC rainwater goods; plasterboard; skim and emulsion per m^2 or roof plan area			
concrete interlocking tile coverings	m^2	115.00	140.00
clay pan tile coverings	m^2	110.00	140.00
composition slate coverings	m^2	120.00	145.00
plain clay tile coverings	m^2	140.00	170.00
natural slate covering	m^2	140.00	175.00
reconstruction stone coverings	m^2	120.00	140.00

Steel truss pitched roofs

Steel trusses and beams; thermal and acoustic insulations; per m^2 of roof plan area			
aluminium profiled composite cladding	m^2	250	300
Steel trusses and glulam beams; thermal and acoustic insulations; per m^2 of roof plan area			
aluminium profiled composite cladding	m^2	250	300

EXTERNAL WALLS

Sheet cladding

Non-asbestos profiled cladding			
Profile 6; single skin; natural grey finish	m^2	21	27

P61 insulated System; natural grey finfish; metal inner lining panel (U-value = 0.30 W/m^{2}K)	m^2	45.5	52
Extra for			
Coloured fibre cement sheeting	m^2	2.3	3
Insulated; 2.8m high block inner skin; emulsion	m^2	27.5	35.5
Insulated; 2.8m high block inner skin plasterboard lining on metal tees; emulsion	m^2	40.5	52
Metal profiled cladding(U-value = 0.3 W/m^{2}K)			
coated steel profiled cladding on steel rails; insulated built up system	m^2	41	53
coated steel micro-rib profiled cladding on steel rails; composite sandwich panel system	m^2	76	98
coated aluminium profiled on steel rails; insulated built up system	m^2	43	55
coated aluminium flat panel cladding on steel rails; insulated built up system.	m^2	110	145

CLASS D: DEMOLITION AND SIT CLEARANCE
BUILDINGS

Demolish building to ground level and dispose off-site			
brickwork with timber floor and roof	m^3		6.56
brickwork with concrete floor and roof	m^3		10.93
masonry with timber floor and roof	m^3		8.57
reinforce concrete frame with brick infill	m^3		11.39
steel frame with brick cladding	m^3		6.2
steel frame with sheet cladding	m^3		5.9
Timber	m^3		5.31
Demolish building with asbestos linings to ground level and dispose off-site			
brickwork with concrete floor and roof	m^3		26.57
reinforce concrete frame with brick infill	m^3		27.69
steel frame with brick cladding	m^3		15.14
steel frame with sheet cladding	m^3		14.62

EXTRACTS FROM: *SPON'S CIVIL ENGINEERING AND HIGHWAY WORKS PRICE BOOK 2012, EDITED BY DAVIS LANGDON 26TH EDITION, SPON PRESS*

APPENDIX 3

Verification of risk analysis output

Explanation Note for Table A3.1

Table A3.1 extends to multiple pages and presents the calculations verifying the risk analysis process for 500 trials runs, 25 bands and estimated LCC value of £791916.79 with respect to component cost items. The table is divided into three sections; component item details, frequency table and the generated random number sections. The component item details section gives the values of the estimated cost as obtained from running the SSE programme. It further gives the likely variations of these estimates as entered by the designer. In this case 10% less or more. This enabled the calculation the minimum value, maximum value and range for each component cost item. The number of trial runs is then used to generate random numbers values between the respective minimums and maximums in line with the Monte Carlo principle. These random values are presented in the third section of the table. Each set (table row) of the random values are summed up to obtain a probable LCC value. It should be noted that while other cost items are expenditures; Residual Value is not and is therefore subtracted from the sum of the other costs.

The third section of the table presents the frequency table of LCC Bands and the frequency of occurrences of the probable LCC values within the respective bands. The number of bands and runs are specified by the user and can be varied to explore various scenarios. As seen in the table, Band 814090.47-820425.79 is the most probable occurrence (48).

Table A3.1: Risk analysis – calculation most probable outcome

Component cost item details						
	A	B	C	D	E	
	Initial Cost	Maint.	Decomm.	Residual Value	Sum (LCC)	
Estimates (£)	261742.80	526825.40	3848.51	499.92	791916.79	
Variation, v (%)	10	10	10	10		
Mini. Values	235568.52	474142.86	3463.659	449.93	712725.11	
Maxi. Values	287917.08	579507.94	4233.361	549.91	871108.47	
Range	52348.56	105365.08	769.702	99.98	158383.36	
Number of trials (seed)					500	
Number of bands					25	
Band					6335.33	
Frequency table for most probable outcome						
					LCC Bands	Freq.
					719060.45	0
					725395.78	6
					731731.11	9
					738066.45	9
					744401.78	16
					750737.12	17
					757072.45	25
					763407.79	25
					769743.12	32
					776078.45	41
					782413.79	31
					788749.12	33
					795084.46	29
					801419.79	26
					807755.13	25
					814090.46	22
					820425.79	**48**
					826761.13	21
					833096.46	19
					839431.80	24
					845767.13	13
					852102.47	11
					858437.80	12
					864773.13	4

					871108.47	2

Random numbers between Mini. and Maxi. values for all components

	K	L	M	N	O	
	Initial Cost	Maint.	Decomm.	Residual Value	Sum (LCC)	
	279146	562631	3619	473	844923	
	252150	475004	4048	513	730689	
	256248	509633	3878	460	769299	
	256235	576965	3617	499	836318	
	284282	485399	3902	453	773130	
	263281	543053	4208	494	810048	
	259984	482899	3643	525	746001	
	253977	518910	3617	518	775986	
	235878	541142	3725	451	780294	
	276054	496816	4139	490	776519	
	239396	520793	4124	481	763832	
	242231	484895	3559	465	730220	
	242873	499987	3479	470	745869	
	260462	504131	4208	482	768319	
	244559	501693	4037	524	749765	
	255631	551237	3552	517	809903	
	286270	481511	3761	497	771045	
	238568	528218	4144	469	770461	
	286457	549152	3641	463	838787	
	262502	477589	4163	524	743730	
	269447	528993	3838	470	801808	
	239879	489723	3620	498	732724	
	264318	572246	3749	531	839782	
	254106	566019	3538	456	823207	
	269588	507960	4067	537	781078	
	254112	506716	3658	511	763975	
	283643	561963	3781	532	848855	
	269019	546776	4128	526	819397	
	243212	524349	3679	514	770726	
	238882	545490	3567	477	787462	
	281267	565479	3952	494	850204	
	263354	514373	3581	510	780798	
	285039	542079	3686	453	830351	
	276505	528589	3791	539	808346	
	241975	497564	3589	544	742584	
	251543	565843	4153	455	821084	
	236580	499717	3735	494	739538	
	268631	513482	3695	502	785306	
	254210	478755	4093	533	736525	
	265181	576414	3634	492	844737	
	278898	561497	4046	502	843939	

	237876	578846	3979	462	820239	
	285797	548310	3783	467	837423	
	254883	568882	4042	530	827277	
	278547	511401	3576	484	793040	
	282734	530252	3558	482	816062	
	244612	574457	3558	495	822132	
	276186	491237	3477	456	770444	
	247315	548317	3812	493	798951	
	276732	527717	3952	544	807857	
	277157	560440	4114	497	841214	
	286305	550731	3978	533	840481	
	257835	574287	3917	543	835496	
	265086	477772	4227	544	746541	
	268305	494992	3671	476	766492	
	245747	477351	3898	485	726511	
	278303	563848	3537	462	845226	
	263218	482118	3606	548	748394	
	275178	501522	3966	543	780123	
	286535	547798	4114	497	837950	
	274508	485354	3963	541	763284	
	259963	544065	3811	543	807296	
	274636	554188	3565	491	831898	
	272025	551828	3913	509	827257	
	247776	517303	3658	530	768207	
	278196	561047	3869	465	842647	
	269888	556125	3785	537	829261	
	247922	572729	3872	532	823991	
	266665	551855	3744	538	821726	
	268376	545028	3836	466	816774	
	270722	565002	3663	493	838894	
	286560	538895	3478	512	828421	
	270206	477655	3536	505	750892	
	260298	505865	3819	531	769451	
	258101	516080	3884	536	777529	
	282683	481845	4157	473	768212	
	262538	500742	4203	489	766994	
	256944	489997	3704	458	750187	
	277128	500654	4002	498	781286	
	274810	510358	4203	533	788838	
	270078	576686	4219	465	850518	
	251140	493514	3955	458	748151	
	276867	574945	4195	542	855465	
	261372	518170	4097	538	783101	
	269280	508410	3836	472	781054	
	276109	492987	4225	511	772810	
	254874	508641	3623	507	766631	
	284270	489236	4147	518	777135	
	259233	501236	3968	493	763944	
	278153	474786	3748	493	756194	

	253522	536889	3696	535	793572	
	257459	564766	3836	463	825598	
	241087	516261	3744	463	760629	
	260296	496175	3650	458	759663	
	253262	522373	3829	514	778950	
	277344	499535	3982	452	780409	
	260105	572153	3611	513	835356	
	252192	575136	4112	478	830962	
	248499	567207	3480	479	818707	
	249762	489800	3956	461	743057	
	265527	516999	3873	537	785862	
	257914	488570	4076	457	750103	
	240639	525593	3638	547	769323	
	260092	511959	3616	514	775153	
	270944	515070	3696	548	789162	
	242590	522512	3537	479	768160	
	275655	540148	3466	478	818791	
	239398	517226	4014	467	760171	
	253723	507686	3861	535	764735	
	268183	563904	3894	479	835502	
	251818	517356	3537	531	772180	
	253166	513214	3537	510	769407	
	279143	544055	3806	488	826516	
	266282	546849	4009	497	816643	
	236676	525687	3945	542	765766	
	244438	532044	3488	463	779507	
	240678	478902	4051	549	723082	
	245555	495128	3494	472	743705	
	284133	531830	4113	538	819538	
	256206	521219	3624	470	780579	
	264130	566506	3538	547	833627	
	278023	547643	4232	476	829422	
	260872	548110	3681	493	812170	
	238005	560467	3524	495	801501	
	251598	481715	3565	499	736379	
	265769	530825	4127	464	800257	
	246795	539976	3826	456	790141	
	270143	543090	4154	542	816845	
	258961	499008	4127	460	761636	
	262737	573849	4105	465	840226	
	245477	560253	3685	524	808891	
	243175	483579	3575	542	729787	
	267660	532137	3824	502	803119	
	257478	572105	3520	516	832587	
	281441	571698	4047	486	856700	
	256584	537380	3811	525	797250	
	277884	554694	3541	540	835579	
	280635	492268	3490	487	775906	
	236001	525464	3811	548	764728	

	255646	530302	4018	514	789452	
	285478	561275	3479	509	849723	
	247081	519239	3951	476	769795	
	256821	541252	4029	462	801640	
	287567	488888	3490	519	779426	
	255643	488894	4139	527	748149	
	278059	561583	3821	463	843000	
	271860	577092	3523	460	852015	
	264935	578882	3838	504	847151	
	264151	525591	3809	499	793052	
	253847	475234	4109	497	732693	
	285380	564433	3851	545	853119	
	249612	500897	3603	545	753567	
	245920	488856	3535	489	737822	
	261106	552969	3515	463	817127	
	251032	530909	3935	532	785344	
	237813	533143	4047	451	774552	
	268485	529014	3844	504	800839	
	284104	564293	4065	465	851997	
	285386	521748	3664	517	810281	
	274958	521302	3584	516	799328	
	284435	568734	3625	513	856281	
	245782	519194	3584	465	768095	
	284422	549520	3857	517	837282	
	236474	545967	4024	463	786002	
	248705	547472	3932	548	799561	
	277328	576950	4230	476	858032	
	285638	511586	4001	460	800765	
	240845	577995	4146	483	822503	
	243077	531743	4186	520	778486	
	272554	549523	3783	470	825390	
	271153	542444	3622	525	816694	
	259186	549094	3477	524	811233	
	272795	509021	4093	459	785450	
	273592	566493	3717	508	843294	
	240104	519494	3739	496	762841	
	245740	522200	3624	537	771027	
	259848	513028	4048	461	776463	
	248366	559390	3733	528	810961	
	267431	482253	3777	543	752918	
	279863	560419	4174	531	843925	
	279011	490329	3766	535	772571	
	282928	504129	3807	521	790343	
	259806	492047	4015	455	755413	
	261171	548905	3472	548	813000	
	250201	536807	4151	513	790646	
	257947	533928	3611	517	794969	
	253220	524560	4029	547	781262	
	283785	544471	3583	455	831384	

	243958	579197	3667	460	826362	
	272477	563508	3816	475	839326	
	267285	547083	4003	538	817833	
	251600	515347	3495	470	769972	
	251277	578179	3606	452	832610	
	260928	500541	4027	474	765022	
	236417	478904	3887	474	718734	
	279176	511723	3532	494	793937	
	280480	530303	3727	534	813976	
	281629	568510	3508	516	853131	
	266687	545555	4066	502	815806	
	251010	509463	3611	520	763564	
	287805	484686	4040	518	776013	
	240137	510948	3639	456	754268	
	242411	563291	4096	496	809302	
	284200	532305	4091	534	820062	
	249470	568556	4044	472	821598	
	246474	495905	3798	469	745708	
	264237	550781	4061	484	818595	
	269432	480228	3479	534	752605	
	239035	570531	3869	460	812975	
	279152	535607	4206	546	818419	
	248877	571139	3496	451	823061	
	251633	516438	3531	454	771148	
	241089	507175	3539	460	751343	
	259629	533778	3973	521	796859	
	235833	533309	4044	499	772687	
	269735	539290	4215	463	812777	
	280045	526638	4017	544	810156	
	251139	565644	3856	484	820155	
	241398	567623	4215	489	812747	
	246380	563505	3825	521	813189	
	264288	488771	3888	452	756495	
	251875	530521	3572	507	785461	
	269144	519197	3756	488	791609	
	252792	499255	4060	509	755598	
	236713	491855	4180	515	732233	
	246928	569655	3481	482	819582	
	257655	578202	4176	477	839556	
	281113	512345	4000	485	796973	
	265568	480049	3512	458	748671	
	286322	571798	4200	500	861820	
	266999	510117	3560	465	780211	
	274548	556575	4074	545	834652	
	272349	549945	3668	526	825436	
	284996	528978	4117	455	817636	
	236204	474705	3645	544	714010	
	237932	560594	3965	480	802011	
	246548	506162	3511	500	755721	

	280323	539285	3956	546	823018	
	272970	575744	3667	483	851898	
	242100	521687	4195	457	767525	
	246039	559141	4233	533	808880	
	273559	474926	4029	519	751995	
	236519	551328	3638	543	790942	
	275964	516763	3706	474	795959	
	256989	551381	4060	534	811896	
	281940	514573	3744	467	799790	
	286044	494232	3963	455	783784	
	273508	517941	4152	533	795068	
	265171	518985	4097	496	787757	
	261927	546327	4100	457	811897	
	284317	565301	3853	505	852966	
	274740	516104	4120	463	794501	
	285452	557868	4144	524	846940	
	277004	500501	3875	520	780860	
	273342	547890	3493	490	824235	
	285360	523733	3903	488	812508	
	284441	522711	3772	478	810446	
	240967	534191	4053	497	778714	
	249553	577218	4100	531	830340	
	283695	516014	3724	525	802908	
	279093	555743	4135	548	838423	
	279566	550501	4143	469	833741	
	279607	515064	4014	482	798203	
	238504	487235	4200	489	729450	
	242206	515172	3945	535	760788	
	278569	577978	3484	492	859539	
	271860	563209	3721	469	838321	
	273119	523397	3761	474	799803	
	266696	539527	3648	518	809353	
	246523	525958	4088	476	776093	
	253347	552104	4110	464	809097	
	247675	573768	3545	457	824531	
	272956	477928	3786	451	754219	
	248821	510357	3528	527	762179	
	261384	561268	3702	458	825896	
	239891	508196	3655	522	751220	
	251301	525685	4091	453	780624	
	283581	513333	3876	526	800264	
	255466	509854	3692	462	768550	
	236999	503922	3748	545	744124	
	254090	547164	3913	475	804692	
	235888	567774	3731	453	806940	
	287170	535857	3626	453	826200	
	264370	508234	3574	491	775687	
	261235	537557	3872	544	802120	
	264590	531793	3946	506	799823	

	263783	525669	3710	531	792631	
	282471	524450	3902	493	810330	
	283744	508789	3992	513	796012	
	250616	479734	3661	457	733554	
	271689	527344	4227	472	802788	
	241280	558238	3508	483	802543	
	284593	565091	3676	467	852893	
	252939	518987	4100	488	775538	
	236894	578002	4211	545	818562	
	250335	491318	4046	495	745204	
	239558	485171	3681	452	727958	
	267851	538506	3725	469	809613	
	267371	540388	3857	461	811155	
	272475	482352	3656	517	757966	
	265617	574008	4215	540	843300	
	264219	474602	3574	545	741850	
	281199	564857	4076	524	849608	
	249155	536111	3523	545	788244	
	252511	526737	3587	465	782370	
	241182	548397	4218	507	793290	
	275014	497051	3761	457	775369	
	240267	479653	3923	464	723379	
	258621	489727	4153	463	752038	
	283043	566431	3866	453	852887	
	287400	555934	3829	513	846650	
	244607	551854	3901	460	799902	
	246520	486887	3562	458	736511	
	258459	569542	3956	539	831418	
	246422	499826	3735	523	749460	
	267805	525557	3886	501	796747	
	264333	519909	3630	488	787384	
	242842	512208	3933	461	758522	
	257290	569935	3553	499	830279	
	271997	483098	3685	467	758313	
	275470	497644	3722	481	776355	
	266743	500654	3911	511	770797	
	259550	502277	3797	479	765145	
	239465	548986	3803	492	791762	
	264861	486448	4184	469	755024	
	279050	493687	3503	470	775770	
	258766	578529	4149	534	840910	
	269374	554133	4211	543	827175	
	247320	571864	4114	519	822779	
	254676	552683	3696	485	810570	
	275511	526047	3722	460	804820	
	237544	478081	3508	539	718594	
	250570	574726	3486	515	828267	
	257215	555808	3554	468	816109	
	258856	546099	4061	525	808491	

	277286	552146	3932	543	832821	
	257383	565672	3616	523	826148	
	278140	506600	3690	544	787886	
	239547	479381	3850	525	722253	
	265666	573504	4218	530	842858	
	275817	523772	3926	478	803037	
	258530	566956	3980	547	828919	
	235864	477365	3621	483	716367	
	237040	505001	3813	521	745333	
	260146	512131	3923	468	775732	
	253706	525512	3466	530	782154	
	258537	503159	3932	473	765155	
	272752	530176	3521	492	805957	
	250484	534112	3555	518	787633	
	269727	476025	4191	475	749468	
	282153	496553	3966	450	782222	
	257741	551264	3776	473	812308	
	277235	539423	3648	501	819805	
	268254	475857	4112	455	747768	
	274843	524169	4042	456	802598	
	236483	480682	4085	508	720742	
	236303	520546	3880	479	760250	
	259019	550963	3613	549	813046	
	237265	512487	3575	543	752784	
	278006	548067	4195	515	829753	
	239343	483970	3842	498	726657	
	238136	573694	3979	492	815317	
	252532	479262	3997	473	735318	
	275282	478100	4149	548	756983	
	258419	497127	3495	515	758526	
	246155	483357	4182	460	733234	
	286048	546022	4042	505	835607	
	268171	556459	3896	512	828014	
	261002	490430	3827	531	754728	
	243864	544304	4056	498	791726	
	263903	543529	3544	511	810465	
	236769	495317	3565	450	735201	
	267286	534523	3703	495	805017	
	283184	497775	4080	450	784589	
	240861	560877	3920	542	805116	
	252279	553495	3730	501	809003	
	266778	555135	4207	476	825644	
	243288	530714	3812	453	777361	
	260841	480300	3897	455	744583	
	237014	510896	3978	485	751403	
	264226	519586	4178	536	787454	
	268675	566871	4187	515	839218	
	273500	504977	3466	502	781441	
	277868	567212	4110	465	848725	

	282806	536131	3775	538	822174	
	262186	545444	3574	511	810693	
	236621	487861	4007	499	727990	
	241463	476333	4027	490	721333	
	254329	540361	3513	452	797751	
	256061	521188	3907	508	780648	
	286069	492155	3868	474	781618	
	268112	515721	3850	490	787193	
	286101	578381	3963	519	867926	
	274669	490243	4219	451	768680	
	238105	510482	3736	503	751820	
	279139	563212	3512	458	845405	
	279013	527182	3487	526	809156	
	236772	477512	3470	514	717240	
	270531	535533	3819	516	809367	
	247400	523030	3516	545	773401	
	283496	556747	4194	491	843946	
	253474	577052	3758	506	833778	
	259171	505522	3696	461	767928	
	273581	537117	3755	512	813941	
	238942	560078	3699	544	802175	
	250403	496449	4022	473	750401	
	277912	551864	4118	493	833401	
	254438	520602	3830	497	778373	
	255146	496942	3654	458	755284	
	287694	513003	4002	511	804188	
	282336	565634	4210	532	851648	
	284890	500695	3671	498	788758	
	253681	524542	3676	477	781422	
	247824	531435	3670	488	782441	
	266741	518295	4230	542	788724	
	284162	531392	4223	457	819320	
	283406	538062	4233	461	825240	
	269439	559892	3845	530	832646	
	275719	577322	4132	521	856652	
	245640	505164	3727	451	754080	
	254512	578922	3790	527	836697	
	279964	492471	3834	548	775721	
	265935	490430	3748	461	759652	
	259936	498003	4084	476	761547	
	238318	531478	3566	472	772890	
	254686	557235	3740	453	815208	
	246677	511054	4146	474	761403	
	249801	515934	3900	453	769182	
	259812	496263	4121	462	759734	
	279503	536721	3783	544	819463	
	251875	526262	3630	495	781272	
	235773	573145	3497	541	811874	
	253397	524956	3623	482	781494	

	242632	478115	4109	500	724356	
	252143	503888	3539	455	759115	
	238952	497870	4122	494	740450	
	243782	538882	3701	503	785862	
	286529	517462	3883	486	807388	
	282819	481104	3543	499	766967	
	236735	557811	4082	484	798144	
	264913	488267	4138	474	756844	
	284791	532826	3618	529	820706	
	237603	515408	4206	480	756737	
	254916	564454	3637	532	822475	
	250616	486396	3946	455	740503	
	264924	539822	3574	458	807862	
	274294	517152	3814	494	794766	
	283456	508160	3545	485	794676	
	274667	523822	3671	473	801687	
	239789	558889	3798	513	801963	
	253636	477831	3999	541	734925	
	279150	566463	3754	484	848883	
	276876	515587	3829	533	795759	
	237040	501807	3949	485	742311	
	261376	552327	4007	469	817241	
	275084	538613	3957	544	817110	
	249260	576121	4231	527	829085	
	257418	575446	3876	485	836255	
	279124	570291	4016	500	852931	
	251747	571660	3525	511	826421	
	269566	501838	3764	489	774679	
	262203	475344	4134	527	741154	
	239004	566204	3987	494	808701	
	243906	558140	3841	464	805423	
	237098	493957	3734	486	734303	
	274268	487329	4130	518	765209	
	279501	516407	3517	471	798954	
	269996	504489	3519	514	777490	
	251455	561101	3676	454	815778	
	258998	484429	3981	537	746871	
	238945	483041	3849	492	725343	
	284338	560085	4196	475	848144	
	235636	558503	4034	472	797701	
	243674	566356	3748	503	813275	
	236042	555125	4190	497	794860	
	261309	518937	4165	512	783899	
	274665	492222	4056	476	770467	
	261271	485865	3833	492	750477	
	264196	491432	3654	531	758751	
	235594	537523	3878	491	776504	
	257317	500474	4000	503	761288	
	277069	535584	3809	479	815983	

	262318	534047	4184	460	800089	
	279872	518126	3886	479	801405	
	268494	491050	4094	453	763185	
	281422	574563	3831	487	859329	
	277604	557795	3613	496	838516	
	257513	504994	3648	500	765655	
	274760	575395	3910	520	853545	
	245047	570727	3963	462	819275	
	238462	532812	3802	505	774571	
	238278	501780	4224	491	743791	
	249770	487771	3998	547	740992	
	260213	510314	3672	462	773737	
	249875	508618	3518	496	761515	
	255601	537105	4046	459	796293	
	273526	517629	3610	493	794272	
	284113	538908	4047	482	826586	
	270571	502402	4038	476	776535	
	248378	504919	4056	459	756894	

APPENDIX 4

BIM FOR SUSTAINABILITY APPRAISAL OF CONCEPTUAL DESIGN EVALUATION QUESTIONNAIRE

Name (optional):

Role:

Work experience in years:

Email:

General impression	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Q1. The system is easy to use	☐	☐	☐	☐	☐
Q2. The system follows a logical order	☐	☐	☐	☐	☐
Q3. The system is capable of informing decision on sustainability	☐	☐	☐	☐	☐

Sustainability appraisal	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Q4. Sustainability indicators are adequate to inform design	☐	☐	☐	☐	☐
Q5. The process of comparing alternative design solutions is clear	☐	☐	☐	☐	☐
Q6. The system reports essential information about appraisal outcomes	☐	☐	☐	☐	☐

Implementation requirements	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Q7. The system considered key structural elements that are generic	☐	☐	☐	☐	☐
Q8. The system displays a good degree of flexibility in operation	☐	☐	☐	☐	☐
Q9. The system is scalable in considering building size, height and number of options	☐	☐	☐	☐	☐
Q10. Time taken to perform analysis is adequate (not too long)	☐	☐	☐	☐	☐

Q11. Is the system capable of improving awareness and application of sustainability measures in early design iteration?

Q12. Is the system likely to create positive impact on sustainable construction?

Q13. Which parts or features of the system did you find particularly useful?

Q14. What are the likely barriers to adopting such systems to inform conceptual design scenarios?

Q15. What additional features or requirements of the system will you recommend?

Q16. Any additional comments

Thanks for your time!