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Draft Review

Literature review of life cycle costing (LCC) and life cycle assessment (LCA)

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Foreword

The literature review in this document relating to Life Cycle Costing (LCC) and Life Cycle Assessments (LCA) in construction has been assembled as part of the research for the project "Life-cycle costing (LCC) as a contribution to sustainable construction – towards a common methodology", commissioned by the EU, in January 2006.

An extensive body of literature exists on both subjects as well as wide-ranging literature reviews were carried out in the past as part of other research projects.

The latest available reviews date to 2002-2003. In order not to duplicate information which is already publicly available and well known, we have decided to concentrate on developments within the last 3-4 years. Obviously if the documents we have to refer to date older than 2002, we shall still list them, but without the in-depth analysis.

The existing literature review documents we have referred to are:

- Doctoral thesis of Eva Sterner – April 2002 – "Green procurement of buildings; estimation of environmental impact and life-cycle cost" at the Lulea University of Technology, Sweden – URL: http://epubl.ltu.se/1402-1544/2002/09/LTU-DT-0209-SE.pdf.
- "Whole life costing in construction – a state of the art review" – research paper 4(18), April 2003 by Mohammed Kishk, Assem Al-Hajj and Robert Pollock (The Robert Gordon University) and Ghassan Aouad, Nick Bakis and Ming Sun (University of Salford) – URL: http://www.rics.org/NR/rdonlyres/E4E31B2A-BC71-4C79-A73C-8280EF283EB2/0/whole_life_costing_in_construction_20030401.pdf

Glossary of Terms and Symbols

Glossary of Terms

Discount Rate	Factor reflecting the time value of money that us used to convert cash flows occurring at different time to a common time.
Inflation/Deflation	Sustained increase/decrease in the general price level.
Life Cycle	The required life span of the constructed asset.
Life Cycle Assessment	The assessment of the environmental impact of a product or service throughout its lifespan.
Life Cycle Costing	A tool or technique that enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational and asset replacement cost.
Life Cycle Inventory	Collection of environmental input/output data for LCA.
Net Present Value	The sum of the discounted future cash flow.
Nominal Discount Rate	Rate used to relate present and future money values in comparable terms taking into account the general inflation/deflation rate.
Period of Analysis	Length of time over which an investment, or LCC assessment, is to be analysed.
Risk	Combination of an abnormal event or failure and the consequences of that event or failure.
Risk Analysis	A systematic use of available information to determine how often specified events may occur and the magnitude of their likely consequences.
Sensitivity analysis	The evaluation of the outcome of a model altering the values of one or more inputs.
Sustainability	A systemic concept, relating to the continuity of economic, social, institutional and environmental aspects of human society.
Sustainable Construction	The use of design and construction methods and materials that are resource efficient and that will not compromise the health of the environment or the associated health of the building occupants, builders, the general public or future generations
Sustainable Development	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.
Uncertainty	lack of certain, deterministic values for the variable inputs used in a LCC analysis of an asset.

Symbols

AC	Annual Cost
AEV	Annual Equivalent Value
AIRR	Adjusted Internal Rate of Return
BCR	Benefit to Cost Ratio
DPP	Discounted Payback Period
EAC	Equivalent Annual Cost
EC	European Commission
ESL	Estimated Service Life
EU	European Union
IRR	Internal Rate of Return
ISO	International Standardization Organization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCC	Life Cycle Costing or Life Cycle Cost
LHS	Latin Hypercube Simulation
MCS	Monte Carlo Simulation
NB	Net Benefits
NPC	Net Present Cost
NPV	Net Present Value
NS	Net Savings
PB	Payback
Pdf	Probability Distribution Function
PV	Present Value
RSL	Reference Service Life
SA	Sensitivity Analysis
SIR	Savings to Investment Ratio
WLC	Whole Life Costing or Whole Life Cost

1 Introduction

Life cycle costing (LCC) is a technique to estimate the total cost of ownership (OGC, 2003). In the building and construction industry, LCC is applied to quantifying costs of whole buildings, systems, and/or building components and materials. The technique can assist decision-making for building investment projects (Flanagan et al., 1989). A LCC process usually includes steps such as planning of LCC analysis (e.g. definition of objectives), selection and development of LCC model (e.g. designing cost breakdown structure, identifying data sources and uncertainties), application of LCC model, and documentation and review of LCC results (NSW Treasury, 2004). There have been extensive research and reports on LCC. Nevertheless, LCC is not commonly applied in Europe.

There have been signs that certain human activities such as industrialisation and urbanisation have caused irrecoverable environmental impacts to the earth. Thus, sustainability development, which aims to ensure that the environment is sustainable for future generations in the dimensions of social, environmental and economic, has been advocated in recent years. Due to the environmental load imposed by the construction industry, there has been an urge to make the construction supply chain more sustainable (CIB, 1999). Research work has been actively undertaken to develop methods and tools to assess the sustainability of a building, mainly in the environmental aspect. Life cycle assessment (LCA) has been adopted as the technique to assess the environmental performance of a building throughout its life cycle, and ISO standards have been established to provide a common framework.

The purpose of this report is to provide a critical review on both LCC and LCA. Their framework, implementation, available methods and tools, and barriers are discussed. Recent academic research work that attempts to integrate both cost and environmental performance of a building is also reviewed.

2 Project framework for literature review

The whole of the body of literature was grouped according to the overall project plan drafted early in the process. Figure 2.1 below shows the project plan and its phases as seen after the initial review.

Topic coverage as shown in the main part of the model is set within the decision process stages and elements of the facility as illustrated in Fig. 1 of TG4 Report (TG4, 2003).

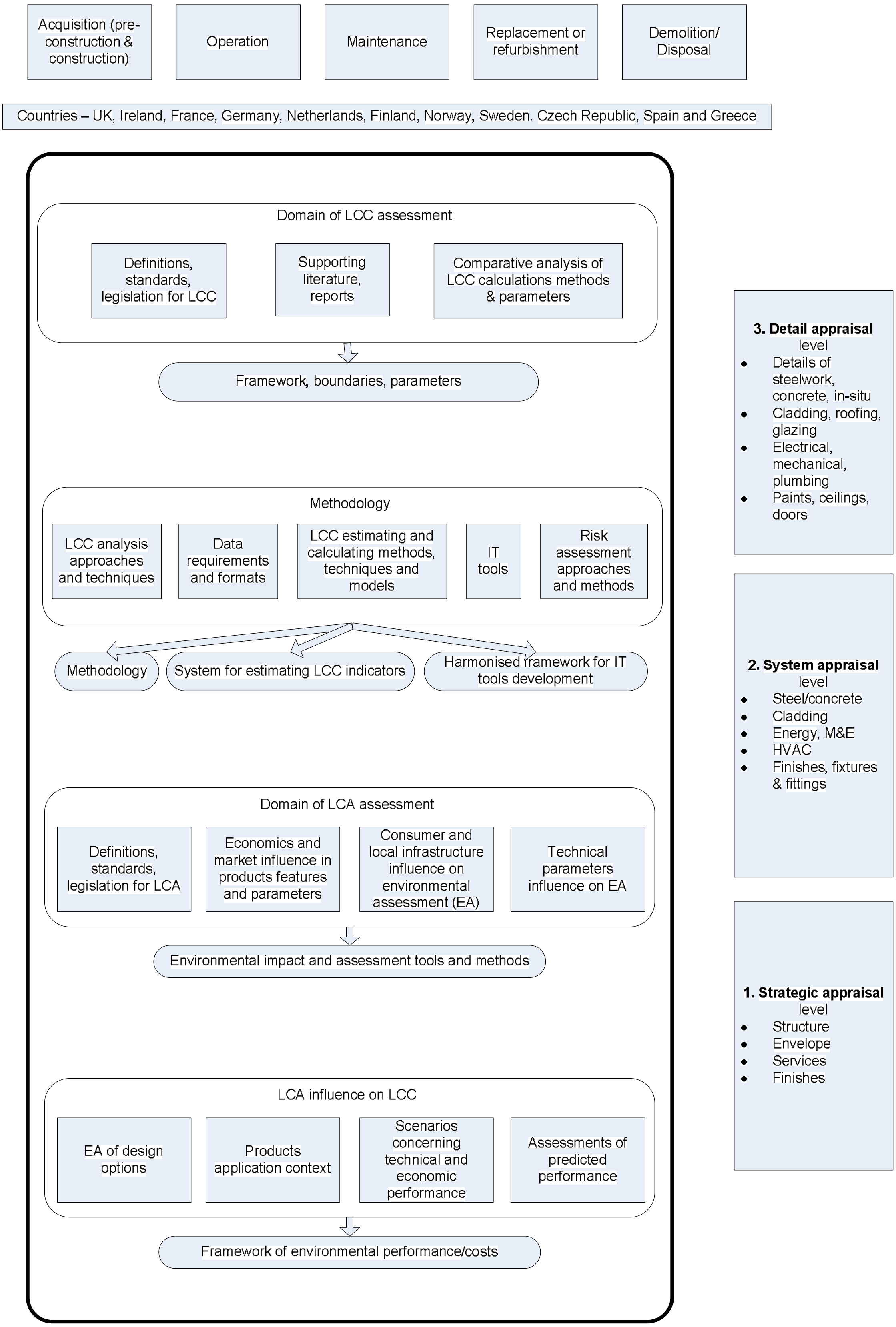

Fig. 2.1 Project Plan

3 Implementation of Life Cycle Costing (LCC)

Procurers of buildings generally wish to lower costs and increase profits (where applicable). Decisions in all stages of the facility's life (acquisition, operation, maintenance, replacement and disposal as per ISO/DIS 15686-5 (ISO, 2006)) bear economic implications. Designers, engineers, contractors, managers, FM operators and owners, all make decisions which affect economics of the facility/project.

Implementation of the economic optimisation and evaluation to the whole "cradle to grave" duration of the project's life has identified savings and benefits which are particularly vigorously pursued in public procurement. In the UK, bodies such as OGC (OGC, 2003 & 2005), HM Treasury (2000), NAO (2001) have issued and endorsed several initiatives and policy reviews in order to change the approach of the public sector to procuring construction projects. Other countries like Norway have taken public procurement a stage further and have issued a standard NS 3454 (1998) identifying and detailing the life cycle costs and methods of economic evaluation.

It has been widely recognised that private sector uses the LCC calculations in a much unstructured way, for their internal purposes. They rarely rely on it for the environmental or quality choices. The implementation of LCC is driven by public sector and is getting recognition and subsequently support in most EU member countries. The effective implementation of life-cycle costing involves utilising a thoughtful, comprehensive design along with quality material and construction practices with selected environmental considerations. Level of detail in the LCC calculations and extend of the model can render the LCC process as overcomplicated and laborious which can defeat the ultimate purpose of it being the strategy incorporated into the frequent decision-making process throughout the life of the facility. After all, the ultimate goal for carrying out LCC calculations is to aid decision-making in:

- Assessing and controlling costs and identifying cost significant items.
- Producing selection of work and expenditure planning profiles.

LCC allows for economical justification for the sustainability considerations, as implementing LCC in planning for construction projects shows that, over a project's life, incorporation of sustainable elements proves cost-effective as well as environmentally beneficial.

4 Relevant EU and national standards, regulations and guidance notes supporting LCC

Life cycle costing (LCC) is used to evaluate the cost performance of a building throughout its life cycle, including acquisition, development, operation, management, repair, disposal and decommissioning. It allows comparisons of cost among different investment scenarios, designs, and specifications. Nevertheless, the use of LCC is still limited. Different sources of information are required in LCC, and thus, the analysis process is viewed as complicated and time-consuming (see Chapter 2). In view of this, LCC documents, guidelines, and standards have been developed to give practitioners the necessary advice for implementing LCC. This Chapter reviews some of the standards, guidelines and reports available for the European Union (EU).

4.1 ISO 15686-5: Building and constructed assets – service life planning (draft)

ISO/DIS 15686-5 (ISO, 2006) is currently in preparation. The review was conducted on the draft version. This part of ISO 15686 aims at providing the procedures for performing LCC analyses of building and constructed assets and their parts, including cost or cash flows, arising from acquisition through operation to disposal. The abundant information in it is foreseen as a major reference for LCC in construction. Its main content covers principles of life cycle costing, instructions for LCC appraisal of options/alternatives, appraisal of life cycle costs in investment options, decision variables, uncertainty and risk, and worked examples.

The key objectives of this part of ISO 15686 are as follows:

- Establish clear terminology and a common methodology for life cycle costing (LCC).
- Enable the practical use of LCC so that it becomes widely used in the construction industry.
- Enable the application of LCC techniques and methodology for a wide range of procurement methods.
- Help to improve decision making and evaluation processes, at relevant stages of any project.
- Address concerns over uncertainties and risks, to improve the confidence in LCC forecasting.
- Make the LCC assessments and the underlying assumptions more transparent and robust.
- Set out the guiding principles, instructions, and definitions for forms of LCC analysis and reporting.
- Providing the framework for consistent life cycle cost predictions and performance assessment, which will facilitate more robust levels of comparative analysis and cost benchmarking.
- Provide a common basis for setting life cycle cost targets during design and construction, against which actual cost performance can be tracked and assessed over the asset life span.
- Clarify the differences between whole life costing (WLC) and life cycle costing; when to undertake it, to what level and what costs and should be considered.
- Provide a generic menu of costs for WLC/LCC compatible with and customisable for specific international cost codes and data structure conventions.
- Help unlock the real value of effectively doing LCC in construction – using service life planning.

ISO 15686-5 intends to distinguish between WLC and LCC. Life cycle cost is viewed as part of whole life cost. Figure 4.1 indicates the cost components of LCC and WLC.

Nevertheless, ISO 15686-5 attempts to create a useable cost structure for assessing LCC in construction, which could be customised and aligned to specific cost coding conventions to suit national application of LCC analysis. For example, acquisition and disposal cost components could be added to LCC. It is reminded in the standard that clients should be clear about the boundaries of the LCC.

A substantial part of the Principles of Life Cycle Costing section is allocated to elaborating on the stages of whole life cycle of building project. The content of the subsequent sections is also briefly discussed in this section.

In the Instruction for LCC Appraisal of Options/Alternatives section, the parameters for LCC are discussed. The parameters required include:

- Service life, life cycle and design life
- Period of analysis
- Cost variables for
  - Acquisition costs
  - Maintenance, operation and management costs
  - Residual values/disposal costs
  - Discount rate
  - Inflation
  - Taxes
  - Utility costs including energy costs.

- **Whole Life Costing (WLC)**
  - Non Construction Costs
    - Acquisition – site for construction or asset purchase/leasing including associated fees and local taxes
    - Finance – interest or cost of money and wider economic impacts
    - Business – Development of client brief and procurement cost, value and risk management, planning, regulatory and legal
    - Business – Design and engineering (client advisors)
    - Business – in house resources and administration
    - Disposal – Demolition, decommissioning and site clean up
  - Income
    - Land sale, grants, tax allowance etc.
    - Sale of interest in asset or sale of salvaged materials for recycling
    - Third party income
- **Life Cycle Costing (LCC)**
  - Construction Costs
    - Design, professional fees and statutory consents (design and build)
    - Temporary works, demolition, site clearance or groundwork
    - Construction, fitting out, commissioning, validation and handover
    - Adaptation, refurbishment, fitting out, commissioning, validation and handover
    - Externals and infrastructure works
    - Project management and planning supervision (CDM Regulations)
    - Fixtures, fittings, furnishings and loose equipment
  - Operation Costs
    - Rates (and rent if applicable)
    - Insurance
    - Energy costs for heating, cooling, power and lighting – and water sewerage costs
    - Facilities management costs, health and safety, security, cleaning and waste management
    - Annual regulatory costs (eg: fire access inspection)
    - Others (local taxation, land charges etc)
  - Maintenance Costs
    - Annual planned service and maintenance regime
    - Repairs, routine component replacement and minor refurbishment
    - Downtime and business disruption costs
  - Replacement Costs
    - Restoration (or replacement) of the main elements or systems to their original aesthetic and functional performance at various stages of the life of the facility, including management costs
    - Downtime and business disruption costs
    - Unanticipated costs resulting from legislation introduced subsequent to completion of the constructed asset (eg health and safety matters)
    - Adaptation, refurbishment, fitting out, commissioning, validation and handover
  - Handover Costs
    - Final condition inspections and associated fees
    - Additional cost of meeting assets contractual performance and condition criteria for handback
    - Provision of spares and consumables

Figure 4.1: Typical scope of costs for WLC and LCC (extracted from ISO 15686-5, Figure 3).

In the Appraisal of Whole Life Costs in Investment Options Appraisals section, the following issues, which are additional to LCC appraisal but not mandatory, are discussed:

- Externalities such as the social, environmental or business costs or benefits of production and consumption.
- Environmental cost impacts
- Social costs and benefits/ sacrifices
- Sustainable construction/ environmental assessment
- Intangibles
- Future income streams
- Financing costs.

The equations for computing LCC decision criteria, such as nominal costs, discounted costs, and net present value (NPV) are provided in the Decision Variables – How to Calculate LCC section. In the Uncertainty and Risk – How to Inform Decision Making Using LCC section, the issues that contribute to uncertainty are first discussed. Two more commonly used risk analysis techniques, Monte Carlo analysis and sensitivity analysis are also discussed.

In the Reporting section, the items that should be included in a LCC report are listed. It also gives advice on data and analysis structure, and necessary records for future reviews. This part of ISO 15686 provides examples of LCC in the appendices.

4.2 NS 3454: Life cycle cost for building and civil engineering work – principles and classification

The Norwegian standard, NS 3454 covers all types of construction projects and building components, and is a tool to facilitate programming and design as well as management, operation, maintenance and development (MOMD). NS 3454 contains the following information:

- Scope
- Normative references
- Terms and definitions
- Cost schedule
  - Main categories
  - Sub-classification of the main categories
- Table A.1 – Standard categories and additional categories
- Table B.1 – Examples of capital costs
- Table B.2 – Examples of management costs
- Table B.3 – Examples of operating costs
- Table B.4 – Examples of maintenance costs
- Table B.5 – Examples of development costs
- Table C.2 – Examples of servicing and support costs
- Table C.3 – Examples of potential of the property
- D.1 Fixed monetary unit
- D.2 Real rate interest
- D.3 Net present value
- D.4 Annuity
- D.5 Net present value calculations and the annuity cost factor.

The standard refers to other Norwegian normative documents, such as NS 3453:1987 – Specification of Building Costs, as part of the standards provisions. The terms and the relevant definitions are provided in Section 3: Terms and Definition. The standard (or main) and additional cost categories of NS 3454 are shown in Table 4.1.

Additional cost categories comprise the servicing and/or support costs or the core activities. The examples of activities for the cost categories are displayed in Tables B.1-B.6 (main cost categories) and Tables C.2-C.3 (addition cost categories). The standard also gives the equations for computing real rate of interest, which takes account into the rate of inflation, net present value (NPV), and annuity

Table 4.1 - The relationships between cost categoris and key collective terms (extracted from NS 3454)

STANDARD CATEGORIES						ADDITIONAL CATEGORIES		
	REAL ESTATE AND PROPERTY MANAGEMENT							
	FM – Facilities Management							
	MOMD							
1 Capital cost	2 Management cost	3 Operating cost	4 Maintenance cost	5 Development cost	6 Unused	7 Servicing and/or support costs for the core activities	8 Potential of the property	9 Unused
10 (Unused)	20 (Unused)	30 (Unused)	40 (Unused)	50 (Unused)	60 (Unused)	70 (Unused)	80 (Unused)	90 (Unused)
11 Project cost	21 Taxes	31 Daily operation	41 Scheduled maintenance	51 Current rebuilding	61	71 Administrative office management	81 Rebuilding	91
12 Residual cost	22 Insurance	32 Cleaning services	42 Replacements	52 Official rules and requirements	62	72 Switchboard and receptionist services	82 Additions / extensions	92
13	23 Administration	33 Energy	43	53 Upgrading	63	73 Canteen and/or catering services	83	93
14	24	34 Water and sewage	44	54	64	74 Furniture, fixtures and fittings	84	94
15	25	35 Waste disposal	45	55	65	75 Moving workplaces and/or job rotation	85	95
16	26	36 Watchguards and security	46	56	66	76 Telecommunications and IT-services	86	96
17	27	37 Outdoor	47 Outdoor	57 Outdoor	67	77 Postal and messenger services	87 Outdoor	97
18	28	38	48	58	68	78 Supplies and copying services	88	98
19 Miscellaneous	29 Miscellaneous	39 Miscellaneous	49 Miscellaneous	59 Miscellaneous	69	79 Miscellaneous	89 Miscellaneous	99

4.3 Task Group 4: Life cycle costs in construction

In September 2001, a task group, TG4, was formed under the framework of the Working Group for Sustainable Construction (2001) for drafting a paper on LCC in construction and to make recommendations on how LCC can be integrated into European policy making. This Task Group (TG4) composed of representatives of different European countries, some Member States and Commission DGs. The report can be downloaded via URL1 (see the References section). In the report, the following seven recommendations are made (Table 4.2)

Table 4.2- Recommendations made in the TG4 report.

No.	Recommendation
1	Adopt a common European Methodology for assessing Life Cycle Costs (LCC) of construction.
2	Encourage data collection for benchmarks, to support best practice and maintenance manuals.
3	Public procurement and contract award incorporating LCC.
4	Life cycle costing indicators should be displayed in buildings open to public.
5	Life cycle costing should be carried out at the early design stage of a project.
6	Fiscal measures to encourage the use of LCC.
7	Develop Guidance and fact sheets.

The content of the report, with the emphasis on the seven recommendations, is as follows:

- Introduction
- LCC Methodology (Recommendation 1)
- Data Collections, Benchmarking and Manuals (Recommendation 2)
- LCC and Public Procurement (Recommendation 3)
- Promoting Sustainability through LCC (Recommendations 4, 5, 6 and 7)

In the LCC methodology section, the issues that improve the LCC process are first mentioned. A three-level LCC process, which is make up of three appraisal levels: strategic, system and detail is elaborated. The strategic decision level is mainly for the initial appraisal stage in the pre-construction phase. In this stage, a lot of assumed inputs are used. The system and the detail decision levels are mainly used in the design stage (pre-construction phase). In these levels, the assumptions made earlier are eventually defined. The life cycle stages considered include acquisition (including pre-construction and construction), operation, maintenance, replacement (or refurbishment), and demolition. The information and decisions for these stages are discussed. In this section, the development of a common methodology of LCC with a classification of cost components at various stages of life cycle is recommended.

In the Data Collections, Benchmarking and Manuals section, the necessity to reduce the uncertainties in data is recognised. More reliable product information should be used, and/or the uncertainties should be accommodated in the LCC system. More research is suggested to address the relationship between the environmental quality and the performance of buildings. In the recommendation, public and private clients are advised to share their cost data. LCC benchmarks at national and European levels, with comprehensive criteria, and maintenance manuals that contain comprehensive maintenance details should also be developed. In the LCC and Public Procurement section, it is recommended that LCC should be incorporated in the Economically Most Advantageous Tender (EMAT) method (Working Group on Abnormally Low Tender, 2001). EMAT is a tender evaluation procedure developed by the EMAT task group. In this procedure, a tender is selected based on not only the price, but also other criteria.

In the Promoting Sustainability through LCC section, the methodology of predicting the service lives of components elaborated in ISO 15686–1 is viewed as an essential step for more accurately estimating the LCC. The Construction Products Directive (89/106/EEC), which was developed for harmonising construction products, is mentioned. The last four recommendations are related to this section, and the explanations on these four recommendations are as follows:

Recommendation 4 – LCC indicators assessed on the basis of the Common European Methodology should be clearly displayed in all new and renovated buildings exceeding 1000m^2 floor area accessible by the public.

Recommendation 5 – The opportunities for modifying the costs of a project are the greatest at the beginning of a project.

Recommendations 6 – members states should examine their fiscal regimes in order to determine whether adjustments can be made to promote life cycle costing linked to the Common European Methodology.

Recommendation 7 – Develop guidelines and fact sheets to demonstrate the benefits of adopting a LCC approach to procuring new and refurbishing existing buildings. These should be supported by case studies.

The appendices contain a lot of useful information about LCC such as LCC methods, tools and case studies. Reports and presentations prepared by TG4 participants, industrial practitioners and researchers are also attached. EuroLifeForm, which was a European RTD project for developing a generic probabilistic LCC approach, is included. Another interesting information in the appendices is the investigation of integrating LCC and life cycle assessment (LCA).

4.4 Procurement guide 07: Whole-life costing and cost management

Procurement Guide 07: Whole-Life Costing and Cost Management (URL2) was published by Office of Government, UK for providing a guideline on managing cost in the WLC. The guide outlines the principles of whole-life cost management and describes a process made up of:

- A framework for cost management
- Establishing baseline costs – expected operational costs of the asset
- Estimating whole-life costs – every cost likely to be incurred from inception of the project to disposal, construction costs and risk allowance
- Cost management and reporting.

Since this guide mainly discusses the strategic issues of WLC, it does not elaborate on the techniques used in the process. Nevertheless, it provides references for certain techniques. For example, it suggests the reader to refer to HM Treasury's Green Book for the advice on sensitivity analysis.

4.5 The Green Book by HM Treasury, UK

The Green Book was published by HM Treasure UK, and is available on the internet (URL3). It aims at promoting efficient policy development and resource allocation across government. It describes how the economic, financial, social and environmental assessments of a policy, programme or project should be combined.

A policy circle ROAMEF, which is the acronym of **R**ationale, **O**bjectives, **A**ppraisal, **M**onitoring, **E**valuation and **F**eedback, is the core of the process, and is extensively elaborated in the book.

Although the Green Book is not specifically written for LCC, certain techniques provided in the book are used as the reference for LCC in the UK. There is a comprehensive section on discounting in the Green Book. In addition, the risk management approach to controlling risks affecting the policy, programme and project lifecycle is elaborated. Risk analysis techniques, Expect Value (EV), Decision Tree, and Sensitivity Analysis provided in this section are applicable to LCC.

A discount rate of 3.5% is proposed in the Green Book, and Annex 6 in the book shows how the value is derived. This discount rate is commonly used for public works in the UK.

5 Financial variables, decision criteria and measures of economic evaluation

5.1 Present Value (PV) and Net Present Value (NPV) or Net Present Cost (NPC)

Project costs that occur at different points in the life of a building cannot be compared or summed directly due to the varying time value of money. They must be discounted back to their present value through the appropriate equations. Costs must first be converted into their time-equivalent value at the base date before being combined to compute the LCC of a project stage or of a whole project. This time-equivalent value is referred to as the Present Value (PV) of the costs. The discount rate is the interest rate used to convert (or “discount”) future expenditures to their present value at the base date, taking into account the investor’s time value of money. The discount rate selected for LCC analysis must make an investor indifferent between a future cash amount and its present value.

The present day equivalence of a future cost, i.e. the present value, can be thought of as the amount of money that would need to be invested today, at an interest rate equal to discount rate, in order to have the money available to meet the future cost at the time when it was predicted to occur. The effects of inflation can also be included in these calculations.

The basic discount equation is as follows:

$$PV = \frac{FV}{(1+d)^n} \qquad [5.1]$$

Where:

PV = the present value of a building or system

FV = the value in the future

d = the decimal discount rate (interest rate)

n = the number of years in the future

LCC according to TG4 Report (2003): LCC in Construction, is calculated as a present value of the accumulated annual future costs (C) over a period of analysis time (t), e.g. 60 years (N), at an agreed discount rate (d), e.g. 2% = 0.02 pa, dependant on prevailing interest and inflation rates. PV is calculated according to the following formula.

$$PV = \sum_{t=0}^{N} \frac{C_t}{(1+d)^t} \quad [5.2]$$

Where:

C_t = sum of all relevant costs less any positive cash flows occurring in period t

N = number of periods comprising the study period

The above formula was adopted by the American Society for Testing and Materials (ASTM 1989) and then by the EU in their TG4 report (2003). The initial ASTM standard practice on LCC was based in part on a publication dated as early as 1980.

PV can be calculated using nominal costs and discount rate based on projected actual future costs to be paid, including general inflation or deflation, and on projected actual future interest rates. Nominal costs are generally appropriate for preparing financial budgets, where the actual monetary amounts are required to ensure that actual amounts are available for payment at the time when they occur.

PV can be calculated also using real costs and discount rate, i.e. present costs (including forecast changes in efficiency and technology, but excluding general inflation or deflation) and real discount rate (d_{real}), which is calculated according to the following formula, where (i) = interest rate and (a) = general inflation (or deflation) rate, all in absolute values pa. e.g. 2% =0.02.

$$d_{real} = \frac{1+i}{1+a} - 1 \quad [5.3]$$

The present value of future costs reduces rapidly over time for different discount rates. This makes capital investment for better long-term performance unattractive to a developer in monetary terms.

In LCC analysis, all relevant present and future costs (less any positive cash flows) associated with an energy system are summed in present or annual value during a given study period (e.g., the life of the system). These costs include, but are not limited to, energy, acquisition, installation, operations and maintenance (O&M), repair, replacement (less salvage value), inflation, and discount rate for the life of the investment (opportunity cost of money invested).

Criteria for cost effectiveness can be subjective depending on the investment decision maker. Generally, a project is cost effective if it has an SIR greater than one, an AIRR greater than the discount rate, an LCC lower than the next best alternative energy system, and a simple payback period shorter than the life of the building.

5.1.1 Dealing with Net Present Value (Sarja, 2005)

A central feature of LCC is the application of Net Present Value. However, even at modest discount rates, the NPV reduces rapidly, hence making Capital investment for long-term performance unattractive to the developer in simple cost terms (Figure 4.1). For example, at a discount rate of only 4%, the NPV is less than 50% of the cost at 20 years, and at higher discount rates the NPV reduces even further. On purely economic grounds this makes it more attractive to spend less now and more later.

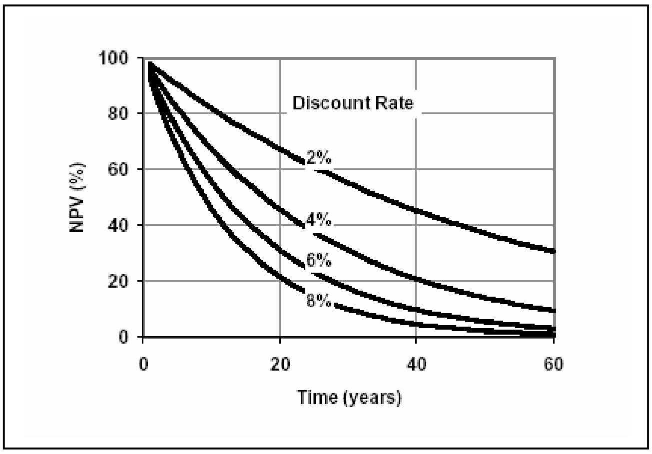

Figure 5.1: The change in Net Present Values with time, expressed as a percentage of current cost.

Furthermore, the uncertainties associated with predicting changes in future interest and inflation rates can be greater than those attached to predictions of service life. Care should be taken, therefore, when applying discount rates within a LLC calculation.

Almost all models found in the literature employ the NPV approach. However, different nomenclature and/or cost breakdown structure are used to describe principal components of LCC. The American Society for Testing and Materials (ASTM 1983) published the following model:

$$NPV = C + R - S + A + M + E(+W + O) \qquad [5.4]$$

Where:

C = investment costs

R = replacement costs

S = the resale value at end of study period (residual costs)

A = Annually recurring operating, maintenance and repair costs

M = Non-annually recurring operating maintenance and repair cost

E = energy costs

W = often isolated – water costs

O = other costs (e.g. costs of contract)

The unique feature of this model is the separation of energy costs, and hence different discount rates can be employed to reflect different inflation rates.

The ASTM WLC model distinguishes between energy and other running costs which is useful in adopting different discount rates for these two cost items.

NPV can be defined as the present value of cash flows minus the present value of costs. The analysis is conducted for a previously determined time span and discounted to the present cash flows and costs; a discount rate has to be arbitrated. In the analysis the value of the discount rate used is crucial since NPV is sensitive to the discount rate chosen. Life cycle costing analysis differs from NPV since cash flows are left out.

5.2 Measures of economic evaluation

5.2.1 Equivalent annual cost (EAC)

The equivalent annual cost (EAC) is the cost per year of owning and operating an asset over its entire lifespan.

EAC is used as a decision making tool in capital budgeting (planning process for determining long time investments) when comparing investment projects of unequal life spans. EAC is calculated by dividing the NPV of a project by the present value of an annual equivalence factor, $A_{t,r}$. Equivalently, the NPV of the project may be multiplied by the loan repayment factor for t years.

$$EAC=NPV*A_{t,r} \quad [5.5]$$

The use of the EAC method implies that the project will be replaced by an identical project.

5.2.2 Discounted payback period (DPP)

The payback period is the length of time until the sum of an investment's cash flows equals its cost. The payback period rule is to take a project if its payback period is less than some pre-specified cut-off. Or in other words: time required for the cumulative savings from an alternative to recover its initial investment cost and other accrued costs, taking into account the time value of money.

The discounted payback period (DPP) is the length of time until the sum of an investment's discounted cash flows equals its cost. The discounted payback period rule is to take an investment if the discounted payback is less than some pre-specified cut-off. It is recommended that it should only be used a screening device in LCC calculations and DPB should be less than study period.

5.2.3 Internal rate of return (IRR) and adjusted Internal Rate of Return (AIRR)

Internal rate of return (IRR) is the discount rate that makes the estimated NPV of an investment equal to zero. The IRR rule is to take a project when its IRR exceeds the required return.

Adjusted internal rate of return (AIRR) is an annual yield from an alternative over the study period, taking into account reinvestment of interim returns at the discount rate. AIRR should be greater than discount rate and is used for ranking projects.

5.2.4 Net benefits (NB) and net savings (NS)

The net savings (NS) is calculated as the difference between the present worth of the income generated by an investment and the amount invested. Or in other words: operational savings less difference in capital investment costs. Preferred alternative has the maximum NS (> 0) for optimal cost effectiveness. The option with the highest NS will also have the lowest LCC.

5.2.5 Savings to Investment Ratio (SIR) and Benefit to Cost Ratio (BCR)

SIR is the ratio of the present worth of the income generated by the investment to the initial investment cost. Or in other words: the ratio of operational savings to difference in capital investment costs. Preferred alternative should have the greatest SIR (> 0) for ranking projects.

5.3 Financial variables

5.3.1 Discounting and discount rate (real and nominal)

Discounting

Discounting is a technique used to compare costs and benefits that occur in different time periods. It is a separate concept from inflation, and is based on the principle that, generally, people prefer to receive goods and services now rather than later (OGC, 2005). This is known as 'time preference'. This guidance does not cover the topic in great detail as it is a procedure common to many cost appraisal methods and well understood by purchasing officers. The subject is fully explained in The Green Book: Appraisal and Evaluation in Central Government (URL3). When comparing two or more options, a common base is necessary to ensure fair evaluation. As the present is the most suitable time reference, all future costs must be adjusted to their present value. Discounting refers to the application of a selected discount rate such that each future cost is adjusted to present time, i.e. the time when the decision is made. Discounting reduces the impact of downstream savings and as such acts as a disincentive to improving the reliability of the product. The procedure for discounting is straightforward and discount rates for government purchases are published in the Green Book. Discount rates used by the industry will vary considerably and care must be taken when comparing LCC analyses which are commercially prepared to ensure a common discount rate is used.

It is important not to confuse discounting and inflation. The Discount Rate is not the inflation rate but is the investment "premium" over and above inflation. Provided inflation for all costs is approximately equal, it is normal practice to exclude inflation effects when undertaking LCC analysis.

In LCC analysis, the discount rate is the parameter used to represent the time value of money. It reflects the opportunity cost of capital to an investor over time. If it does not matter when costs and benefits incur they can be added without consideration. However, if the timing of costs and benefit flows is important, the investment calculus needs to reflect this. A common technique is the use of discounting. The time value of money, expressed as a discount rate, depends on inflation, cost of capital, investment opportunities and personal consumption preferences. If the discount rate is set to 0% this means that the timing does not matter; the higher the discount rate the more importance is given to the near-present.

Two types of discount rates are used in computing the present value: a "real" rate or a "nominal" rate. The real discount rate reflects the time value of money without accounting for the effects of inflation and deflation. That is, it reflects the real earning power of money over time. The real discount rate (excluding the rate of inflation) is used when all cost data are denominated in terms of “constant” currency, that is, currency with constant purchasing power. Nominal or market discount rates take into account general inflation or deflation plus the real earning power of money. A nominal rate is used when all cost data are denominated in “current” currency, that is, currency that change in value from year to year depending on the general price level. The need for a nominal or market discount rate often arises when the future cost estimates are based on a maintenance contract that is typically specified to be paid in current currency in future time periods.

In the private sector, an individual investor’s discount rate is determined by the investor’s minimum acceptable rate of return for investments, as governed by available investment opportunities and his or her risk tolerance. Because different investors have different investment opportunities available to them as well as different levels of acceptable risk, private discount rates vary greatly.

Most environmental projects will be sponsored by government agencies rather than by private investors. Government agencies in member countries generally publish discount rates to be used in the economic analysis of government projects. The frequency and level of detail vary from country to country.

It is recommended to use two real discount rates, e.g. 0 and 2 percent and then evaluate possible differences of these results. Real discount rate reflects general productivity of producer, sector or field. Usually general productivity has been between 0 and 2 % in long term. Buildings have long service lives. Because of difficulties to predict inflation in long term, it is recommendable to use real costs (without inflation) and the real discount rate. Over a long period of time, the real discount rate is usually 0 - 2% pa only. At low discount rates, long-term future costs and savings are immediately meaningful, and therefore, investment for a better future would look more rewarding.

The Treasury discount is i = 3.5 percent. For the majority of public sector projects, particularly at the options appraisal stage, the Treasury discount rate of 3.5 percent will be used. Whilst it would be incorrect to say that this rate is net of inflation it does not need to be adjusted for inflation.

Discount rate	The factor reflecting the time value of money that is used to convert cash flows occurring at different times to a common time	Eg To convert future values to present values and vice versa.
Discounted cost	The resulting cost when real cost is discounted by the real discount rate or when nominal cost is discounted by the nominal discount rate	
Real discount rate	A rate used to relate present and future money values in comparable terms, not taking into account inflation (whether general or specific to a particular asset under consideration)	

Figure: 5.2 Definitions and extracts from ISO standard 15686

Selection of Discount Rate

As the life cycle costs are discounted to their present value, selection of a suitable discount rate is a crucial decision in a LCC analysis. A high discount rate will tend to favour options with low capital cost, short life and high recurring cost, whilst a low discount rate will have the opposite effect. The discount rate may reflect the effect of only the real earning power of money invested over time or it may also reflect the effects of inflation (Woodward, 1997).

Much of the literature in this area offers little in the way of firm recommendations regarding the final selection of an appropriate rate - estimates vary between 3-4% and in excess of 20%. Furthermore, there is a variety of views within the general discourse regarding the actual composition of the discount rate. The most popular methodologies appear to be:

- at the current or expected rate the organisation must pay for the use of its borrowed funds;
- at the rate of return that could be expected from the loaning of money, but which is denied to the organisation by the need to fund its own projects (sometimes referred to as the opportunity cost);
- at the lowest rate of industrial borrowing for a financially sound, well-established company;
- a test discount rate can be used based on the assumption that when inflation rates are reasonably low there is a stable relationship between inflation and base rate, implying a real discount rate of 4%;
- investments in long-term treasury bonds can be assumed to have no risk. Therefore, the discount rate can be taken as the Treasury bond rate less an allowance for the expected rate of inflation.

The appropriate discount rate will vary significantly from organisation to organisation, and will need to be determined by the skill of the industrial accountant rather than by mere arbitrary selection. As in the case of estimating the appropriate rate of inflation, calculating the relevant discount rate is rarely easy. However, help is available from the financial management sub-discipline of accounting, where over the years many sophisticated techniques have been developed to assist with this particular problem.

When undertaking a LCC analysis, there may be some key parameters about which uncertainty exists, usually because of the inadequacy of the input data. How sensitive are the results to variations in these uncertain parameters? For example, the following variables could be suggested to be the subject of sensitivity analysis:

- frequency of the maintenance factor;
- variation of the asset's utilisation or operating time;
- extent of the system's self-diagnostic capability;
- variation of corrective maintenance hours per operating hour;
- product demand rate;
- product distribution time (the 'logistics pipeline');
- the discount rate.

Generally the five data categories could be identified, according to Kishk et al. (2003):

- economic variables
- cost data
- occupancy data
- physical data
- performance and quality data

According to NSW Treasury (2004), the discounting of costs takes account of three elements:

- the interest rate available from long term investment in bank or government bonds
- the interest rate that business would expect as a return for risk
- the inflation rate that would affect the purchasing power of the currency.

Discounting does not incorporate changes due to price movements as a result of changes in efficiency, technology, etc. since these are in essence real changes in value. The discount rate reflects the net changes in real value due to the compounding effect of interest (potentially) earned on money and the discounting effects of inflation as expressed in the following formula. The Discount Rate reflects the real rate of interest at which money is borrowed or lent ie. the absolute (or nominal) interest rate at which money is borrowed or lent discounted for the effects of inflation. Consequently, the terms discount rate and real interest rate are synonymous.

In general, if a project alternative is to be considered cost effective on a life-cycle cost basis, it must have a lower LCC than the base case, Net Savings greater than 0, an SIR greater than 1.0, and an AIRR greater than the minimum acceptable rate of return (i.e., the discount rate). These are all consistent measures of economic analysis; that is, they will all show that a given project alternative is either cost effective or not cost effective relative to the specified base case.

Discount Rate Philosophies as per Ozbay et al. (2003)

In practice, estimating the discount rate is not a straightforward matter. Most of the public projects are financed by more than one funding source. Furthermore, there is no consensus on how to value the real earning capacity of these public funds. The choice of the discount rate is one of the most debatable topics in public project evaluation. Several philosophies have been suggested over the years for choosing the appropriate discount rate. Important among them are:

- Opportunity Cost of Capital: Opportunity cost is the cost of the forgone investment that would have been taken if not invested by this project. The opportunity cost of capital rationale assumes that the money used for funding public projects is withdrawn from private savings, which would have gone otherwise into private investment. Accordingly, the discount rate should be the pre-tax rate of return that would have been experienced on the private uses of funds.
- Societal rate of time preference: This is the interest rate that reflects the government’s judgment about the relative value, which the society as a whole assigns, or which the government feels it ought to assign, to present versus future consumption. The societal time preference rate is not observed in the market and bears no relation to the rates of return in the private sector, interest rates, or any other measurable market phenomena.
- Zero Interest Rate: Advocates of a zero interest rate argue that when tax monies (e.g., highway user taxes) are used, such funds are “free money”, because no principal or interest payments are required. The counter argument is that zero or very low interest rates can produce positive benefit/cost ratios even for very marginal projects and thereby take money away from more truly deserving projects. A zero interest rate also fails to discount future expenditures, making tomorrow’s relatively uncertain expected costs just as important to the decision as today’s known costs.

- Cost of Borrowing Funds: The interest rate should match the rate paid by government for borrowed money. This approach is favored by many agencies and is supported by the argument that government bonds are in direct competition with other investment opportunities available in the private sector.

Handling Inflation and Increasing Costs

In an inflationary environment, the future price increases for goods and services are greater or less than the general inflation rate, and the costs or benefits associated with an alternative are expressed in actual currency. Actual currency reflect both the earning power and the purchasing power of money, and before they can be discounted they must be adjusted to constant currency to negate the effect of inflation or deflation. If the specific inflation rate (k) for a particular cost item is increasing at a faster rate than the general inflation rate (j), the future value of the item expressed in constant currency will also increase. This increase in future constant currency may have a significant impact on the PV.

Many times an increase in costs is due to an increase in the quantity or quality of goods and services rather than inflation. For example, as building systems or components age they may require an increasing level of maintenance and repairs. Such a non-inflationary escalation (e) will also increase the constant currency value of future costs.

The following general formula shows the relationship between today's and future constant currency in an inflationary environment.

$$\text{Constant Currency at Year } n = (\text{Actual Currency Today}) * (1+e)^n (1+k)^n (1+j)^n \qquad [5.6]$$

Where:

e = non-inflationary escalation rate

k = specific inflationary rate

j = general inflationary rate

e, k, and j can be negative, zero, or positive and are expressed as a decimal

5.3.2 Discounted costs

Discounted costs are calculated by taking costs that occur in future years and reducing them by a factor derived from the discount rate. Different discount rates apply depending on whether nominal costs or real costs are being discounted. With nominal costs, the discount rate should include an inflation factor. If real costs are used, the discount rate should not include an inflation component (Glucha & Baumannb, 2003).

Different discount rates also apply to different organisations and individuals.

To convert a real cost to a discounted cost:

$$q = \frac{1}{(1+d)^n} \qquad [5.7]$$

where

q = the discount factor;

d = the expected real discount rate per annum;

n = the number of years between the base date and the occurrence of the cost.

To convert a nominal cost to a discounted cost:

$$q = \frac{1}{(1+d)^n (1+a)^n} \quad [5.8]$$

where

q = the discount factor;

d = the expected real discount rate per annum;

a = the expected percentage increase in general prices per annum;

n = the number of years between the base date and the occurrence of the cost.

An alternative given by for example Gray et al. [25] is to use an environmental hurdle rate technique. This technique is exemplified in the box by three hurdle rates: a 'green discount rate' for costs that do not contribute to negative impact on the environment, a 'yellow rate' for costs that have an uncertain contribution to negative impact on the environment, and a 'red rate' for costs that have a certain negative impacts on the environment. If 'red rates' are set to 0% in the LCC calculation, 'red' types of costs do not get discounted over time and therefore cause a more significant contribution to the total result when discounted. The use of 'red rates' is valid as long as future damage is assumed as negative as today's. For example, discharging toxic waste tomorrow should be as negative for the environment as discharging toxic waste is today. However, from an environmental point of view, the timing of the emissions depends on the state of the environment, which can improve or deteriorate with time. In addition, waste management technology may also improve in the future. Because of such developments, it may be more viable that certain environmental costs are considered as green or yellow and thus discounted in the LCC calculation. This reasoning illustrates how complex and difficult it is to handle environmental costs and how over-simplification can misguide environmental decisions-making.

Another way of handling the time problem is to indicate which costs may be expected to increase more than other costs. A differential escalation rate can thus be used to indicate relative price changes.

5.3.3 Real and nominal costs

Real Cost

Real cost is the cost expressed in values of the base date excluding inflation but including price movements due to changes in efficiency, technology, etc.

Nominal Cost

Nominal cost is the expected price that will be paid when a cost is due to be paid (i.e. including inflation and price movements due to changes in efficiency, technology, etc.)

Discounted Cost, C_D = NPV [5.9]

The Real Cost discounted by the Real Discount Rate is equivalent to the Nominal Cost discounted by the Nominal Interest (or Discount) Rate. The Discounted Cost is thus often referred to as the Net (or Discounted) Present Value. Therefore, for an asset component having a Nominal Cost, C_N in Year n, then the Real Cost (or Present Value), CR at the base date (Year 0) is given by:

$$C_R = C_N (1+f)^{-n} \quad [5.10]$$

and the Discounted Cost (or Net Present Value), C_D at the base date (Year 0) is thus:

$$\begin{aligned} C_D &= C_R(1+d)^{-n} \\ &= C_N(1+f)^{-n}(1+d)^{-n} \\ &= C_N(1+f)^{-n}\frac{(1+i)^{-n}}{(1+f)^{-n}} \\ &= C_N(1+i)^{-n} \end{aligned}$$

$$(1+\mathrm{d}) = \frac{(1+\mathrm{i})}{(1+\mathrm{f})}$$

$$\mathrm{d} = \frac{(1+\mathrm{i})}{(1+\mathrm{f})} - 1$$

where d = (Real) Discount Rate

i = Nominal Interest (or Discount) Rate

f = Inflation Rate

For this reason, *i* is often referred to as *the Nominal Discount Rate* since it is the rate applied when discounting Nominal Costs.

[5.11]

5.3.4 Inflation

Besides the above discussion of the effects of inflation on the discount rate in LCC, inflation can be utilized for another purpose in LCC. It is not uncommon to find that the available documented prices of construction, material, labor, or any LCC-related components are dated. When this is the case, these unit prices must be converted to today's value by "inflating" them. This can be done by multiplying the "dated" price by the relative increase in the price index between the date of the price and the present. Price indexes can be a broad-based price index, such as the implicit deflator for Gross Domestic Product (GDP) or the Consumer Price Index when the "dated" prices concern general items such as the value of time. Alternatively, a specific price index such as the Highway Construction price index can be considered a better indicator for prices related to construction activities.

Treatment of Inflation or Deflation in Cost Estimates

General price inflation/deflation causes a reduction/increase in the purchasing power of the currency over time. The analysis can be calculated in constant-currency terms (explicitly excluding changes in the general price level) or in current-currency terms (including changes in the general price level). When excluding inflation, express all costs in terms of base date currency and use the real discount rate. On the other hand, if costs are expressed in current currency (i.e., if they include changes in prices), then a consistent projection of general price inflation must be used throughout the cost estimates.

It is preferable to use constant-currency analysis since it eliminates the need to estimate the rate of inflation over the duration of the study period. Current-currency analysis may be used if there are budgeting considerations based on current currency included in the analysis. For example, if cost data are based on a multiyear contract with fixed current currency amounts, adjust future expenditures for inflation.

Where the Treasury discount rate is not appropriate, present value calculations will take account of inflation (Hunter et al. 2005). Inflation is a rise in the general price level reflecting a decline in the purchasing power of money. The arguments regarding inflation are long and complex. Some authors say that it can be ignored altogether based on the reasoning that income also goes up with inflation. Inflation becomes complex when the rates of inflation for differing items are not constant, e.g. the price of electricity may be rising at a rate in excess of the general inflation rate. In general, a rate based on the difference between the bank base rate and the inflation rate should give a satisfactory rate for comparative calculations.

5.3.5 Taxes

There are two aspects in considering taxes in LCC calculations. The first deals with the probability that environmentally inefficient structures will attract future environmental taxes, and hence, LCC is an essential activity insuring elimination of this kind of risks. This can be addressed in the same way as any other risks. For each risk, the probability of occurrence and the likely impact can be established and a risk allowance made.

The second deals with general allowances for unspecified taxes in the calculations. There are several areas where costs might increase at a rate higher than inflation for a variety of reasons. Including taxes in the LCC calculations favours projects with reduced initial costs as the general experience is that tax relieves are generally applicable against repairs and maintenance. Although capital costs for plant and equipment are usually a budgeted one-off attracting various tax allowances, the ongoing reliability, efficiency and maintainability will affect the bottom line for the life of the equipment.

5.3.6 Residual values

The residual value of a structure, a system or a component is its remaining value at the end of the contract, or at the time it is replaced during the contract period. Residual values can be based on the value in place, resale value, salvage value, or scrap value, net of any selling, conversion, or disposal costs. As a rule of thumb, the residual value of a system with remaining useful life in place can be calculated by linearly prorating its initial costs. For example, for a system with an expected useful life of 15 years, which was installed 5 years before the end of the contract, the residual value would be approximately two third of its initial cost.

5.4 Methods of economic evaluation

Method	Application	Comments
Present Value LCC - LCC in present value currency of a building or system, including all costs (costs included depend on purpose of evaluation and model selected)	To building decisions for which determining factor is cost effectiveness. For deciding whether to accept or reject a given investment by identifying cost-effective components, systems, O&M models, etc.	LCC is used to determine if an investment in a given system or modification is worthwhile.
Net benefits (NB) and net savings (NS) – NB = time-adjusted (benefits minus costs) NS = time adjusted (savings – costs) when no benefits but reduction in future cost	For finding the economically efficient choice among building alternatives. For budget allocation decisions.	It additionally accounts for variations in benefits as well as costs among alternatives. Not currency measurable benefits or savings not accounted for. NB or NS should be positive for accepting the investment decisions.
Benefit-to-Cost-Ratio (BCR) and Savings-to-Investment-Ratio (SIR) – numerical ratios whose size indicates the economic performance of an investment	Used to determine if project is acceptable on economic grounds. Particularly applicable when investment's advantage is lower costs.	SIR is to BCR as is NS to NB A ration less than 1 indicated uneconomic investment. If computed based on incremental rather than total benefits and costs, can be used to design or size projects.
Internal Rate of Return (IRR) and minimum acceptable rate of return (MARR) – IRR is compared against the investor's MARR. IRR = value of discount rate which will result of NB or NS = 0 when used to discount benefits or costs.	Should be used with caution. Should be only used for deciding whether accept or reject a given project.	MARR is based on the opportunity cost of capital and = discount rate. IRR has 3 shortcomings – may overstate profitability, cause selection of less productive alternative and possibility of non-unique solution.
Overall Rate-of-Return (ORR) – annual yield from a project over the study period taking into account reinvestments of interim receipts.	Used for comparing projects , will indicate project with greater NB. Use ORR for the same applications as BCR and SIR. Can be used to decide whether accept or reject projects, to combine interdependent projects and to allocate funding among competing uses.	ORR developed to overcome shortcomings of IRR. When the reinvestment rate is made explicit, all investment costs are expressed as time-equivalent initial outlay and all non-investment cash flows as a time equivalent terminal amount. ORR needs to re-computed if the discount rate (reinvestment rate) is changed.
Payback (PB) – measures how long it takes to recover investment costs. Simple Payback (SPB) ignores time value of money and Discounted Payback (DPB) does not.	Should be used as a supplementary measure of economic performance. (if used alone – results can be misleading).	DPB is a form of breakdown analysis when project's life is uncertain.

5.5 Variables needed for economic evaluation

Variables, models & formulas	Source	Comments
Discount rate – d (equal to investor's MARR)	UK – HM Treasury – currently 3.5%	Discounting process essential for comparing future and present amounts on a consistent basis.
Models for cash flows Simplified models (discrete and continuous) and compounding Variables – the effective annual interest rate (actual yield) and the quoted annual interest rate (without regard for compounding)	Calculations based on given and expected interest rates	Helpful to support the calculations with early cash-flow diagrams.
Single compound amount (SCA) discount factor	Most engineering economics and financial textbooks from official sources (e.g. HM Treasury, ASTM, etc.)	Variable for adjusting cash-flows to make them time-equivalent – time equivalence formulas
Single Present Value (SPV) discount factor	Most engineering economics and financial textbooks from official sources (e.g. HM Treasury, ASTM, etc.)	Variable for adjusting cash-flows to make them time-equivalent – time equivalence formulas
Uniform Present Value (UPV) discount factor	Most engineering economics and financial textbooks from official sources (e.g. HM Treasury, ASTM, etc.)	Variable for adjusting cash-flows to make them time-equivalent – time equivalence formulas
Uniform Capital Recovery (UCR) discount factor	Most engineering economics and financial textbooks from official sources (e.g. HM Treasury, ASTM, etc.)	Variable for adjusting cash-flows to make them time-equivalent – time equivalence formulas

6 Facility-related duration and cost data

The two major dimensions in the calculation of life cycle cost (LCC) are time and cost. Thus, the majority of the information required is time- and cost-related. Since construction activities and materials used in a construction project used are usually diverse, and its life cycle involves different phases, the information required for conducting detailed LCC is usually massive and will be acquired from different sources. The lack of useful, reliable and consistent WLC data is regarded as one of the difficulties in implementing LCC (El-Haram and Horner, 2002; Kishk et al., 2003). This chapter reviews the LCC data required for LCC.

6.1 Analysis period

The analysis period is the period of time over which the life cycle cost is to be evaluated. The length of analysis period, which can be 20 or 40 years, is dependent on the building owner's preference. Salway (1986) suggested that the time scale for analysis should be the least of physical, functional, and economic lives. Nevertheless, the economic life is usually adopted in the analysis for cost optimisation (Kirk and Dell'Isola, 1995). Generally, there is a consensus that the analysis period should not be too long, since the discounting factor applied in the analysis tends to make the future costs less significant. In addition, the uncertainties in the future cannot be effectively defined based on the existing data. In ISO 15686-5, the typical analysis periods are listed as follows:

- The period of foreseeable need or occupation of the constructed asset (the life cycle);

- A period determined by a contractual liability (e.g. for maintenance of the asset or for a mortgage financing the investment);
- A standard investment analysis period applied withing an organisation;
- If the life cycle of the asset is longer than 100 years, the period of analysis used in the calculations may be 100 years as the calculation is unlikely to be significantly affected beyond this point.

6.2 Prediction of service life of building components

It is necessary to know the service life of building components and buildings for anticipating the maintenance and replacement cycle and costs in the design stage (Marteinsson, 2003). Since sustainability has become a major concern in the construction industry, there is a need to estimate the service lives of different components. The service lives are taken into consideration in life cycle assessment (LCA), which will be elaborated in later chapters. Alternatives of building component with different service lives will affect the outcomes of LCA. EOTA (1999) and ISO (2000) published the assumed working lives for construction products of different categories (Tables 6.1 and 6.2). It is suggested in ISO 15686-5 that the estimated life cycle of a component should not be less than the assumed working life.

The actual design life of a component can be affected by different factors such as the product quality and workmanship. In ISO 15686-8 (ISO, 2000), a factor method for estimating the service life (equation [6.1]) is elaborated. In the equation, the reference service life of a product is multiplied by factors, which are assessed and decided by the designer. The reference service life of a product can possibly be obtained from the manufacturer's data. ISO 15686-8 (ISO, 2006) suggested the range of factor values should fall within 0.8 and 1.2 (more preferably, 0.9-1.1). The factor values are still largely dependent on designers' experience and subjective judgement. Thus, it is doubtful if designers will have sufficient information to decide more accurate input values for the service life and the factors (Marteinsson, 2003; CIB, 2004).

$$ESLC = RSLC \times A \times B \times C \times D \times E \times F \times G \qquad [6.1]$$

where

ESLC	= estimated service life;
RSLC	= reference service life;
A	= quality of components;
B	= design level;
C	= work execution level;
D	= indoor environment;
E	= outdoor environment;
F	= in-use conditions;
G	= maintenance level.

Table 6.1 – Assumed working lives of works and construction products (adopted from EOTA, 1999).

Assumed working life of works (years)		Working life of construction products (years)		
Category	**Years**	**Category**		
		Repairable or easily replaceable	**Less easily repairable or replaceable**	**Lifetime of works [2]**
Short	10	10 [1]	10	10
Medium	25	10 [1]	25	25
Normal	50	10 [1]	25	50
Long	100	10 [1]	25	100

[1] In exceptional and justified cases, e.g. for certain repair products, a working life of 3 to 6 years may be envisage (when agreed by EOTA TB or CEN respectively).
[2] When not repairable or replaceable "easily" or "with some more efforts".

Table 6.2 – Suggested minimum design lives for components (adopted from ISO, 2000).

Design life of building	**Components**			**Building services**
	Inaccessible or structural	Replacement is expensive or difficult*	Major replaceable	
Unlimited	Unlimited	100	40	25
150	150	100	40	25
100	100	100	40	25
60	60	60	40	25
25	25	25	25	25
15	15	15	15	15
10	10	10	10	10

Note 1: Easy to replace components may have design lives of 3 or 6 years.
Note 2: An unlimited design life should very rarely be used, as it significantly reduces design options.
* including below ground drainage.

Equation [6.1] only produces deterministic estimated service lives for products. Since the life of any construction product is usually statistically scatter, it has been advocated to develop a stochastic service life prediction model for accommodating the uncertainties (CIB 2004, Boussabaine and Kirkham, 2005). A stochastic work example for service life estimation is included in ISO 15686-5 (ISO, 2006). The factor inputs for equation [1] can be defined in the form of probability distribution functions (pdf's) using supplier information, test data, or estimates from previous experience. If historical data are not available, subjective pdf's can be defined. However, subjective data may contain biases. Monte Carlo simulation (MCS) can be applied to generating a pdf of service life for a product, and discrete statistical outputs, such as mean, standard deviation, and 90th percentile, can then be calculated.

6.3 Sources of data

Using reliable and up-to-date information can enhance the accuracy of life cycle cost computed. Flanagan et al. (1987) and Boussabaine and Kirkham (2005) listed three major data sources for LCC:

- Data from manufacturers, suppliers, contractors and testing specialists
  - Material and product suppliers and manufacturers;
  - Government testing bodies;
  - Institutions such as Building Research Establishment (BRE), American Society of Civil Engineers.
- Forecasting models

If the required data is not available, mathematical models can be developed for analysing costs. Statistical techniques can be incorporated to address the uncertainties.

- Historical data

In the UK, the consistent sources such as BCIS and Spons are available for cost estimation. Other sources include clients' and surveyors' records, and journal papers. The metrics used in the data are usually in the format of cost/unit. These metrics may not provide effective information applicable to variety of the procurement methods EU-wide.

Overall list of sources of data can be assembled as follows:

- Project agreed life expectancies (UK-BCIS - Survey of Life Expectancies)
- Manufacturers, Suppliers and Trade Associations
- Research Organisations (UK - BRE, CIRIA, TRADA)
- Test Houses and Certification Bodies
- British and European Standards
- Research papers and reports
- UK - CIBSE Economic Life Factor codes
- UK – BCIS – Building Cost Info Service (BMI – Building maintenance info)
- UK - HAPM, BPG (part of BRE) and BLP Component Life Manuals
- UK - Occupiers Property Database (OPD)
- UK – BRE - Green Guide to Building Specification

6.4 Cost variables

LCC usually requires many cost inputs for calculating the costs for different phases of a project life cycle. The cost variables are usually categorised into groups. Thus, ISO 15686-5 (ISO, 2006) have provided a list of cost variables required, which will be illustrated in this section.

Acquisitions costs

Acquisition Costs include:

- site costs;
- temporary works;
- design/engineering costs;
- regulatory/planning costs;
- construction and earthworks;
- commissioning costs/fees;
- in-house administration.

Maintenance, operation and management costs

Maintenance, operation and management are necessary for ensuring that a building functions and operates properly throughout its life cycle. The cost items to be considered in this phase in are as follows:

- rates (this is an operation cost);
- insurance (this is an operation cost);
- energy costs (this is an operation cost);
- water and sewage costs;
- facilities management (this is operation/management cost);
- cleaning (this is an operation cost);

- security (this is an operation cost);
- annual regulatory costs (e.g. fire, access inspections) and regulatory maintenance costs (this is an maintenance cost);
- maintenance (e.g. repairs, replacement, refurbishment);
- revenue from ownership or use of the asset (e.g. rent, service charges etc).

Other costs to be considered in this phase include:
- demolition;
- cost of disposal;
- unanticipated costs resulting from legislation introduced subsequent to completion of the constructed asset, e.g. in relation to environmental, health and safety requirements or fiscal matters

The maintenance activities usually include inspection, monitoring, testing, condition surveys/inspections, maintenance planning, repairing, refurbishing, and partial replacements. The following indirect impacts of maintenance works can also be taken into account:
- down time (loss of function for a period);
- the disruption of business activity;
- the non-availability of a building/structure;
- the cost effects of aesthetic condition;
- the maintenance strategy;
- external costs/saving data;
- whether any other costs or savings will be made as part of the option appraisal process, with this being identified in the LCC analysis.

Residual values/disposal costs

A few alternatives are recommended in ISO 15686-5 for estimating residual value:
- the prices for similar assets current on sale in the market;
- book estimates of the resale value available from the industry or government sources;
- using accepted practice to assess asset values.

For estimating disposal costs, environmental legislation must be taken into account.

Other cost variables

Other cost variables to be considered in LCC are:
- Discount Rate;
- Inflation;
- Taxes and subsidies;
- Utility costs including energy costs.

The environmental cost variables are currently not considered in the ISO standard. Nevertheless, there have been attempts to incorporate eco-costs in LCC (see Chapter 14).

7 Mathematical models for LCC

A mathematical model for LCC contains the mathematical equations that can be explicitly applied to quantifying the LCC of a building. In the TG4: LCC in Construction report and ISO 15686-5, the LCC of a building is suggested to include acquisition costs (pre-construction and construction), operation costs, maintenance costs, replacement costs, and residual values / disposal costs. The models elaborated in this chapter make use of NPV, whose generic form is shown in equation [7.1], for comparing different alternatives. In the models, different costs are grouped according to their types.

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} \qquad [7.1]$$

Where

NPV = Net present value;

Ct = Cost of item t;

r = discount rate;

T = The analysis period in years.

The ASTM (1983) LCC model is shown in equation [7.2]. The model has all the energy costs grouped in a single component, which will help evaluating the total energy cost under different discount rates.

$$NPV = C + R + A + M + E - S \qquad [7.2]$$

Where

C = the initial cost;

R = the present value of replacement costs;

A = the present value of annually recurring operating, maintenance and repair cost (excluding energy costs);

M = the present value of non-annually recurring operating, maintenance and repair cost (excluding energy costs);

E = the present value of energy costs;

S = the present resale value.

Bromilow and Pawsey (1998) developed a simple model for quantifying the life cycle costs of university buildings. Most of the costs are categorised into either annual cost, which are continuous over time, such as maintenance, cleaning, energy and security, and cost for discontinuous tasks such as repainting or replacement of building components.

$$NPV = c_0 + \sum_{i}^{n} \sum_{t=1}^{T} c_{it}(1+r_{it})^{-t} + \sum \sum c_{jt}(1+r_{jt})^{-t} - d(1-r_d)^{-T} \qquad [7.3]$$

Where

C_0 = the procurement cost at time t = 0;

c_{it} = the annual cost at time t of support function i;

c_{jt} = the cost at time t of discontinuous function j;

r_{it} and r_{jt} = the discount rates applicable to support functions i and j respectively;

d = the value of asset on disposal, less the disposal cost;

r_d = the discount rate applicable to asset disposal over pertiod 0 to T.

Al-Hajj and Horner (1998) developed a simple model (equation [7.4]) for estimating the maintenance and running costs of university buildings. Base on a set of building data in certain category of buildings, the models only take into account the cost significant items, which are selected based on Pareto's 80/20 rule, and the cost model factor (CMF), which is the ratio of the cost of the cost-significant items to the total cost, is computed. The cost data from different years of survey will be discounted to reflect the current cost values. The total maintenance and running costs of a building are estimated based on the cost of these significant items for this building and the CMF.

$$T_C = \frac{1}{CMF}\sum_{i=1}^{n} CSI_i \qquad [7.4]$$

Where

T_C = the total cost;

CMF = the cost model factor;

CSI_i = the cost of the *i*th cost-significant item.

In this model, the data of buildings, which are different in terms of type and size, have to be normalised. However, the inconsistency in cost normalisation will affect the accuracy of the results. In addition, certain buildings will have occasional high cost items, and thus, this model cannot provide an accurate estimated cost value for this category of buildings.

Due to the lack of past data and the long period of analysis, LCC usually involves subjective judgements. Fuzzy set theory has long been regarded as an effective technique for capturing subjective or linguistic information (Ross, 1995). A typical triangular fuzzy set for representing a possible range of values for a linguistic description, such as tall or short, is shown in Figure 1. In the fuzzy set, the value *m* is the most possible value with the membership value of 1.0, and *l* and *h* are the lowest and highest possible values respectively, with the membership values of 0. Thus, with the use of fuzzy set theory, assessors do not need to specify the exact values for certain subjective inputs. The fuzzy operations and arithmetic algorithms can be applied to aggregate the fuzzy sets (Ross, 1995).

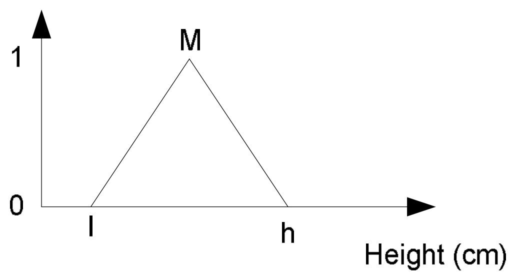

Figure 7.1: A triangular fuzzy set representing a subjective term.

Sobanjo (1999) presented a framework of a fuzzy sets-based methodology for LCC analysis of facilities, including applications to buildings. The present value of LCC is represented by equation [7.5].

$$[P_l, P_m, P_h] = \sum [CI_l, CI_m, CI_h] + \sum [F_l, F_m, F_h][(1+r)^{-n}] + \sum [A_b, A_m, A_h][r^{-1}][1-(1+r)^{-n}] \qquad [7.5]$$

Where

P = Present worth equivalent;

CI = Initial cost;

F = Single future cost (salvage);

r = Discount rate;

A = Annual uniform series of maintenance costs.

In the model, the years of analysis and the discount rate are assumed to be fixed. Based on the fuzzy arithmetic addition (Ross, 1995), the individual values for *l*, *m* and *h* on the right hand side of the equation are processed separately for computing the outcomes in terms of P_l, P_m and P_h. The outcomes of different alternatives, which are in the form of fuzzy sets, are compared using the 'qualified comparison' approach. The simple structure of the model can effectively handle the single future costs and annual costs. However, non-annual recurring costs will have to be treated as a set of single future cost, which will require more computation effort (Kishk et al., 2003).

Kishk and Al-Hajj (2000) developed a fuzzy life cycle costing model, which is shown as equation [7.6]. In this model, the discount factors for annual costs and non-annual costs are formulated for simplifying the time and effort required in the computation process. All the variables in the equations are treated as fuzzy sets, and the NPV is quantified by making use of the fuzzy arithmetic multiplication, addition and subtraction. The fuzzy sets of NPV of different alternatives can be normalised and compared.

$$NPV_i = C_{0i} + PWA\sum_{j=1}^{nar_i} A_{ij} + \sum C_{ik} PWN_{ik} - PWS \bullet S_i \qquad [7.6]$$

Where

C_{0i} = the initial cost of alternative i;

PWA = present worth factor for annual recurring costs = $\frac{1}{r}[1-(1+r)^{-T}]$;

A_{ij} = annual recurring costs of alternative i;

C_{ik} = non-recurring costs of alternative i.

PWN = the present worth factor for a non-annual recurring cost = $\frac{1-(1+r)^{-n_{ik}f_{ik}}}{(1+r)^{f_{ik}}-1}$;

PWS = the present worth factor for a single future cost = $(1+r)^{-T}$;

S_i = the salvage value of alternative I, at the end of the analysis period;

f_{ik} = the frequencies of non-annual recurring costs, C_{ik} of alternative i;

n_{ik} = the number of recurrences of non-annual recurring costs C_{ik} of alternative i.

Kirkham et al. (1999) made use of regression technique to model the energy cost of sport centres. In the regression models, the floor area and the number of users are the two independent inputs. The models developed have different coefficients and constants. Two examples of the models are shown as [7.7a] and [7.7b]. Mean

Absolute Percentage Error (MAPE) was used to test the accuracy of the models. In order to develop an accurate regression cost model, abundant information for a specific cost component is usually required. However, its application is limited to that particular cost component.

$$C_E = 1.203 + 0.97 * area \quad [7.7a]$$

$$C_E = 1.217 + 0.642 * area + 0.206 * user \quad [7.7b]$$

Where

C_E = Energy Cost.

8 LCC calculation methods

There is available a diverse array of techniques and applications of LCC. In some instances, LCC appears to be little more than a straightforward application of standard economic principles. In other cases, LCC criteria support sophisticated mathematical programming techniques seeking optimal infrastructure maintenance and repair policies. Still other instances of LCC illustrate some mix of sensitivity, risk, and (or) multi-attribute decision analyses.

To reach a satisfactory classification it is necessary to:

- identify and organise the progressive development of LCC methods in a logical and meaningful way
- separate genuine methodological advancements from sophisticated application of straightforward LCC principles, and
- separate credible from questionable developments in the theory and practice of LCC.

8.1 Deterministic methods of LCC

The basic deterministic methods are underlying virtually all LCC investigations. The process begins with customer needs and ultimately ends with the customer selecting a preferred option. In this context, the LCC procedure employed exists to support a decision-making process focused on customer satisfaction.

The needs of owner (customer) are translated to a set of requirements that the proposed, mutually exclusive options must meet to satisfy certain criteria. Once a set of feasible options emerge, each must be analysed in the context of life cycle cost, broadly according to following steps:

- The first step is to generate cost profiles corresponding to each considered option. Each cost profile is a series of planning, construction, maintenance, support, use, and disposal cost estimates calculated over the intended service life of the corresponding facility option.
- Next, each cost profile is translated to an equivalence measure to support a common and credible basis of comparison among considered options. This involves the straightforward application of time – value of money factors to convert a forecasted stream of costs to a single comparable index. Common equivalence measures used to compare feasible design options include: e.g. annual worth and present worth, etc. (ASTM 2002).
- Third, the results of the time value of money computations are used to rank the options according to life cycle cost, with the least life cycle cost (measured in

annual or present worth terms) ranking above all other feasible options and is therefore presented as the recommended option.

- Finally, the results of the LCC procedure are passed on to the infrastructure owner to support rational decision making.

The deterministic approach assigns each LCC input variable a fixed, discrete value. The analyst determines the value most likely to occur for each input parameter. This determination is usually based on historical evidence or professional judgment. Collectively, these input values are used to compute a single LCC estimate. Traditionally, applications of LCC have been deterministic ones. A deterministic LCC computation is straightforward and can be conducted manually using a calculator or automatically with a spreadsheet. However, it fails to convey the degree of uncertainty associated with the PV estimate.

It is important to note that the derivation of cost profiles for each option analysed within a LCC procedure ranges from straightforward to sophisticated ones. More sophisticated means of deriving cost profiles for LCC investigations include the combining of optimisation techniques and (stochastic) life cycle performance predictions in developing optimal maintenance strategies pertinent to a particular structure. Derivation of cost profiles may be found in (Ehlen, 1999, Maharsia and Jerro, 2002, Meiarashi et al. 2002 and Nystrom et al. 2003). Regardless of the computational sophistication involved, however, the derivation of cost profiles pertinent to infrastructure related options within LCC investigations will rely on supporting cost estimating techniques relevant to the options at hand.

The deterministic method underlying LCC investigations provides a logical ordering of analytical activities and a credible means of ranking feasible options pertinent to the construction, refurbishment, and on-going management and support of infrastructure see Figure 8.1 below. However, this straightforward deterministic approach provides little guidance to the engineer or designer attempting to adequately represent the complexity and uncertainty inherent to LCC investigations. For this reason, the basic method is typically extended within LCC applications to permit a logical means of addressing these shortcomings (Ehlen 1997; Arrien et al. 2001).

Of these, a common extension to the basic method of LCC involves the use of sensitivity analysis and risk analysis.

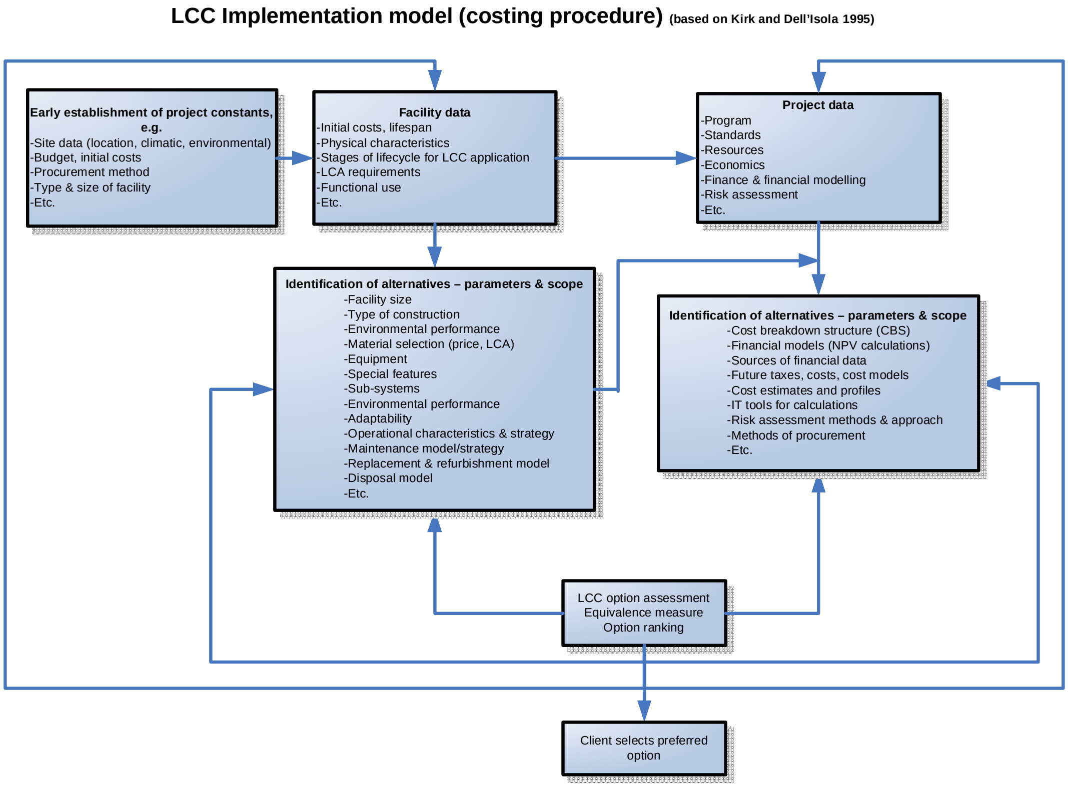

Figure 8.1: LCC implementation – deterministic method with iterations.

8.2 Sensitivity analysis

In general, sensitivity analysis involves the behaviour of model variables over predetermined bounds to determine their relative effect on model outcome. Through this process, analysts can:

- identify some subset of model variables that exert significant influence on model results and (or)
- determine break-even points that alter the ranking of considered options.

Each of these goals provides important insight to decision makers who are rightly sceptical of fixed values and attendant results. Sensitivity analysis, then, is a direct admission that uncertainty often plagues even the most careful and judicious deterministic analyses.

Following an initial deterministic ranking of feasible design options, sensitivity analysis is employed to establish the sensitivity of model results (i.e. annual or present worth measures) and rankings across model variables of particular concern to analysts and decision makers – see Figure 8.2. In the LCC literature, demonstrations of this method may be found in many articles (Clemen, 1996, Ehlen and Marshall, 1996, Hartmann et al., 2000, Kent and Murphy, 2000, Maharsia and Jerro, 2002 and Meiarashi et al., 2002).

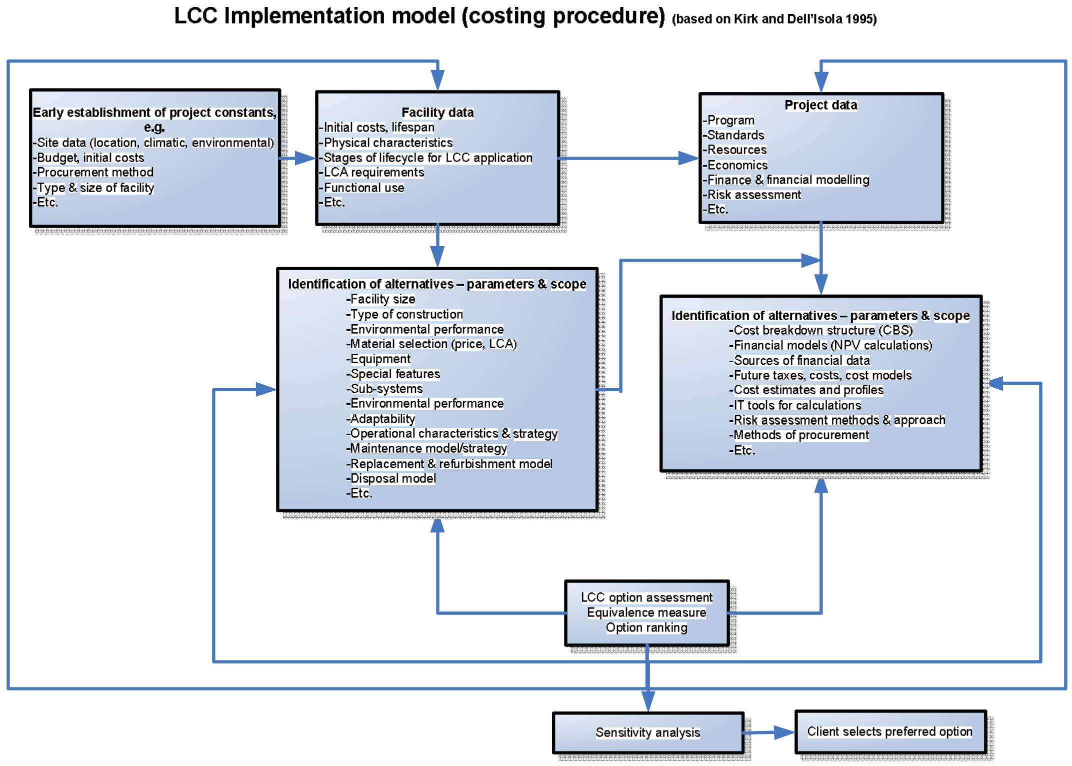

Figure 8.2: LCC implementation with sensitivity analysis.

While pertinent literature demonstrates the ease with which sensitivity analysis may be employed to derive important insights regarding model results and attendant rankings, the arbitrary application of sensitivity analysis can prove misleading. The information employed in sensitivity analyses must be based on some sense of likely maximum and minimum values. For example, in a LCC exercise an analyst may draw on expert engineering judgement to estimate the upper and lower bounds corresponding to certain costing variables. To ensure the bounds established are consistent across model variables, the analyst should encourage the engineer to estimate minimum and maximum values based on, for instance, a confidence interval of 95% (i.e. the engineer is 95% certain that the actual value lies between the two estimates provided). This avoids arbitrary variations in LCC model variables that may or may not reflect the likelihood that the “true” value falls within the established bounds, effectively skewing insights drawn from the sensitivity analysis.

8.3 Probabilistic comparison of options (risk analysis)

While sensitivity analysis provides decision-makers some insight regarding the flexibility of model results across a range of variable estimates and corresponding bounds, it suffers three important shortcomings.

First, it may fail to identify a dominant alternative among considered design options (this is certainly the case where perturbations in model variables disturb the ranking of feasible design options).

Second, since sensitivity analysis typically involves the independent perturbation of each model variable, engineers and, therefore, customers do not gain a sense of the combined and simultaneous influence of several “perturbed” model variables on LCC results and rankings.

Finally, in the absence of defined probability distributions, the likelihood that particular values occur is left unexplored.

The purpose of risk analysis is to address these shortcomings through probabilistic comparison of considered options. In risk analysis, values assigned model variables are described by probability mass functions or frequency distributions. Through exact or random sampling methods, the probabilistic assessment of model variables is employed within the relevant computational procedure to generate a cumulative distribution of model outcomes corresponding to each option included in the analysis. The cumulative distributions, in turn, form the basis of comparison among considered options, most generally in terms of expected values and rules of stochastic dominance. Comprehensive yet readable introductions to risk analysis, relevant probability and sampling concepts, and pertinent measures of comparison are found in Clemen (1996).

Employed properly, risk analysis addresses the bulk of limitations associated with sensitivity analysis.

First, model variables are more completely described through the introduction of probabilities (i.e., random variables replace deterministic variables).

Second, since sampling techniques implicitly and repeatedly “combine” a random assortment of likely values, the cumulative distribution assigned to each option included in the analysis represents the combined influence of all model variables on model outcome.

Finally, while a dominant alternative may still fail to emerge, the cumulative distribution assigned to each option provides a clearer and more descriptive picture of associated outcomes for purposes of comparison. Figure 8.3 extends Figure 8.2 by adding a risk analysis component.

LCC Implementation model (costing procedure) (based on Kirk and Dell'Isola 1995)

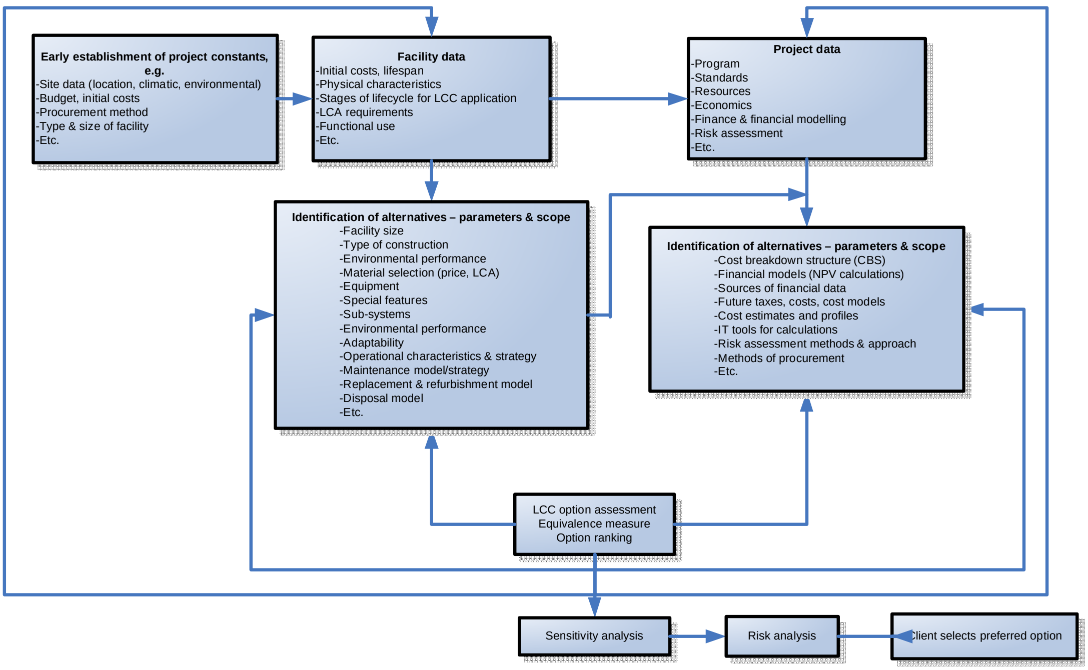

Figure 8.3: LCC implementation model with sensitivity analysis and risk analysis.

Despite the introduction of risk analysis, however, note that sensitivity analysis remains a part of any well ordered LCC method. The reason for this is strictly pragmatic.

Obtaining probabilistic data for model variables can be a costly and time-consuming process (even where expert engineering judgement is employed to efficiently extract useful information). Hence, it is best to focus data gathering activities around model variables that hold significant sway over LCC results and rankings. It is typically the case that sensitivity analysis reveals only a handful of model variables that exert substantive influence on LCC results and rankings (reflecting a “90/10 rule” where, in practice, 90% of model variability is explained by 10% of model variables). Clearly, identifying these key variables provides focus to subsequent data gathering activities needed to support risk analysis. The key linkage of sensitivity and risk analyses is fundamental to the practice of decision analysis. A number of researchers recommend the inclusion of risk analysis within well-ordered LCC investigations.

From a broadly methodological standpoint, relevant literature includes Fabrycky and Blanchard (1991), ASTM (2002), and Hawk (2003). A good example of risk analysis employed to evaluate innovative infrastructure designs is found in Ehlen (1999).

Risk analysis often involves a reassessment of considered options in the context of risk preference. Where owners are risk neutral, comparison of alternatives may proceed on the basis of expected monetary value alone. However, where attitudes are risk averse or risk seeking, the probabilistic distribution of life cycle costs is translated to some measure of utility. The measure of utility assigned to each alternative then forms the basis for ranking. For the purposes of this chapter, however, attention is limited to the case of risk neutrality – a common practice where public infrastructure investment is concerned. With regards to this issue, Townley (1998) includes pertinent and readable discussions involving individual versus collective risk and the Arrow-Lind theorem.

9 Risk analysis in life cycle costing

Building projects, throughout their lifecycles, are consistently affected by risks and uncertainties, which if not appropriately managed, will incur additional cost. It has been recognised that the incorporation of risk analysis in LCC can help anticipate the impacts due to risks and uncertainties, and assist the decision making process (TG4, 2003; Boussabaine and Kirkham, 2005). The construction and property industry is no stranger to risk analysis, as it is an essential step in project risk management, which has been widely discussed and promoted in the past two decades (Flanagan et al., 1987; CIRIA, 1996; APM, 1997; ICE et al., 1998). Risk analysis is made up of two parts, i.e. qualitative risk analysis and quantitative risk analysis. Numerous risk analysis techniques have been developed in the past, and those that can be applied in LCC are discussed in this chapter. The selection of technique for a project is largely based on the type and extent of details required by project participants.

9.1 Qualitative risk analysis

Qualitative risk analysis, which is also known as risk identification and assessment, aims at identifying risks and assessing the attributes of risks, such as probability of occurrence, risk impact and risk ownership. It is a very critical part of a risk management process, as its outcomes are used extensively in the subsequent steps of risk management (Smith, 1999).

9.1.1 Brainstorming

Brainstorming involves the open discussion among a group of participants to exhaustively identify and assess risks for a project. Each participant can express his view freely, without receiving criticisms from others. A brainstorming session is usually led by a facilitator, who needs to convey the objectives of the session to participants. A well mix of group members in terms of expertise, knowledge and experience is essential to more effectively identify different sources of risks (Chapman, 1998). Osborn (1963) suggests that the optimum size of a brainstorming group should consist of 12 members.

9.1.2 Interviews

Interviews with experts are conducted on a one-to-one basis. Their opinions on risks are acquired in the interviews. However, this technique is time consuming. Thus, questions must be properly structured, and vague and confusing questions must be avoided. Another concern about this technique is experts' judgements on risks may not be free from bias.

9.1.3 Checklists

Checklists contain the data of risks occurred in past projects. They are often used as an aid to the risk identification process for minimising the reoccurrence of risks. Nevertheless, checklists should not be used to initiate the risk identification process, as they will confine the finding of new risks (ICE et al., 1998).

9.1.4 Cause-and-effect diagrams

Cause-and-effect diagrams, which are also known as fishbone diagrams or Ishikawa diagrams, are a graphical presentation of the relationships between risk factors and their effects. In each diagram, only an effect is allowed, and its risk factors are listed in the fishbone structure (see Figure 9.1). The main branches are filled in with the main risk factors. The next level horizontal lines represent the relevant sub-factors. Nevertheless, the rigid structure does not investigate the relationships between risk factors.

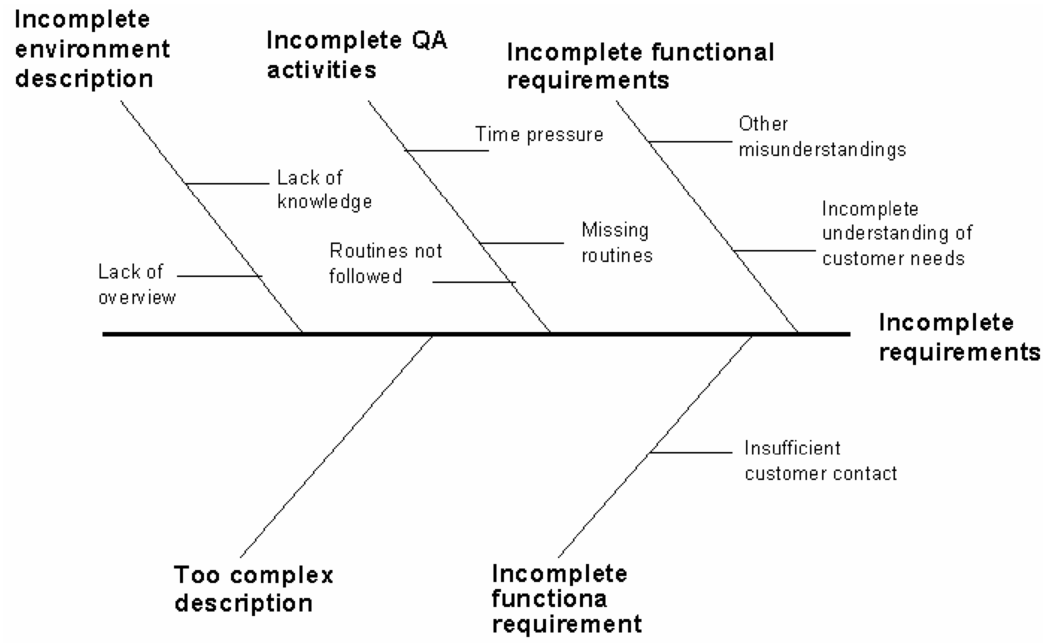

Figure 9.1: Cause-and-effect diagram.

9.1.5 Risk matrices

		Likelihood of Occurrence		
		Low	Medium	High
Risk Impact	Low	1	2	2
	Medium	2	3	4
	High	3	4	5

Figure 9.2: Risk matrices.

Risk matrices are a tabular format for assessing and ranking risks (Figure 9.2). Two risk attributes of likelihood of occurrence and risk impact form the column and row of the tables. The attribute descriptions are in the form of verbal or numerical scale. The value of each cell in the table can be the result of the multiplication of the scale values, an arbitrary number, or an alphabet. For each risk, its attributes can be assessed and assigned qualitatively, such as Low, Medium and High. Based on the scores of the risks being assessed, they can be ranked, and attention can be focused on the more critical risks. APM (1997) emphasises that the assessment of risk attributes should be undertaken by referring to common terms in order to achieve consistency in the results.

9.1.6 Influence diagrams

Influence diagrams are directed graphs for modelling uncertainties in decision making processes. In an influence diagram, variables are represented by nodes, and dependencies or relationships among the variables are represented by directed arcs. Influence diagrams are effective in providing an understanding of a complex situation. However, an influence diagram will become too complex to analyse if it contains too many variables. Isaac (1995) suggests that there should not be more than 15 variables in an influence diagram.

9.1.7 Risk registers

Risk registers are a format to systematically record the outcomes of risk identification and assessment, and the information should be consistently updated throughout the project lifecycle (Boussabaine and Kirkham, 2005). Risk registers provide an effective means to communicate risk knowledge among project participants (Patterson and Neailey, 2002). The information available in risk registers can be used to initiate quantitative risk analysis, and to support the subsequent risk mitigation process (Williams, 1994). Database systems are usually utilised to store and maintain the risk data, which will be massive for large projects. The following information has been suggested for inclusion in risk registers (Williams, 1993; APM, 1997; ICE et al., 1998):

- The title and description of risk;
- The description of causes;
- The date of the risk identified and modified;
- The risk code;
- The ownership of risk;
- The likelihood of occurrence;
- The risk impact;
- The risk ranking;
- The risk mitigation action plan;
- The residual risk effects;

9.2 Quantitative risk analysis

Quantitative risk analysis involves the formulation of a model for computing the risk impacts on the quantifiable project performance measures of cost and duration. In LCC, cost risks are the major concern. Techniques available are either deterministic or stochastic. Stochastic techniques assume that uncertainties are random in nature, and the probabilities of occurrence can be quantified accurately based on historical data. However, uncertainties can be caused by vague and incomplete information, and the ambiguities and subjectivities cannot be captured effectively in stochastic methods. In construction, due to the uniqueness of construction projects, historical data, if available, cannot fit a future project perfectly. Subjective judgements are usually made throughout the decision-making process. Although methods have been developed to convert subjectivities to subjective probabilities for stochastic techniques, construction practitioners often lack the knowledge to do so. Hence, stochastic techniques are viewed as complex tools, and are not commonly applied (Akintoye and MacLeod, 1997).

9.2.1 Sensitivity analysis (SA)

Sensitivity analysis (SA) is a more commonly used non-probabilistic tool in the construction industry due to its simplicity. It evaluates the impact of change in a variable, say discount rate, on a performance measure of a project, such as the NPV. The results of SA are usually displayed in the graphical format of ‘spider diagram’. Probability contour can be incorporated in the diagram to indicate the likelihood of occurrence of the variable (Smith, 1999). Nevertheless, its assumption that other variables will remain unchanged while a variable is being analysed has become its major limitation (Flanagan et al., 1987). In practice, risk variables do not occur one at a time. Variables evaluated in SA are assumed to be independent of each other, but certain variables can be interdependent.

9.2.2 Decision trees

Decision trees are a technique that comprehensively displays alternatives or scenarios for a project in a tree-like structure. In an investment decision-making process, the costs, payoffs, and probabilities for the alternative can be assigned to the decision tree. The expected monetary value (EMV) is computed by summing the payoffs weighted by their probability values. Nevertheless, this technique assumes that the nature of projects is static, but construction projects are usually dynamic in nature (Thompson and Perry, 1992). In addition, it does not take into account decision-makers' risk attitudes. An alternative with higher EMV may come with higher risk.

9.2.3 Monte Carlo simulation (MCS)

Monte Carlo simulation (MCS) is a stochastic technique that randomly sample values from the probability distribution functions (pdf's) of variables in a model to compute the likely outcomes. A substantial amount of iterations is run to cover different possible scenarios, and the results are used to form a pdf of probable outcomes (Figure 9.3). Deterministic statistical outputs, such as mean, median, different levels of confidence (e.g. 90^{th} percentile) and standard deviation, can be computed from the results. Commercial software packages, such as @Risk and Crystal Ball, are available to handle the simple but tedious computational process, which can have thousands of iterations. Different types of pdf's for defining the inputs are provided in the software packages.

Due to the lack of historical cost data and the uniqueness of construction projects, the selection of pdf's for cost is usually based on subjective judgements. Research work (Chau, 1995a&b; Wall, 1997) has been undertaken to investigate the types of pdf for more accurately representing cost components in construction projects have been undertaken. Generally, pdf's with positive skews (with tails towards the right hand side), such as lognormal distribution, are favoured for representing cost uncertainties. The reason is substantially high cost with low probability of occurrence can be effectively represented in this type of pdf's (Chau, 1995a). Boussabaine and Kirkham (2005) propose the appropriate types of pdf's for some cost components in LCC. In MCS, dependencies between any two variables can be modelled using coefficients of correlation, but they lack intuitive appeals (Vose, 1996). In addition, the coefficients can only represent linear relationship.

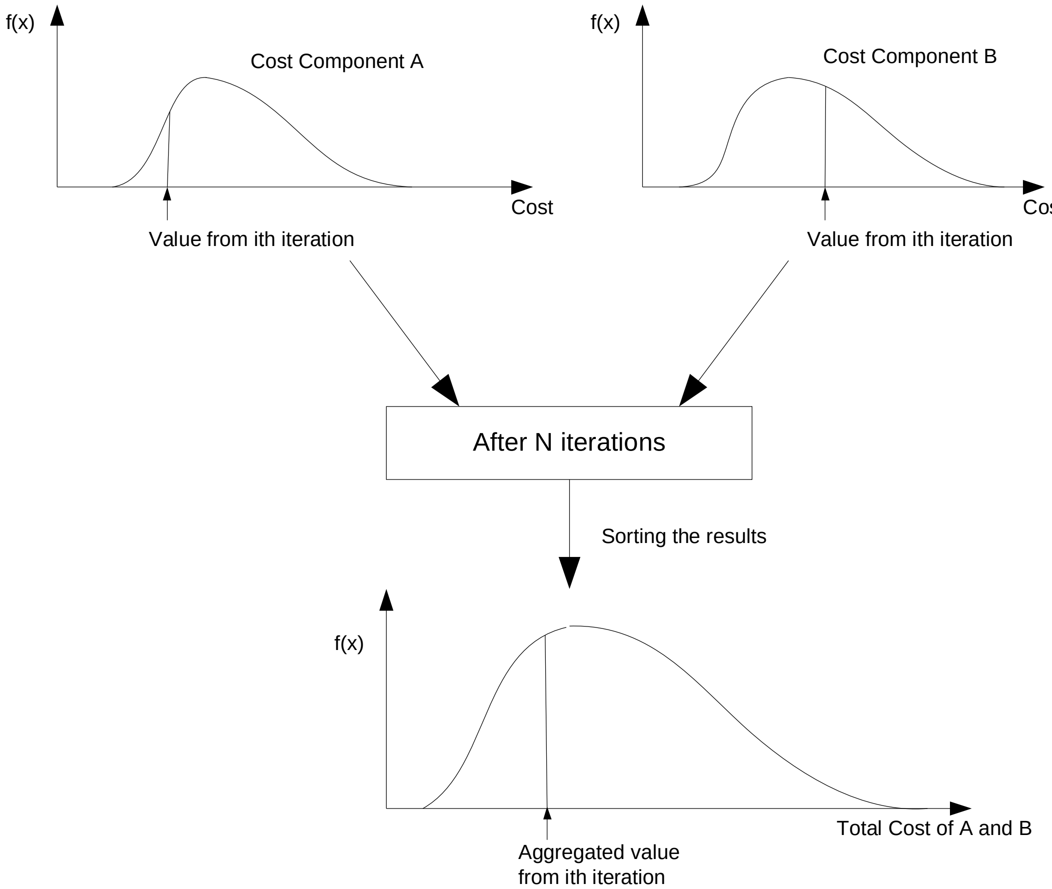

Figure 9.3: Monte Carlo simulation.

9.2.4 Latin hypercube simulation (LHS)

Latin hypercube simulation (LHS) adopts the similar approach as MCS, but stratifies the input pdf into intervals of equal probability. In the simulation, each interval will have equal chance to be selected, i.e. equal amounts of values will be sampled from the intervals. Hence, LHS requires less number of iterations to produce a uniform distribution for the output. Nevertheless, today's computer power can handle a large number of iterations comfortably. In commercial MCS software packages, the LHS option is usually available alongside the MCS option.

9.2.5 Markov chain

A Markov chain is a stochastic process with the *memoryless* property. In the process, the previous states will not affect the prediction of the subsequent states if the knowledge of the current state is known. Hence, the conditional probability distribution of a future state X_{n+1} given the present and past states is a function of the present state X_n alone:

$$P(X_{n+1} = x \mid X_0 = x_0, X_1 = x_1, ..., X_n = x_n) = P(X_{n+1} = x \mid X_n = x_n)$$

The Markov chain can be used to estimate the probability for the condition of a building to change from 'good' to 'bad' for a certain time period. It has been applied to predicting the residual service life of buildings (Kirkham and

Boussabaine, 2005) and the life cycle performance of building components (Zhang et al., 2005).

9.2.6 Multiple linear regression technique

The multiple linear regression technique involves the development of an equation to represent the statistical relationship between an effect and its causal factors. Substantial amount of statistical data is required for developing a model. If historical data is not available, the survey method can be used to identify the more critical factors and define the relevant coefficients of correlation for the model. The relationship in an regression equation is assumed to be linear, and this assumption may oversimplify their actual relationship. Kirkham et al. (1999) develop a simple regression equation, which takes into account the floor area and the number of user, for estimating the energy cost for sport centres.

9.2.7 Fuzzy set theory and fuzzy logic

Fuzzy set theory and fuzzy logic is an artificial intelligence (AI) technique that can effectively model and infer vague and subjective information (Ross, 1995). Risk information is usually subjective, and can be conveniently described qualitatively in linguistic terms. With the use of fuzzy set theory, the linguistic risk descriptions can be modelled mathematically in the form of fuzzy sets. *If-then* rules are used to represent the expected inputs and outputs of a problem domain. With a set of actual inputs, fuzzy logic can be used to fire the rules, and to infer a linguistic outcome.

Fuzzy set theory and fuzzy logic has been extensively attempted in project risk analysis. Albeit this advantage, a practical fuzzy risk model has yet to be adopted in the industry. Fuzzy LCC models, which make use of fuzzy set theory for modelling the cost uncertainties, have been developed to process the subjectivities in LCC (Sobanjo, 1999; Kishk, 2004). Kishk (2004) emphasises that in the absence of historical data, the cost variables can be more conveniently defined and modified in fuzzy sets.

9.3 Integrated framework for LCC in buildings

Kishk and Al-Hajj (1999) developed an integrated framework (Figure 4) to handle uncertainty in LCC. It is based on the idea that a complex problem may be deconstructed into simpler tasks. Different tools can then be used to handle the subsets of tasks. Fuzzy set theory and artificial neural networks are applied to improve the quality of LCC as decision making tools.

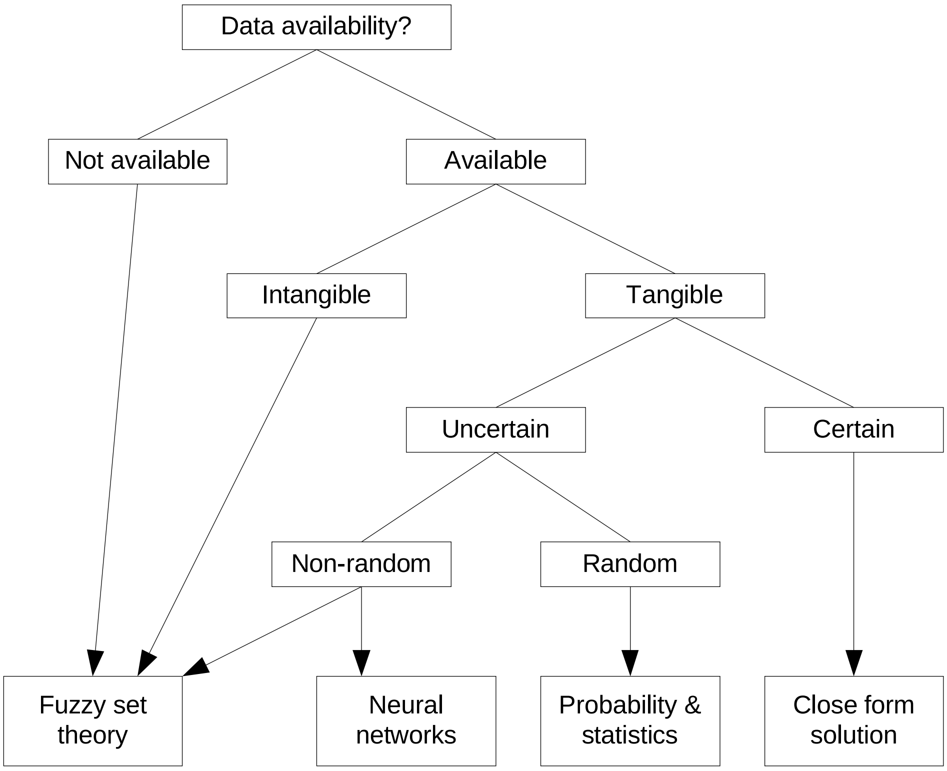

Figure 4: Schematic representation of the integrated framework (adapted from Kishk and Al-Hajj, 1999).

10 Relevant EU and national standards, guidance notes and government regulations for Sustainable Construction

The construction and building industry consumes a significant amount of natural resources and energy (TG1, 2000). The activities throughout the supply chain usually involve extraction of irrecoverable natural resources and release of waste. The construction industry has been urged to impose measures to attain sustainable development (CIB, 1999; DETR, 2000; Working Group for Sustainable Construction, 2001). A common definition of sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Standards, guides and reports have been developed to facilitate the process. Although sustainable development consists of three dimensions – social, economic, and environmental (CICA, 2002), the main focus of these documents is on the environmental aspect, such as the environmental quality of construction materials, and the energy performance of buildings.

10.1 BS 7543: 1992 – Guide to durability of buildings and building elements, components and materials (BSI 1992)

British Standard 7543 states that basic causes of deterioration in buildings are due to the action of weathering, biological infestation, stress, chemical interactions, physical interactions and normal use. BS 7453 also states that deterioration will be accelerated by:

- poor design/detailing
- inappropriate selection of material or
- component for intended use

- quality of material or component used
- adverse onsite storage and handling
- poor workmanship
- inadequate maintenance
- inappropriate use.

These factors all result from human endeavours and therefore do not lend themselves to accurate prediction. This is the key problem associated with estimating component life expectancy.

The design and construction process tries to minimise these factors and experience suggests that it is usually a combination of factors that leads to failure. For example, a poor design that is poorly built and poorly maintained will fail when getting any one of these processes right would allow it to perform adequately.

10.2 France - XP P01010-1 environmental quality of construction products

The development of the quantitative part is based on the ISO TR 14025 while the quantitative information is based on LCA ISO 1404x series methodology. The aim of the scheme is to provide information *and* to give opportunities to improve (design for environment), and not to compare competitive products.

The French standardisation committee P01E in AFNOR have been the ultimate authors and endorsers of the methodology and are aiming to improve it and update it until it becomes a standard (URL19).

Title	Aspect	Content
Main features	Title	Information concerning the environmental characteristics of construction products. It is one standard (XP P01-010) in two parts (1&2) : Part 1 : Methodology and model of data declaration Part 2 : Guidelines for the application of environmental characteristics to given construction work.
	Country	in France
	Organisation	AFNOR (French Association for Standardisation)
	Status	The scheme is public and is accepted as an experimental standard. It is a published experimental standard. Part 1 was published in April 2001. Part 2 has been published in April 2002. Historically, in 1994, the private French association of producers of construction products (AIMCC), concerned by the development in France of High Environmental Quality (HQE) building, launched a working group on environmental data. This group produced a first format of environmental declaration for construction product, aiming at producing both qualitative and quantitative environmental information on products. The development of the quantitative part was based on the ISO TR 14025. Thus, quantitative information is based on LCA ISO 1404x series methodology, and qualitative information must respect requirements of environmental information, particularly ISO 14 020. The aim of the scheme is to provide information *and* to give opportunities to improve (design for environment), and not to compare competitive products. The work of this group has been captured, developed and improved by the French standardisation committee P01E in AFNOR, until it becomes a standard. 5 declarations have been produced at the moment, and 15 are about to come in the 6 coming months (see list in appendix). The different stakeholders seem to feel rather satisfied with the scheme: both the use of ISO 1404x series methodology and the common format should prevent from misuses of such declarations. However, some industries still adopt a prudent attitude, waiting for the feedback of stakeholders about this kind of information.
	(Policy) context	It is not clear at the moment how the scheme will be used in the future. There are different possibilities: The High Environmental Quality building reference is still active and promotes

		the use of these data by architects and designers of buildings; Stakeholders who developed the scheme are active in ISO TC 59, which captured environmental performance in building; Communication to customers by industry.
	Development s	The revision of the standard is forecast for June 2003 for a public enquiry in order to transform it into a NF standard (ratified standard). It is also a waited result from the ISO TC 59.
Conceptional features	Objective and target	The objective of the standard is to establish rules and specifications for a methodology and a model for the declaration for environmental data of construction products. It lays a common basis for the communication of information. The standard does not provide criteria for the choice, the hierarchy, or the interpretation of the information provided, since this would require precise knowledge of the context in which the information is to be used. The publication of environmental declaration is initiated by the producer.
	Applications and target groups	Users of the scheme are either individual companies (when they cover a wide part of the products sold in France), or association of companies. This is not a rule in the standard, but this is observed at the moment: declarations are rather produced by associations of producers, who produce average data for a specific building product. In the first clauses of XP P01010-1it is stated who can use this standard or the result of the use of the standard (the environmental declaration): *architects*, *designers*…, and also *consumers* (who were participating to the drafting of the standard and would use mainly the sanitary information directly). Designers and architects had been asking for a long time to producers a lot of environmental data for their projects.
	Stakeholders involved	Technical Committee P01E in AFNOR gathered members from industry, French ministries, technical experts in the building sector, builders, architects, LCA experts, and consumers. The standard specifies that the users of the French standards are both: the data provider; the data user, who must understand how the information was produced, in order to read, understand, and use it properly (in terms of systems using comparable bases). The declaration is the initiative of the industry, who may perform the LCA study itself, or commission an independent LCA consultant.
	Declaration topic	Building materials that are used in an application in a specific building.
	Type	Type III declaration, without critical review.
	Procedure	The standards part 1 and part 2 define the requirements of the scheme. Standard part 1 gathers methodological choices and assumptions that have to be followed to perform the study. Some examples are provided as well. Standard part 1 and part 2 are available in AFNOR, in French and in English. The declaration is the initiative of the industry : *the LCI/A data might be produced by the industry itself, or by an independent LCA expert commissioned by the industry, and using specific data of the industry;* *the health risk characteristics and contribution of the product to internal comfort in building are rather produced by the industry itself. It has to be noticed that specifications about comfort and health risk are also closely linked to the existing European and French regulations (and sometimes to agreed-by-state international protocols). This means it cannot be on the single will of the producer.* The standard is recent. Data producers have not forecast updates at the moment. However : *if the experimental standard, when it will become a full standard includes modifications, published data should be updated at that time;* *moreover, updated data could be published if the industry improves its products or processes;* *some producers forecast to produce data on designed for environment products in the future, to assess the improvement in comparison with the reference product.*
	Validation and verification	Internal validation and quality requirements are part of the standard part 1. The verification of the correct use of the scheme, with a critical review for instance is not mandatory, since there is no comparison between products. However, an ISO critical review has been performed by some industries.
	Presentation	The format of presentation is standardised.

		In standard part 1, inventory data are presented for the whole life cycle, and detailed step by step (production, transportation, implementation, utilisation and end of life), for the total life of the product, and for an average year. Those inventory data concern energy resources consumption, non-energy resources consumption, emissions to air, water and soil, and production of waste. An extract of the format is presented in appendix. In standard part 2, environmental impact indicators are presented, and information on the contribution of the product to control health risk and comfort aspects in the building.
	Acceptance	See status above.
	Cost to perform a profile	Any scheme, based on LCI/LCA needs at least the performing of an LCA. There are different reflections now in France (see ADEME, DRIRE, etc.) to study how to help SMI to perform such LCA/LCI at lower costs.
LCA-methodology	ISO conformity	AFNOR experimental standard XP P 01-010-1 has been developed in compliance with ISO TR 14025 (XP P01-010 is a sector-based application of ISO TR 14025). It is in compliance with ISO 14040, 41, 42 and 43.
	Methodology transparency	The standard part 1 and its annex gather definitions, methodology choices, assumption and examples that let the methodology be transparent.
	Functional unit (FU)	The functional unit is defined in the context of use of the product in a given application in a building. There is no average typical building for all construction products. However, the definition of the FU requires the definition of a building where the building is implemented. The choice of the building should correspond to the main application of the product in buildings (dwellings, or offices, or industrial buildings, etc.) The functional unit is defined (for instance 1 m^2 or 100 m^2, or else, of usage of the product in a building), with specific technical characteristics (e.g. light transmission factor, heat losses, sound insulation, etc.). The functional unit also takes into account an average year of use, which corresponds to the total impacts of the product during its life cycle (including maintenance), divided by lifetime of the product. The functional unit might precise that the product is used in France, or in Europe (importance for transportation distances and energy modelling).
	Choice of product for the declaration	The declaration might cover a specific product from a specific producer. It might also be a product group from associated producers and sellers in France of those products. The declaration must concern an actual product. This does not exclude producers to perform further calculation on products under development and use the reference actual product to assess the improvement.
	Systems boundaries and modelling of the life cycle	The cradle to grave life cycle is covered: production of the product and its raw material, packaging and transportation to the building site, implementation in the building, utilisation including maintenance and end of life of the product. Cut-off rules: mass cut-off rule of 95% of input flows is applied. This does not apply if dangerous substances (according to Directive 67/548/EEC) are used in the manufacture of the product. Transportation distances and means of transportation correspond to the average situation of distribution of the product by the producers in France. Modelling of the use phase (1): maintenance of the product during the use phase is included in the system boundaries. Energy consumption for heating the building during the use phase is excluded. Energy savings allowed by the product among the life cycle of the building, if they are included in the system boundaries, must be presented very clearly and in full transparency. Modelling of the use phase (2): specific information is required in order to take into account indoor environment. These are presented separately from the LCI data. Part 2 of standard requires information on health risk management and indoor comfort. Modelling of service life, replacements and maintenance: replacements and maintenance of products are included in the system boundaries (see above). These are based on both technical requirements provided by the producer, and practical knowledge on life of products in buildings. Modelling end-of-life scenarios: based on actual national scenario for the outcome of products at the end of life. The default scenario defined in the standard is land filling. The landfill model generally used in the declarations corresponds to an inert waste landfill, with partial leaching. Exclusion of capital goods Exclusion of transport of personnel
	Allocation	Modelling of co-products: the hierarchy proposed follows the ISO 1404x, and ISO 14049 (draft) series requirements : avoid allocation, either by collecting more detailed data, or extend the system

		boundaries; if allocation cannot be avoided, prefer allocation on a physicochemical relationship (mass, energy content, etc.). Modelling of product recovery or recycling, either during the production process or at the end of life; if it is closed loop recycling or re use : no specific methodological treatment; if it is open loop, either extension of system boundaries (if recycled once), either use a calculation rule that takes into account the number of recycling.
	Main indicators underlying the scheme	Part 1 of the standard produces Life Cycle Inventory data. Part 2 of the standard includes some indicators, common for all construction products: some inventory flows (energy resources consumption, non energy resources consumption, water consumption, waste production); climate change, calculated from CO_2, CH_4 and N_2O emissions, and using CML 2000 characterisation factors; acidification, using CML 2000 method; air pollution, using an equivalency calculation performed with limited level of regulated emissions; water pollution using an equivalency calculation performed with limited level of regulated emissions. Part 2 of the standard also includes some indicators that might be relevant only for some construction products: soil contamination (qualitative); ozone layer depletion, using CML 2000 method; photochemical oxidant formation, using CML 2000 method; biodiversity (transparent information to be provided). Part 2 of the standard also includes health risk characteristics and contribution of the product to internal comfort (see above). Air pollution and water pollution indicators are linked with French regulations (threshold level of emissions). Hazardous substances, according to Directive 67/548/EEC, should appear in the complete inventory of the part 1 of the standard. The standard specify that no cut-off rule can be applied on hazardous substances. However, hazardous substances do not appear as core indicators in the results. Health and safety issues are taken into account by two means in the standard: in part 1, air, water, and soil emissions are provided at two levels for the implementation and utilisation steps : as part of the whole life cycle (e.g. upstream emissions from the production of the glue, or electricity to clean …), and as well as specific emissions for health and safety issues for the workers (emissions when gluing) and the inhabitants. The latest should be documented by studies performed by the industry on the behaviour of their products in buildings. That might include the risk approach, which supposes a transparent scenario to be defined to be in accordance with ISO 14020. in part 2, with the data on health risk characteristics and contribution of the product to internal comfort.
	Data sources	Part 1 of the standard propose reference data for generic data: for electricity, it corresponds to French electricity model. The standard provides with data on the breakdown of energy sources in France in 1998, and energy efficiency of the power station; for fossil fuel, NCV are provided; reference inventory for the supply and combustion of main fuels are also provided in the standard. Those data are based on ETHZ and Ecobilan work on nuclear fuel cycle. Data are provided for light fuel oil, heavy fuel oil, lignite, coal and natural gas. For upstream data (raw material used to produce the building product), the request for specific data from the furnisher of the producer should be tries whenever possible. Otherwise literature data generally accepted in LCA are used (APME, Buwal, ETHZ, FEFCO, IISI, etc.) No generic model is proposed for end of life landfilling. Data specific to the process of production come from the industry that launches the declaration, either from a single producer, either average data when the declaration is performed by an association of producers.
	Data quality requirements	Data quality is ensured by the level of transparency required on the study (data sources, cut off rules, etc.). Moreover, the producer must provide explicit information of data quality. Specific known emissions from the producer process must be described in any cases (even with estimations; no data gap allowed).

		All producer information shall be justified (part 1) and measures, controls, etc. performed by laboratories (for example) should be indicated (with the reference document that was used). When the LCA is commissioned to an LCA expert, data quality process within its company provides useful information. Data representativeness is dealt in the standard, requiring for data in accordance with the functional unit and system boundaries: geographical, time related and technological representativeness. In case of group averages, what has been done is a mass balance based on volume of production between data of each producer. When such average are performed, the rules of calculation that have been used are made clear in the declaration (in accordance with ISO 14020). For completeness, the input data should be complete. However, a 95% cut off rule is allowed throughout the lifecycle (except for dangerous substances, according to Directive 67/548/EEC).

10.3 The Construction Product Directive (CPD) (Council Directive 89/106/EEC)

The Construction Product Directive (CPD) (Council Directive 89/106/EEC) (URL4) was developed to standardise the construction products across the EU member states, and aimed at removing the technical barrier of international trade in construction products. The CPD contains the following main elements:

- General product requirements;
- A system of harmonised technical specification (products standards and technical approvals);
- An agreed system of Attestation of Conformation (AOC) for each product family (with the product specifications);
- A framework of Notified Bodies;
- The CE marking of construction products.

The CPD tries to harmonise the methods of test, the methods of product performance values, and the method of conformity assessment. Nevertheless, the national regulators are allowed to determine the required values for the intended uses.

10.4 M/350 EN standardisation mandate to CEN

The goal of the commission (URL5) is to provide an approach to voluntarily providing environmental information for supporting the construction of sustainable works. The similar work is currently being undertaken by ISO TC59/SC17 for sustainability in building construction. However, this commission was initiated to cover areas that will not be agreed or elaborated within the ISO committees. The works undertaken in this mandate are as follows:

Section 1: Framework Standard

- A framework standard for integrated environmental building framework, which is intended to provide the methodology for the assessment and the subsequent declaration of the integrated environmental performance of complete buildings and construction works.
- A horizontal standard on the aggregation of LCA results of individual materials into the building.

Section 2: Building Products and Materials Related Standards

- A horizontal standard on the LCA methodology for building products/materials – including data quality of LCI data
- A horizontal standard on the communication format/EPD: Business-to-business.

- A horizontal standard on the communication format/EPD: Business-to-consumer.
- A technical report on generic data

Section 3: Construction and Demolition Processes Related Standards

A technical report on the assessment of the environmental performance of the construction process of a building

A technical report on the assessment of the environmental performance of the end of life phase process (demolition, recycling, waste treated process) of a building and products.

Section 4: Building Operation Related Standards

A technical report on the assessment of issues of building products related to the life time of the building (service life, durability, design, maintenance and replacement).

The workgroup CEN/TC 350 (2006) has been set up, and the work currently being undertaken are shown in Table 10.1.

Table 10.1 – Works undertaken by CEN/TC 350 (extracted from http://www.normapme.com).

Project Reference	Title	Target Date of Completion
00350001	Sustainability of construction works - Framework for assessment of buildings	2007-07
00350002	Sustainability of construction works - Assessment of environmental performance of buildings - Calculation methods	2008-02
00350004	Sustainability of construction works - Environmental product declarations - Product category rules	2009-05

10.5 Reports by Working Group for Sustainable Construction

The Working Group for Sustainable Construction of European Commission, which was set up for promoting environmentally friendly construction materials and energy efficiency in buildings, and waste management, have produced three strategy reports on these areas (Table 10.2). In the reports, relevant information, references and recommendations are provided.

Table 10.2 – Reports produced by task groups

Report	Summary
Task Group 1: Environmentally Friendly Construction Materials (EFCM)	The environmental impacts of materials, and the main preventative and remedial measures already in place are listed. Analysing what the construction materials industry has achieved in improving its environmental performance. Recommendations on how the industry can further improve are made.
Task Group 2: Energy Efficiency in Buildings	The objective of this strategy paper is to accelerate the installation of appropriate energy efficiency measures in all kinds of existing and new buildings, including specific actions for common and co-ordinated policies and measures at community, Member State and industry level.
Task Group 3: Construction and Demolition Waste Management	The main purpose is to provide recommendations to the WG Sustainable Construction on how to improve construction and demolition waste management.

11 Life cycle assessment - principles and framework

Life cycle assessment (LCA) is a systematic approach to systematically measuring the potential environmental impacts of a product of service throughout its lifecycle. LCA considers the potential environmental impacts throughout a product's life cycle (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. LCA can assist in the following aspects:

- Identification of improvement opportunities for the studied product or service throughout its whole life.
- Decision-making in industry, governmental and non-governmental organizations.
- Selection of relevant environmental performance indicators and adequate measurement techniques.
- Marketing opportunities for products, e.g. an environmental claim, eco-labelling scheme, or environmental product declaration (EPD).

In the building industry, LCA is usually employed to compare different design alternatives of a new building, or to assess the environmental performance of an existing building. Four ISO standards have been developed specifically for LCA:

- ISO 14040: Principles and framework;
- ISO 14041: Goal and scope definition and inventory analysis;
- ISO 14042: Life cycle impact assessment;
- ISO 14043: Interpretation.

11.1 Phases of LCA in ISO 14040

According to ISO 14040, LCA is divided into four phases:

- Goal and scope definition;
- Inventory analysis;
- Impact assessment;
- Interpretation.

As illustrated in Figure 11.1, LCA is essentially an iterative process. Adjustment may need to be made as the study progresses and additional information is collected as a consequence.

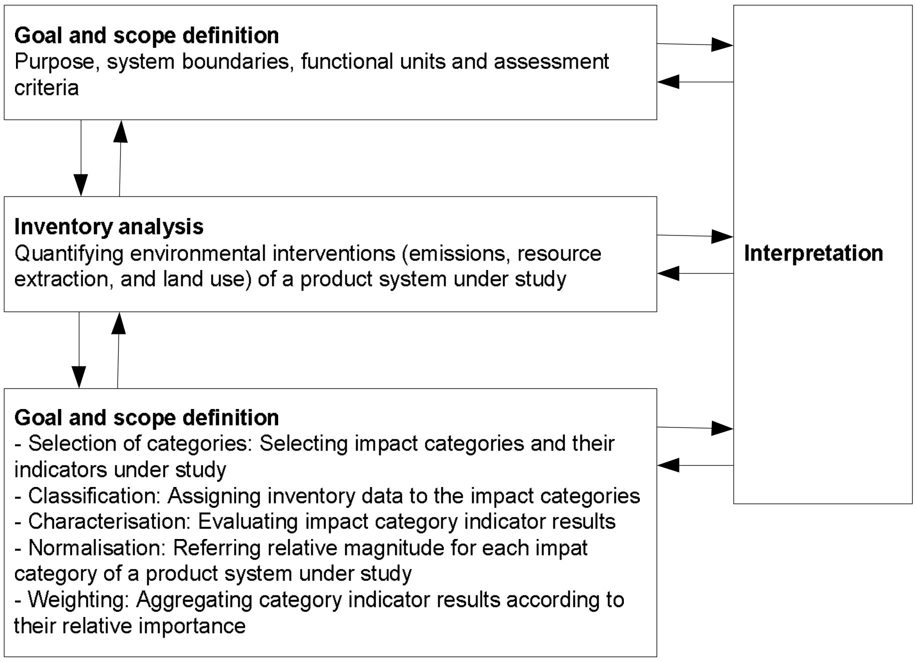

Figure 11.1: Life-cycle assessment framework in ISO 14040:1997.

11.2 Goal and scope definition

The goal and scope definition is the first step in LCA. The subsequent steps of LCA should be consistent with the goal and scope defined. ISO 14041 states that the goal of any study shall unambiguously state the intended application, the intended audience, and the reasons for carrying out the study. The scope defines the important elements of the methodology used in LCA. Since LCA is an iterative process, the initial definitions can still be modified in the later stage when more information is available. Elements that should be considered and stated clearly include:

- The function of the product system.
- The functional unit.
- The system boundaries.
- Allocation procedures.
- Type of impact assessment methodology and interpretation to be performed.
- Data requirements.
- Assumptions and limitations.
- Data quality requirements.
- Type of critical review, if any.
- Type and format of the report required for the study.

Functional unit

The functional unit is an important element of LCA. The functional unit is a measure of the function of the system for comparing and evaluating different systems. It is sometimes difficult to define the functional unit if two systems have totally different performance measures.

System boundaries

A product system tends to interrelate with other systems, and taking all the correlations into consideration will make the calculation too massive and complex.

The system boundaries determine which unit processes to be included in the LCA study. Subjective judgement is sometimes required to define the system boundaries in the initial stage. The following boundaries can be considered:

- Boundaries between the technological system and nature. A life cycle usually begins at the extraction point of raw materials and energy carriers from nature. Final stages normally include waste generation and/or heat production.
- Geographical area. Geography plays a crucial role in most LCA studies, e.g. infrastructures, such as electricity production, waste management and transport systems, vary from one region to another. Moreover, ecosystems sensitivity to environmental impacts differs regionally too.
- Time horizon. Boundaries must be set not only in space, but also in time. Basically LCAs are carried out to evaluate present impacts and predict future scenarios. Limitations to time boundaries are given by technologies involved, pollutants lifespan, etc.
- Boundaries between the current life cycle and related life cycles of other technical systems. Most activities are interrelated, and therefore must be isolated from each other for further study. For example production of capital goods, economic feasibility of new and more environmentally friendly processes can be evaluated in comparison with currently used technology.

Data quality requirements

The accuracy and reliability of the results from LCA studies relies on the extent to which data quality requirements are met. The following parameters should be taken into account:

- Time-related coverage.
- Geographical coverage.
- Technology coverage.
- Precision, completeness and representativeness of the data.
- Consistency and reproducibility of the methods used throughout the data collection.
- Uncertainty of the information and data gaps.

Allocation

The processes usually contain more than one function or output. The environmental load of a process should be allocated over the different functions. The following recommendations are available for allocation:

- Wherever possible, allocation should be avoided, by splitting the process in such a way that it can be described as two separate processes that each has a single output.
- Where allocation is not avoidable, inputs and outputs should be partitioned between its different functions or products in a way that reflects the underlying physical relationships between them.
- If the latter is not possible, allocation should be carried out based on other existing relationships (e.g. in proportion to the economic value of products).

The last option is usually used, since it conveniently relates waste to the economic outputs, and it states the relative importance of an output.

11.3 Life cycle inventory (LCI) analysis in ISO 14041

This phase is the most demanding part of LCA. LCI comprises all stages dealing with data retrieval and management (Figure 11.2). The data can be categorised into:

- Foreground data, which refers to very specific data required to model the system. The data are usually acquired by conducting questionnaire surveys.
- Background data, which is data for generic materials, energy, transports and others. This category of data can be obtained from LCI databases such as Ecoinvent and IVAM.

The data collection forms for foreground data must be properly designed for optimal collection. Subsequently data are validated and related to the functional unit in order to allow the aggregation of results. Data from other studies can be reused to reduce the effort required. However, it is necessary to ensure that the data are representative.

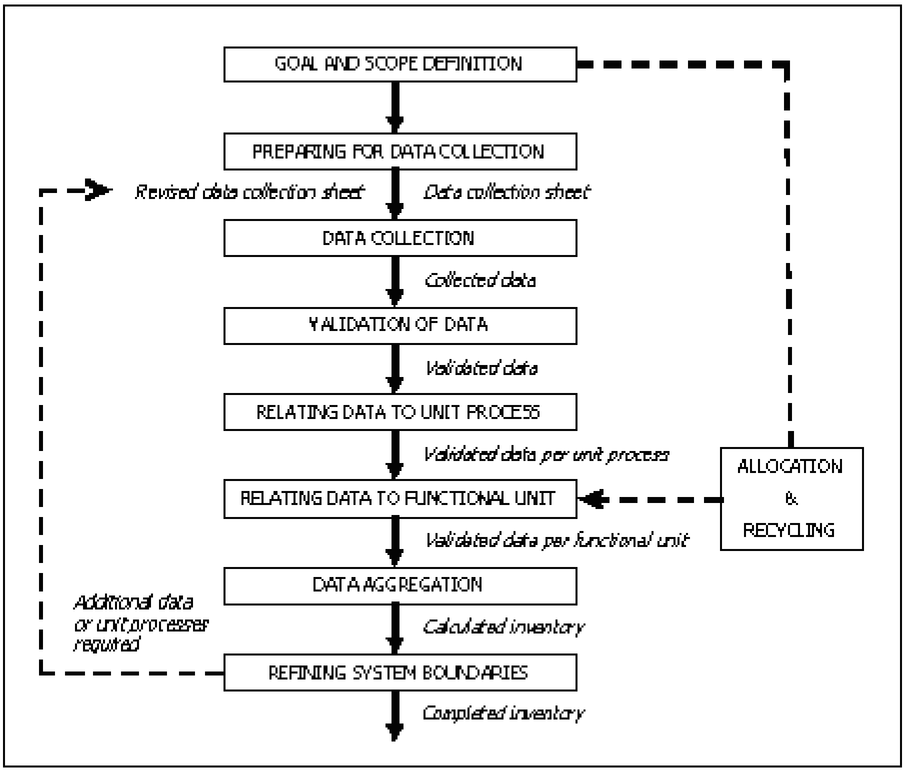

Figure 11.2: Data collection and management process defined in ISO 14041:1998(E)

11.4 Life cycle impact assessment (LCIA) in ISO 14042

The purpose of Life Cycle Impact Assessment (LCIA) is to assess the LCI of a system for evaluating its environmental impacts. Assessors usually select the available assessment methodologies such as Eco-Indicator 99 and CML 2001 to perform LCIA. According to ISO 14042, this phase is divided into the following steps:

Mandatory elements:

- Selection of impact categories, category indicators and characterisation models.

- Classification: Assignment of individual inventory parameters to impact categories, e.g. CO_2 and CH_4 are assigned to the "Global Warming" impact category, while SO2 is assigned to the "Acidification" impact category.
- Characterization: Conversion of LCI results to common units within each impact category, so that results can be aggregated into category indicator results.

Optional elements:

- Normalisation: The magnitude of the category indicator results is calculated relatively to reference information, e.g. the CO_2 emission in year 2000 is used as a base line to assess the CO_2 emission in the future. The existing value can be divided by the base value for obtaining an index value.
- Weighting: Indicator results coming from the different impact categories are converted to a common unit by using factors based on value-choices. Weights are usually assigned subjectively, and the values sometimes cause controversies, especially for the mid-point assessment methods (see Chapter 12 for mid-point assessment methods), since the number of indicators to be evaluated is usually large.
- Grouping: The impact categories are assigned into one or more groups sorted after geographic relevance, company priorities etc.

11.5 Interpretation in ISO 14043

The LCA results are interpreted in relation to the goal definition phase of the LCA study, involving review of the scope of the LCA, as well as the nature and quality of the data collected.

The aim of the interpretation phase is to reach conclusions and recommendations in accordance with the defined goal and scope of the study. Results from the LCI and LCIA are combined together and reported in order to give a complete and unbiased account of the study. The interpretation is to be made iteratively with the other phases.

The life cycle interpretation of an LCA or an LCI comprises three main elements:

- Identification of the significant issues based on the results of the LCI and LCIA phases of a LCA.
- Evaluation of results, which considers completeness, sensitivity and consistency checks.
- Conclusions and recommendations.

In ISO 14040, it is recommended that a critical review should be performed.

12 Facility environmental and performance data

The life cycle of a building project usually involves different activities, which consume resources (inputs) and release waste (outputs) to the environment. The environmental impacts due to these inflows and outflows can be modelled and measured using life cycle assessment (LCA). A LCA process consists of four iterative steps: goal and scope, life cycle inventory (LCI), impact assessment and interpretation. The goal and scope defined is used as a guideline for consistently implementing LCA. Data collection in the step of life cycle inventory is the most demanding task. Although background LCI databases have been developed, not all the processes or materials to be analysed are readily available, and certain data may not be representative or up-to-date. This chapter elaborates on the quality requirements and sources of LCI data (LCI) and the life cycle impact assessment (LCIA) methods available. Apart from the ISO 14040 series, a useful guideline on LCA has been published by European Energy Commission (1997).

12.1 LCI data quality

LCA involves the development of a model for assessing the environmental impacts of a product. The accuracy of the results is largely dependent on the quality of the LCI data used. LCI for a complex process can contains thousands of unit processes (Bretz, 1998), and the data are usually derived from various sources. The quality of data has been discussed in the past (Weidema, 1998). Table 12.1 provides a list of data quality indicators proposed in the literature (URL6) for investigating the data quality, in which some of them have been mentioned in Chapter 10. Erixon et al. (2003) proposed a similar set of data quality dimensions, as displayed in Figure 12.1.

Table 12.1 – Indicators for LCI data quality.

Category	Indicator	Remarks
Accuracy	Statistical representivity	The size of population or the length of time in the measurement
	Age of data	How old is the data?
	Acquisition method	Actual measurement or theoretical calculation.
Completeness	Exhaustivity of the flows	The inclusion of all signication flow.
	Aggregation level of the flows	How are the flows aggregated?
	Mass balance at process level	
Representivity	Geographical representivity	
	Time representivity	
	Tehnological representivity	
Repeatability	Transparency	
	Coherence	
Variability	Variability	Data should be provided with a range of possible values.

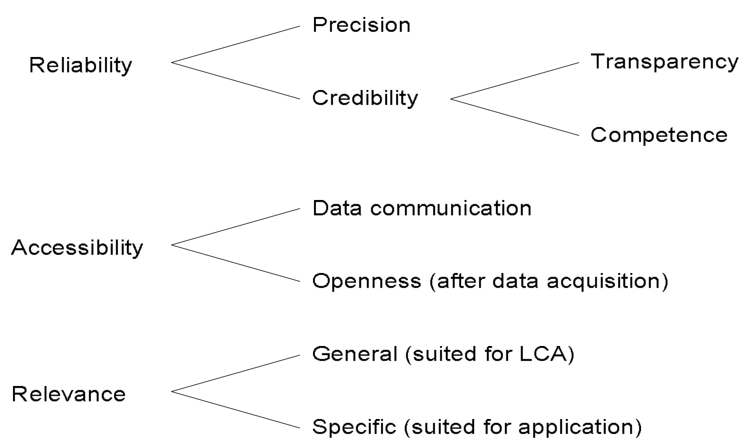

Figure 12.1: The data quality dimensions.

12.2 Life cycle inventory database

Environmental institutions have taken the initiative to develop LCI background database, in order to provide standard data to LCA assessors. The databases are continuously updated and maintained in order to ensure that the LCI data are up-to-date, consistent, and reliable. Some databases provide regional data, while others only contain national data. The available LCI databases usually also provide the facility for life cycle impact assessment (LCIA) based on the common assessment methodologies, such as Eco-indicator 99 and CML 2001.

12.2.1 Ecoinvent

The ecoinvent database (URL7) covers more than 2500 processes for areas, including energy, transportation, waste disposal, construction, chemicals, detergents, paper and board, agriculture and waste management. It is the most widely used LCI database in Europe, and the data are valid for Swiss and Western European conditions. The different categories of data are updated and maintained by different Swiss institutions (Figure 12.2).

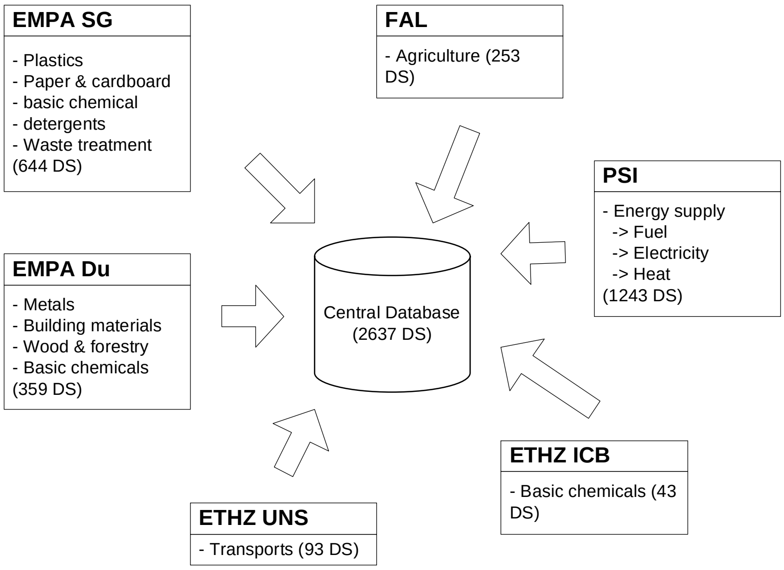

Figure 12.2: Ecoinvent database.

Each process is available in two versions, i.e. unit processes and system processes. A unit process contains only emission and resources inputs from one process steps, and references to input from other unit processes. In a system process, the emissions from all the phases are included in a black-box format. Ecoinvent is linked to LCA tools such as EQUER, SimaPro, and GaBi 4.

12.2.2 Gabi 4

GaBi 4 Professional database (URL8) includes approximately 650 sets of data, compiled by IKP/PE. The data were developed based on the cooperation with industries, patent and technical literature. The areas covered include metals, organic and non-organic pre-products, synthetics, minerals, provision of energy (steam, thermal energy, electricity mixes and power stations), end of life and disposal processes. 15 extension database modules for specific needs are also available for purchase individually.

12.2.3 IVAM

The IVAM database (URL9) consists of about 1350 processes, leading to more than 350 materials. The data can be used for LCA applications in various sectors. In the data, material production is further split into individual process sub-steps. The majority of the LCI data were gathered during previous LCA research by IVAM, and most of the data are applicable to Western Europe.

12.2.4 Boustead Model

The Boustead Model (URL10) is a computer modelling tool for lifecycle inventory calculations. There are three main groups of files: the program files, the core data files, and the top data files, as shown in Figure 12.3.

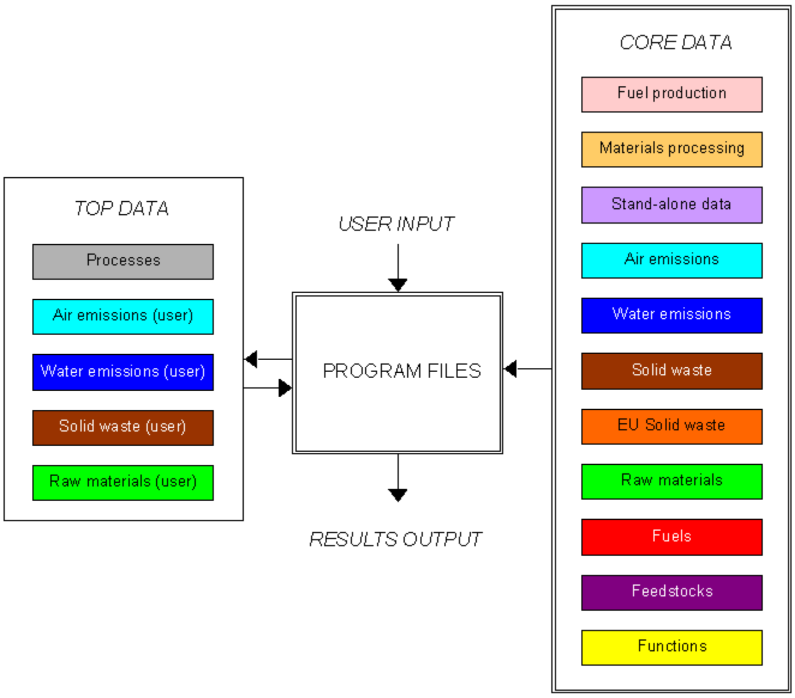

Figure 12.3: Structure of the Boustead Model showing the three main groups of files.

The program files consist of user interfaces to accept inputs and to show outputs. The top data files are used to store the information for unit operations created by the user. The user usually creates the data, which are not readily available in the core database. The core data files contained information on a range of different fuel production and materials processing operations. Table 12.2 shows the files kept in the core.

Table 12.2 – Files stored in the core of the Boustead model.

File	Description
Fuel production	The records in this file contain fuel production data for almost all of the countries around the world as well as data for the different regions of the USA and Canada.
Materials processing	The records in this file contain actual production data for a wide variety of materials processing and transport operations.
Stand-alone data	The records in this file contain information on materials production operations, usually averaged over a number of different production plants. This type of information usually refers to bulk commodity materials, which are bought on the open market but the source is usually unknown.
Air emissions	The records in this file contain the names of the air emissions used in the materials processing, fuel production and stand-alone operations.
Water emissions	The records in this file contain the names of the water emissions used in the materials processing, fuel production and stand-alone operations.
Solid waste	The records in this file contain the names of the solid waste categories used in the

	materials processing, fuel production and stand-alone operations. This is an empirical list containing the main categories of solid waste that can usually be identified by process operators. It essentially identifies the wastes that are generated by the process.
EU solid waste	This file therefore lists all of the EU categories published by the EC. This file essentially categorises the solid wastes by the way in which they may be handled and subsequently used for other purposes.
Raw materials	The records in this file contain the names of the raw materials used in the materials processing, fuel production and stand-alone operations.
Fuels	The records in this file contain the names of the fuel types used in the materials processing, fuel production and stand-alone operations.
Feedstocks	The records in this file contain the names of the feedstock types used in the materials processing, fuel production and stand-alone operations.
Functions	The records in these files are essentially instructions to force the computer to manipulate data in specific ways. The use of these functions is discussed in more detail later.

The database within the model holds information on a large number of unit operations. A unit operation is defined as a process which produces a single product. Reference to any unit operation is made using the code number of the record as a reference.

12.3 Life cycle assessment indicators

Life cycle assessment is part of sustainability assessment, which covers the environmental, social and economic dimensions. Global Reporting Initiative (URL11) has published a report, Sustainability Reporting Guidelines, which aims at assisting organisations in articulating and understanding contributions of the reporting organisation to sustainable development. Core and additional indictors for environment, social and economic aspects are systematically listed. European governments have also taken the initiative to develop sustainability assessment frameworks. An example of sustainability indicators in the UK's shared framework sustainable development, which was developed by DEFRA (2005), is shown as follows:

- Greenhouse gas emissions: Kyoto target and CO_2 emissions
- Resource use: Domestic Material Consumption and GDP
- Waste: arising by (a) sector (b) method of disposal
- Bird populations: bird population indices (a) farmland bids (b) woodland birds (c) birds of coasts and estuaries
- Fish stocks: fish stocks around the UK within sustainable limits
- Ecological impacts of air pollution: area of UK habitat sensitive to acidification and eutrophication with critical overloading
- Rive quality: rivers of good (a) biological (b) chemical quality
- Economic output: Gross Domestic Product
- Active community participation: civic participation, informal and formal volunteering at least once a month
- Crime: crime survey and recorded crime for (a) vehicles (b) domestic burglary (c) violence
- Employment: people of working age in employment
- Workless households: population living in workless households (a) children (b) working age
- Childhood poverty: children in relative low-income household (a) before housing costs (b) after housing costs
- Pensioner poverty: pensioners in relative low-income households (a) before housing costs (b) after housing costs
- Education: 19 year olds with level 2 qualification and above

- Health inequality: (a) infant mortality (by socio-economic group) (b) life expectancy (by are) for men and women
- Mobility: (a) number of trips per person by mode (b) distance travelled per person per year by broad trip purpose
- Social justice
- Environmental equality
- Well being

LCA only focuses on assessing the environmental performance. There is a wide range of impact category indicators. Generally, the indicators are categorised according to the endpoints. Endpoints are also known as damage categories, including Human Health, Ecosystem Quality, Climate Change and Resources. They are the issues of environmental concern. ISO 14042 advises that endpoints should be selected carefully. The indicators are the measures between the emissions and resource extraction parameters from LCI and the damage categories, and thus, they are also referred to as midpoints. All the impact category indicators in a category normally have the same units of measurement. There are two categories of assessment methods available (Jolliet et al., 2002):

- Classical impact assessment or midpoint methods, which quantifies the results in the early stage in the cause-effect chain to limit the uncertainties, and group LCI results in so-called midpoint categories according to themes like climate changes. CML 2001 is an example of these methods.
- Damage oriented methods, which try to model the cause-effect chain up to the endpoint, or damage, sometimes with high uncertainties. Eco-indicator 99 and EPS 2000 belong to this category.

12.3.1 Eco-indicator 99

Eco-indicator 99 (Goedkoop and Spriensma, 2000) is a damage oriented method, since its impact category indicators are defined close to three damage categories, i.e. Resources, Ecosystem Quality, and Human Health (Figure 12.4). The method is made up of three steps:

- Damage factors for the pollutants or resource uses are calculated for the impact categories.
- Normalisation of the impact factors.
- Weighting of the three damage categories and calculation of weighted Eco-indicator 99 damage factors.

The weights for the damage categories are proposed in the Eco-indicator report. Nevertheless, without the last step, the outputs for three categories will be presented.

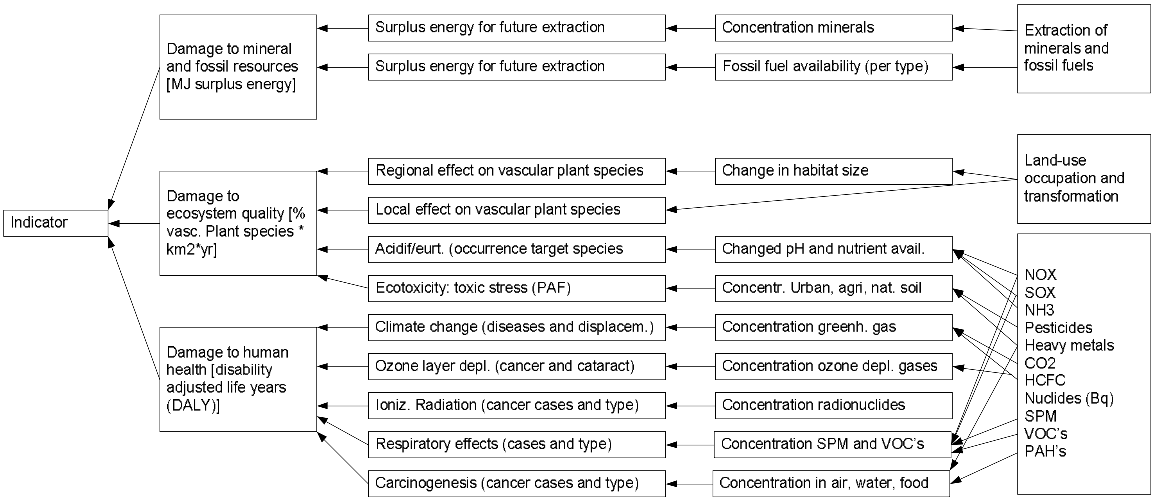

Figure 12.4: Eco-indicator 99 methodology.

12.3.2 CML 2001

CML 2001 is a midpoint method (Goedkopp et al., 2006). The impact category indicators selected are relatively closer to the LCI emission. The indicators in CML include acidification potential, climate change, eutrophication potential, freshwater aquatic ecotoxicity, freshwater sediment ecotoxicity, human ecotoxicity, marine sediment ecotoxicity, photochemical oxidation (summer smog), resources, stratospheric ozone depletion, and terrestrial ecotoxicity (Althaus, 2004).

12.3.3 EPS 2000

The EPS 2000 impact assessment method (URL12) is the default method in the EPS system, which is used for comparing products in the product development process. It is a damage-oriented method, and adopts a top-down approach, i.e. more important issues are considered first, followed by less important ones. The following five safe guard categories are selected: human health; ecosystem production capacity; biotic stock resources; bio-diversity; and cultural and recreational values.

The assessment makes use of indexes. The inventory results of individual flows for an activity will be multiplied by pre-fixed weighting factors, and summed up to produce a single total value. The prefix weighting factors have the units of Environmental Load Units (ELU) according to the willing to pay (WTP) to restore impact on the safeguard subjects as an OECD inhabitant. Hence, ELU can be measured in the monetary term, and 1 ELU is assumed equivalent to 1 Euro.

12.3.4 IMPACT 2002+

The IMPACT 2002+ LCIA methodology (Jollient et al., 2003) proposes a feasible implementation of a combined midpoint/damage approach. It links all types of LCI results via 14 midpoints to four damage categories (Figure 12.5). New concepts and methods have been developed in IMPACT 2002+, especially for the comparative assessment of human toxicity and ecotoxicity. Human Damage Factors are calculated for carcinogens and non-carcinogens, employing intake fractions, best estimates of dose-response slope factors, as well as severities. The transfer of contaminants into the human food is no more based on consumption surveys, but accounts for agricultural and livestock productions levels. Indoor and outdoor air emissions can be compared and the intermittent character of rainfall is considered. Both human toxicity and ecotoxicity effect factors are based on mean responses rather than on conservative assumptions. Other midpoint categories are adapted from the methods Eco-indicator 99 and CML 2002. all midpoint scores are expressed in units of a reference substance and related to the four damage categories: human health, ecosystem quality, climate change, and resources. Normalisation can be performed either at midpoint or at damage level.

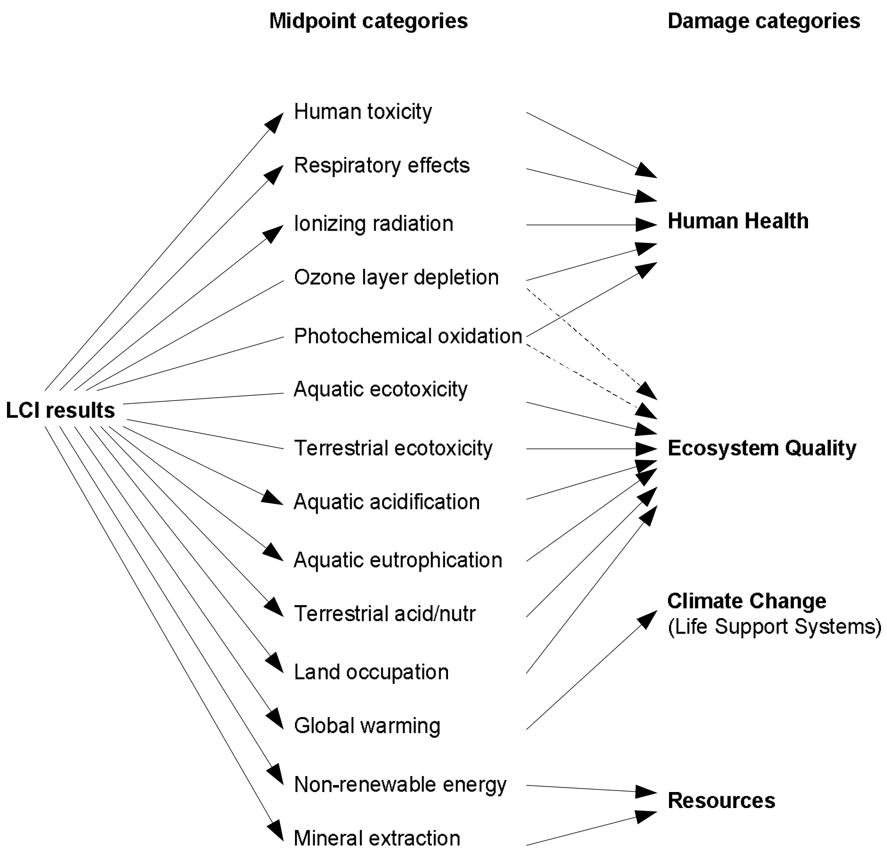

Figure 12.5: The overall scheme of the IMPACT 2002+ framework (adopted from Jolliet et al., 2003).

12.3.5 EDIP

EDIP97 (URL13) is a midpoint approach covering most of the emission-related impacts, resource use and working environment impacts with normalisation based on person equivalents and weighting based on political reduction targets for environmental impacts and working environmental impacts, and supply horizon for resources. It is site-generic, and the exclusion of spatial information sometimes lead to erroneous results. In view of this, EDIP2003 was developed to support spatial characterisation, and can be used for either site-generic or site-specific modelling (URL14). It also covers a larger part of the cause-effect. Some of the category indicators are selected closer to the endpoints. Thus, EDIP2003 lies closer to the damage-oriented approach.

13 Life cycle costing (LCC) and life cycle assessment (LCA) IT tools and methods

Life cycle costing (LCC) and life cycle assessment (LCA) involve certain core steps for generating the necessary outcomes for measuring the economic and environmental performance for buildings. Although the standard for LCC, ISO 15686-5 is currently being drafted, LCC has long been implemented in the construction industry. The standards for LCA, which include ISO 14040, ISO 14041, ISO 14042, and ISO 14043, structurally define the necessary steps for LCA. IT tools have been developed for facilitating the LCC and LCA processes. Assessment methods for rating how environmentally friendly a building is have also been developed. This chapter provides the information on the common LCC and LCA tools available for the construction and building industry.

13.1 LCC tools without LCA

The life cycle costing (LCC) process involves simple but tedious cost calculation. Thus, IT tools have been developed for facilitating the cost quantification and decision making processes. The following LCC tools have been reviewed and shown in Appendix A:

- ACEIT (http://www.aceit.com);
- Ampsol (http://www.ampsol.com);
- Bid-Builder (http://www.bid-builder.co.uk);
- BLCC 5.3 (http://www.eere.energy.gov);
- Kostenreferentiemodel (http://www.sbr.nl);
- LCCID (http://www.wbdg.org/tools/lccid.php);
- LCProfit (http://www.statsbygg.no);
- LCCWare 3.0 (http://www.isograph-software.com/index.htm);
- PARAP (http://www.bk.tudelft.nl/reh/projects/parap/);
- RealCost 2.1 (http://www.fhwa.dot.gov/infrastructure/asstmgmt/rc2104.htm);
- Relex LCC (http://www.relexsoftware.co.uk).

Some of the LCC IT tools for construction are available for free. Commercial LCC tools usually provide some advanced function, such as integration with CAD tools. Certain commercial LCC tools are generic, and are usually used in the manufacturing and production industry. These tools require the formulation of equations for quantifying the life cycle costs for construction projects. Hence, additional efforts are needed if these tools are selected.

All the tools provide Net Present Value (NPV) as the primary measures for the projects. BLCC 5.3, which was developed by National Institute of Standards and Technology (NIST), also provides other measures such as NS and SIR. Most of the tools only generate deterministic results, though it is recognised in the TG4 report that uncertainties and risks should be taken into account in the LCC process. Among the tools, BridgeLCC 2.0 provides the functions of Monte Carlo simulation and sensitivity analysis. Nevertheless, its application is only limited to bridge construction, based on the American standard. In addition, fuzzy models, which have been advocated for its ability to accommodate subjectivities and ambiguities (Kishk, 2001), are not adopted in the developed tools.

It is necessary to remind that some tools were developed based on the LCC standards of certain countries. Hence, changes, if allowed in the software package, must be made if one of these tools is to be adopted in other country.

13.2 LCC methods with LCA

Since sustainability is becoming an important issue, certain LCC tools have attempted to provide the environmental impact assessment function. EuroLifeForm is a European RTD project for developing a risk-based, probabilistic LCC tool (URL15). It consists of three distinct elements: a probabilistic life cycle cost model, a probabilistic deterioration model and a decision support application. Cost inputs are defined in the form of probability distribution functions (pdf's). The program was developed in MS Excel VBA, and add-on @Risk was used to perform Monte Carlo simulation to produce statistical outcomes. The environmental impacts are difficult to be valued in monetary terms, and thus, multi-criteria decision-making that takes into account both impacts was attempted using the software, Logical Decision5.1 (TG4, 2003). The user can optimise the results by providing his priorities and weights between the criteria.

EcoProP, which was developed by VTT, is a software tool for systematic management of building project requirements. The system consists of 12 assessment categories (classification of building properties) - eleven at the building level and one process related:

- Conformity to business process: core processes, supporting processes, and corporate image.
- Life cycle costs: investment costs, service costs, maintenance costs, and refurbishment costs.
- Location: site characteristic, transportation, services, and land use.
- Indoor conditions: indoor climate, acoustics, and lighting.
- Service life and deterioration risk.
- Adaptability.
- Environmental burdens during operation: a) energy and water consumption, emissions of the building; b) users' energy and water consumption, emissions.
- Embodied environmental loads: energy and raw content, emissions, and recycling.
- Safety: structural safety, fire safety, security in use, intrusion protection, natural catastrophes, and comfort.
- Loadings to immediate surroundings
- Process requirements.

The system is primarily addressed to clients (owners and developers) in the early phases of development and design of buildings. It can be also applied to other users and also in other phases of the process. A limitation identified is the assessment principles for many of the individual criteria are subjective.

13.3 LCA Methods and Tools

In the building industry, life cycle assessment (LCA) is used to systematically assess the environmental performance of buildings throughout their life cycles. Various LCA tools, in which many of them were developed in Europe and North America, are available for helping designers/architecture design 'greener' buildings and for assessing the environmental impact of existing buildings. Basically, these tools evaluate issues of concern, such as the protection of human health and ecosystems, and the efficient use of resources.

Most of the LCA tools are computer-based models providing life cycle impact assessment (LCIA), while others, such as BREEAM, are methodologies available in the form of reports. With the use of the LCA software tools, the user only needs to provide the necessary inputs, and does not have to worry about the computation of performance measures. There are estimated to be over 200 LCA software packages currently being used. Many LCA tools are commercial products. The tools usually contain regional product databases for more accurately assessing buildings in the particular regions. The life cycle inventory database, Ecoinvent, which are developed and maintained by Swiss Centre for the Life Cycle Inventories, are more commonly adopted. In the absence of certain required input data, assumptions available in the tools can be utilised.

Generally, the tools adopt either bottom-up approach or top-down approach in the assessment process (Erlandsson and Borg, 2003). The former focuses on material selection, and then assesses the total impact by combining the selected building materials. The latter first selects the shape and size of a building, followed by specifying the materials used. Among the LCA tools evaluated in the review, the bottom-up approach is more commonly used. A 3-level classification system (Trusty, 1999) has been proposed to classify the LCA tools based on their areas of application:

- Level 1 refers to product comparison tools and information sources. The tools are primarily used in the procurement stage, and the examples of Level 1 tools are BEES and TEAM.
- Level 2 are for whole building decision support tools. The tools are used for assessing certain area(s) of concern, such as operating energy and life cycle environmental effects. The tools for Level 2 include EQUER and Envest.
- Level 3 encompasses whole building frameworks, such as BREEAM and ECOPROFILE. The frameworks make use of the information generated from the Level 2 tools, and cover broad sustainability aspects such as environment, economic performance, and social issues.

The tool information is mainly drawn from the literature reviews available on the internet (URL16; URL17: URL18), the product websites, and the evaluation of available demonstration versions of LCA tools. The purpose of the review is to give the reader a general idea about the tools in terms of their type, area of application, input required, and output generated. The information of the following LCA tools is provided in Appendix A:

- Environmental Impact Estimator 3.0 by Athena (http://www.athenasmi.ca/);
- BEAT 2002 (http://www.sbi.dk/en/publications/programs/beat-2002);
- BEES 3.0 (http://www.bfrl.nist.gov/oae/software/bees.html);
- BREEAM (http://www.breeam.org/);
- CASBEE (http://www.ibec.or.jp/CASBEE/english/index.htm);
- CEEQUAL (http://www.ceequal.com);
- Eco-Quantum (http://www.ivam.uva.nl/uk/index.htm);
- Ecoprofile (http://www.ecoprofile.com);
- ECOTECT (http://www.squ1.com);
- ENVEST (http://envest2.bre.co.uk);
- EQUER (http://www-cenerg.ensmp.fr);

- GaBi 4 (http://www.gabi-software.com);
- GBTool (http://www.iisbe.org);
- GREENCALC (http://www.greencalc.com);
- HQE Process (http://assohqe.org);
- LCAid (http://www.projectweb.gov.com.au/dataweb/lcaid/);
- LISA (http://www.lisa.au.com);
- LEED (http://www.usgbc.org/LEED/publications.asp);
- LEGOE (http://www.legoe.de);
- OGIP (http://www.crb.ch);
- SimaPro 7.0 (http://www.pre.nl/pre/pre_consultants.htm);
- TEAM for Building (http://www.ecobalance.com/index_uk.html).

14 Life cycle assessment (LCA) in life cycle costing (LCC)

Life cycle costing (LCC) and life cycle assessment (LCA) measure cost and environmental performance of a building respectively. Though the assessments are in different dimensions, both are important in the decision making process for building design or tender selection. Attempts have been undertaken for developing evaluation approaches that accommodate both cost and environmental elements.

Tupamaki (1998) proposed the total LCC approach, which tries to convert LCA impacts to cost, and all the LCC and LCA variables are taken into account in quantifying the cost (equation [4.1]). In equation [14.1], environmental factors refer to different environmental impacts that various materials and actions have. Occupational factors refer to health, comfort, productivity, safety and security. Location factors refer to the location of a building. Tupamaki (2005) argued that since there are already established LCA approaches that convert environmental impacts to scores like Ecopoints or equivalent CO_2, there should be a way to link the points to cost. However, this requires further research, and the links may be complex, and not directly proportional. In addition, some hidden environmental and social costs cannot be accurately quantified.

LCC = First cost (capital investment) + NPV [(use & maintenance) + (operating cost) + (major repairs + modernisation + rehabilitation) + (salvage value) + (environmental LCA factors) + (occupational LCA factors) + (location LCA factors)] [14.1]

Boussabaine and Kirkham (2004) advocated incorporating eco-costs into LCA for making well-informed decisions on improving environmental performance and investment. They also suggested that eco-costs should form part of the LCC for effectively evaluating eco-design alternatives. The proposed eco-cost model contains a cost-breakdown structure that is made up of the following items:

- Cost of controlling atmospheric emissions;
- Cost of resources (i.e. energy and water consumptions) used in the extraction and production of production;
- Cost of waste disposal;
- Cost of waste treatment including solid and other waste;
- Cost of eco-taxes;
- Cost of pollution rehabilitation measures;
- Cost of environmental management.

Eco-costs for different phases in the life cycle of a building should be quantified. However, the required environmental cost information may not be readily available. An environmental cost database that has the appropriate data structure for LCC should be developed for facilitating the tedious LCC process.

Another approach is to use multi-criteria decision making system for assessing projects. Tupamaki (2005) mentioned the incorporation of Logical Decisions 5.1, which is a software package for multi-criteria decision-making, in EuroLifeForm for assessing both environmental and cost impacts of projects.

Sterner (2002) developed a multi-attribute tender evaluation model. The two attributes to be considered alongside the tender price are life cycle energy cost and its associated environmental impact, which is represented by the environmental index (EI_X) (equation [14.2]). The approach requires the conversion of environmental index to cost. The conversion requires some subjective conversion factors, and the results will be dependent on the user's attitude.

$$TCT = f(p, LCC_E, EI_X) \quad [14.2]$$

Where

TCT = total tender price;

p = the tender sum;

LCC_E = life-cycle energy cost;

EI_X = environmental index.

Vogtlander (2001) developed the Eco-costs/Value Ratio (EVR) model that combines the value chain with the ecological product chain for product designs. EVR is defined in equation [3]. The five components of the eco-costs include 3 'direct' components and 2 'indirect' components:

- Virtual pollution prevention costs, i.e. the costs required to reduce the emission of the production processes to a sustainable level.
- Eco-costs of energy, being the prices for renewable energy sources.
- Materials depletion costs, being (costs of raw materials) × (1-•), where • is the recycled fraction.
- Eco-costs of depreciation, being the eco-costs related with the use of equipment, building and others.
- Eco-costs of labour, being the eco-costs related to labour, such as commuting and the use of the office (building, heating, lighting, electricity for computers, paper, office products, and others).

EVR = eco-costs : value [3]

The eco-cost of a product is calculated by multiplying the cost elements with the relevant EVRs. These specific EVRs have been computed on the basis of LCAs.

15 Overall conclusions from literature review

The literature review has concentrated on the existing body of knowledge in Europe. There has been a considerable research and development carried out in the field of LCL and LCA in the US, Canada and Australia. However, because the ultimate aim is to develop a methodology for the EU member countries, the New World's literature is only reviewed when it brings into light important issues.

There is an enormous amount of literature which relates to LCC and LCA. Some of it (particularly academic papers) develops numerous models of high level of technical complexity but displaying a rather low level of practicality. After investigating existing practices and case studies within Davis Langdon as well as talking to other cost consultancies (all using their unique house-developed cost models), it was discovered that the scope and range of information which clients find useful and need from the LCC calculations is not that extensive.

The methods of financial evaluation concentrate on calculating and analysing NPV, NPV, IRR/AIRR, SIR/BCR, NB/NS, basic sensitivity analysis, and top level risk assessment.

Discount rate and its influence on the outcome of the LCC calculations is another factor which is mentioned in almost all literature. However the reality is that the publicly procured projects predominantly use discount rate set by national governments/treasury/banks, (e.g. UK's current one is 3.5%). The private procurement use discount rates between 2-14%, however as the methodology is concerned with public projects, the issue of selection of the discount rate tends to be resolved.

The still open topic is the quality of data which goes into the LCC models. The facility data (environmental, performance and cost) is provided by variety of organisations. It is often incomplete and in variety of incomparable formats. The main sources of the facility data are listed in 6.3.

In order for the methodology to provide comparable results and outputs a significant amount of work is needed to normalise data in existing sources across the member countries. It needs to be continuously updated.

Risk evaluation has been researched and analysed in great details, clear division of methods into qualitative (risk registers, matrices, etc.) and quantitative (mathematical modelling of uncertainty) gives forecasters powerful tools. Clients, however use mainly sensitivity analysis results – calculations using likelihood/probability of projected values within pre-determined ranges and Monte Carlo simulation.

Motive scenarios and analysis of a range of service lives is usually considered as the most informative and useful.

Data for LCA and sustainability assessment is widely available and quite extensive. Clients however still are mainly concerned with CO_2 emissions and energy use as the two main environmental indicators.

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Appendix A: LCC and LCA Tools and Methods

DTI (2005) has commissioned a study on "Whole Life Cycle Costing" which has assembled a list of tools and guides in their Annex 2 with recommendations for targeted users, appropriateness of use in selected life stage of the facility/project with sources of further information. The list is particularly useful because it positions the tools within the life cycle. It is also comprehensive and current.

The table A.1 assembled below concentrates on the IT tools and their appropriateness for the construction sector. It assesses type of economic outputs and approach to risk.

Table A.1: LCC IT tools for the construction sector

Software	Developer	Availability	Areas of Application	Inputs	Outputs	Risk	Remark
ACEIT	Tecolote Reseach Inc., USA. www.aceit.com	Commercial (Windows)	General	WBS, inputs variables of material quantity and cost, discount rate.	NPV	SA, MCS	- It is a generic LCC tool. - A spreadsheet is used for presenting the cost structure and defining input values. - Equations are formulate to represent the relationships among variables.
Ampsol	Ampsol Ltd., UK www.ampsol.com	Free (web-based)	Buildings	Year of analysis, costs of acquisition, maintenance, and refurbishment, discount factors, and inflation rates are required.	NPV	None	- It only performs simple LCC calculation. - It cannot compare different designs.
Bid-Builder	Bid-Builder Ltd, UK. www.bid-builder.co.uk	Commercial (Windows)	Construction projects (including PFI/PPP)	BCIS and sub-elemental levels, or BOQ levels (if quantities are known)	NPV, net capital cost, annual life cycle spend	None	- What-if analysis can be performed. - It can perform up to 50-years life-cycle forecasts. - It is 'pre-configured' with industry-standard building cost data and life-cycle cost forecasts based upon a wealth of PFI life-cycle forecasting experience.

Software	Developer	Availability	Areas of Application	Inputs	Outputs	Risk	Remark
BLCC 5.3	National Institute of Standards and Technology, USA http://www.eere.energy.gov/	Free (platform-independent)	Energy and non-energy projects	Inputs similar to those for LCCID are required. Air pollution emission can also be entered.	NPV, NS, SIR, IRR, and DPB	None	- Files are saved in the XML format. - Only the energy price escalation rates in the USA are available.
BridgeLCC 2.0	National Institute of Standards and Technology, USA http://www.bfrl.nist.gov/bridgelcc/welcome.html	Free (Windows)	Bridge construction	Information similar to that for Ampsol is required. Cost elements are also required. Pdf's can be assigned to the inputs.	NPV	MCS, SA	- It is based on ASTM E917. - It helps evaluating the cost effectiveness of alternative construction materials. -It can only be used for bridge construction.
Kostenreferentiemodel	Stichting Bouwresearch, Netherland http://www.sbr.nl/	Windows	Residential buildings	Information of size, shape, costs and consumptions of a building.	NPV	None	- Since the language of the tool is Dutch, the review was based on the information in the report of TG4: Life Cycle Costs in Construction. - The user can give either detailed input or rough estimation using verbal inputs. - The calculation is based on the Dutch standard
LCCID	Building Systems Laboratory, US http://www.wbdg.org/tools/lccid.php	Free (Windows)	Military and non-military building construction	Costs of acquisition, maintenance, and refurbishment, and discount factor are required. Energy price escalation rates can also be entered.	NPV	None	- It provides the option for energy study. - The user can provide rates of price escalation for fuel and non-fuel items. - Alternatives for cost comparison are allowed.
Relex LCC	Relex, US www.relexsoftware.co.uk	Commercial (Windows)	A generic LCC tool (for the manufacturing industry)	Inflation factors, quantities and unit rates of items, and other manufacturing costs.	NPV	SA	- It does not have the pre-built equations for LCC for buildings. - It is not an ideal tool for construction.

Software	Developer	Availability	Areas of Application	Inputs	Outputs	Risk	Remark
LCProfit	Statsbygg, Norway http://www.statsbygg.no	Free (MS Excel)	Buildings (for rent)	Details prepared by the owner and the designer/planner.	The landlord's and the tenants' annual costs in MOM	None	- It is based on NS 3454 (The Norwegian standard). - Uncertainties are not captured. - Calculation factors (e.g. discounting factor) are fixed and revised annually by Statsbygg.
LCCWare 3.0	Isograph Inc., US http://www.isograph-software.com/index.htm	Commercial (Windows)	A generic LCC model (can be applied to buildings)	Costs are saved in a tree-like cost breakdown structure.	NPV	SA	- Data can be imported from or exported to MS Access and MS Excel. - The generic LCC software requires the formulation of equations, which are commonly available in LCC cost models for buildings.
PARAP	Delft University of Technology, Netherlands. http://www.bk.tudelft.nl/re-h/projects/parap/	Web-based (demo version is available)	Building cost calculation	Number of person expressed in full-time equivalent (FTE), location type, type of building, basement (yes/no), and number of storeys	Required function area, usable area, letable area, gloss floor area, capital costs.	N/A	- In the demo version, only the capital costs (total and building elements) are available.
RealCost 2.1	Department of Transportation, US http://www.fhwa.dot.gov/infrastructure/asstmgmt/rc2104.htm	Free (MS Excel VBA)	Pavement projects	Inputs required include number of lanes, traffic-related information, discount factor, analysis period, and construction cost, minor maintenance cost, and service life of pavement.	NPV	MCS	- It compares two alternatives at a time. - It is only applied to highway projects.

Where MOM = Management, operation, and maintenance; MCS = Monte Carlo simulation; Pdf = Probability distribution function; SA = Sensitivity analysis; NS = Net savings; SIR = Savings-to-investment ratio; IRR = Internal rate of return; SPB = Simple payback; DPB = Discounted payback.

Sustainability assessment and LCA methods and tools:

Environmental Impact Estimator 3.0 by Athena

Developer:	Athena Institute, Canada. http://www.athenasmi.ca/
Aim of Application:	It enables LCA-based analysis of design and material choices for commercial buildings.
Availability:	Windows (commercial) – a demo version is available.
Targeted users:	Architects, engineers, designers, environmental consultants.
Level:	2
Approach:	Bottom-up.
Database:	It contains details North American (primarily Canadian) life cycle inventory databases for specific structural assemblies of different material types and configurations, and for a variety of building envelope components and materials.
Input:	The quantities and types of building components are specified. Depending on the assembly, the user may have to answer prompts about design information.
Output:	Environment impacts in terms of energy consumption, air pollution index, water pollution index, solid waste emissions, global warming potential, and resource use can be shown in tables or graphs. Alternative designs can be compared.
Remarks:	

BEAT 2002

Developer:	SBi, Danish Building Research Institute, Denmark. http://www.sbi.dk/en/publications/programs/beat-2002
Aim of Application:	It is a PC tool for performing environmental assessment of products, building elements and buildings.
Availability:	Windows (commercial)
Targeted users:	Producers of building products, architects and engineers
Level:	2
Approach:	Bottom-up
Database:	BEAT mainly contains data for energy sources, means of transport and products which are commonly used in the Danish building industry. The user is allowed to add, edit and delete data.
Input:	The quantities and types of building materials and energy sources used are defined.
Output:	It can present the airborne emissions, liquid effluents and solid waste in different phases of the building. It can also show environmental effect tables, i.e. where raw material consumption and emissions are converted to environmental effects using the Danish EDIP method. These can also be presented graphically as so-called environmental profiles (bar charts), i.e. the environmental effects and their distribution on the individual components in a building. The results for different building alternatives (up to six) can also be seen at once. This makes it easy to compare alternatives. Finally the results can be presented as so-called aggregated environmental effects (environmental effects summed up, to reduce the number of indicators) in the form of an environmental profile (bar chart), where each components (eg each type of building element in a building) individual contribution to each environmental effect can be seen
Remarks:	The current version is available in Danish, English, French, German and Spanish.

BEES 3.0

Developer:	National Institute of Standards and Technology, USA. http://www.bfrl.nist.gov/oae/software/bees.html
Aim of Application:	It is used for selecting cost-effective, environmentally preferable building products based on the approach specified in ISO 14040.
Availability:	Windows (free)
Targeted users:	Designers, specifiers, builders, product manufacturers, purchasers, researchers, and policy makers.
Level:	1
Approach:	Bottom-up
Database:	It uses ASTM standard classification system, UNIFORMAT to organise the comparable building products into groups.
Input:	First define the relative weights for 12 environmental impact scores (such as global warming, ozone depletion, and etc.), discount rate, and the weights between environmental and economic performance. Then select the product alternatives for comparison.
Output:	Graphs depicting the performance of alternatives are shown.

Remarks:	- It considers multiple environmental and economic impacts over the entire life of the building product. - The economic performance is measured using ASTM E917 for life-cycle cost. - It is only applicable to LCA and LCC in the USA.

BREEAM

Developer:	BRE, UK. http://www.breeam.org/
Aim of Application:	It is a methodology for assessing the performance of buildings in the following areas: management, energy use, health and well-being, pollution, transport, land use, ecology, materials, and water.
Availability:	Guidelines (commercial).
Targeted users:	Developers, designers, property agents, owners, planners.
Level:	3
Approach:	-
Database:	None.
Input:	Credits are awarded in each area according to performance. A set of environmental weightings are used to produce a single overall score.
Output:	The building is rated on a scale of PASS, GOOD, VERY GOOD or EXCELLENT, and a certificate will be awarded.
Remarks:	- Different versions are available for offices, home, industrial units, retail units and schools. - BRE provides the training for those who wish to become qualified BREEAM assessors.

CASBEE

Developer:	Japan Sustainable Building Consortium, Japan. http://www.ibec.or.jp/CASBEE/english/index.htm
Aim of Application:	CASBEE is intended for implementation of the environmental assessment based on new concepts including BEE (Building Environmental Efficiency).
Availability:	Spreadsheet and manual (can be downloaded from the website)
Targeted users:	building owners, designers and users
Level:	3
Approach:	N/A
Database:	None.
Input:	The score sheet is divided into sections representing the assessment categories. Based on the restructure of assessment items, Q (Building Environment Quality & Performance) is broken down into three categories of Q-1 (Indoor Environment), Q-2 (Quality of Service) and Q-3 (Outdoor Environment on Site). LR (Reduction of Building Environmental Loadings) is also sub-grouped into LR-1 (Energy), LR-2 (Resources& Materials) and LR-3 (Off-site Environment).
Output:	Scores are given based on the scoring criteria for each assessment item. These criteria applied to assessments are determined taking into consideration of the level of technical and social standards at the time of assessment. A five-level scoring system is used, and a score of level 3 indicates an "average".
Remarks:	- The CASBEE assessment tools are CASBEE for Pre-design, CASBEE for New Construction, CASBEE for Existing Building and CASBEE for Renovation, to serve at each stage of the design process. - Each assessment item, such as Q-1, Q-2 and Q-3, is weighted so that all the weighting coefficients within the assessment category Q sum up to 1.0. The scores for each assessment item are multiplied by the weighting coefficient, and aggregated into SQ; total scores for Q or LR; total scores for LR respectively.

CEEQUAL

Developer:	Maintained by CIRIA and Crane Environmental Ltd, UK. http://www.ceequal.com
Aim of Application:	It is a credit-based assessment framework, which is applicable to any civil engineering project and includes environmental aspects such as the use of water, energy and land as well as ecology, landscape, nuisance to neighbours, archaeology, waste minimisation and management, and community amenity.
Availability:	Guidelines (can be ordered online).
Targeted users:	Contractors, designers, private sector clients (developers and end-users of civil engineering projects), public sector clients, funders and regulators of construction schemes.
Level:	3
Approach:	-

Database:	None.
Input:	The assessor completes a questionnaire with 180 questions, which carry scores, covering 12 topic areas such as use of materials and waste management. Using the CEEQUAL Scoresheet, the assessor completes the "Initial Assessment Score" column for each of the 180 questions. On completion of the questionnaire a Verifier checks the scores and either approves or amends the Assessor's score.
Output:	The Award thresholds, based on the maximum possible score for that project as scoped by the Assessor and Verifier, are: Exceeded by 25% – Pass Exceeded by 40% – Good Exceeded by 60% – Very Good Exceeded by 75% – Excellent (the actual score is given on the Award Certificate.)
Remarks:	- CEEQUAL is similar to BREEAM for buildings, but is for civil engineering projects.

Eco-Quantum

Developer:	IVAM, Netherlands. http://www.ivam.uva.nl/uk/index.htm
Aim of Application:	It is a tool for determining the environmental performance of a residential building over its total life span.
Availability:	Windows (in Dutch)
Targeted users:	Architects, designers, and local governments.
Level:	2
Approach:	Bottom-up
Database:	It contains the Dutch inventory database.
Input:	It requires the types of material and actual quantities for the building components.
Output:	A set of environmental performance measures are aggregated into 4 environmental scores: resources, emissions, energy and waste.
Remarks:	- The database cannot be extended by the user. - Detailed data on building materials used are required. The information may not be available in the initial design stage.

Ecoprofile

Developer:	Norwegian Building Research Institute, Norway. http://www.ecoprofile.com
Aim of Application:	It is a method for assessing and environmentally classifying existing office and residential buildings.
Availability:	A guideline.
Targeted users:	Investors, owners, planners, constructors, consultants
Level:	3
Approach:	Top-down
Database:	None
Input:	It is divided into 3 principal components: External Environment, Resources and Indoor Climate. Each component is divided into sub-areas, which are weighted based on their impacts on the principal component. The sub-areas and the underlying sub-areas are made up of 82 parameters, which are to be assessed based on the grading scales of lesser environmental impact (1), medium environmental impact (2), and greater environmental impact (3).
Output:	For most of the sub-area, the classification is just the average of the classifications fo the parameters that make up the sub-area. For each principal component, its classification is computed by aggregating the classifications of the sub-areas based on their weights.
Remarks:	- Computer programs, Enok Normtall and Indoor Climate are linked to Ecoprofile.

ECOTECT

Developer:	Square One Research, UK. http://www.squ1.com/
Aim of Application:	It is a complete environmental design tool which couples an intuitive 3D modelling interface with extensive solar, thermal, lighting, acoustic and cost analysis functions.
Availability:	Windows (commercial) – the website is currently closed for maintenance.
Targeted users:	Architects, engineers, environmental consultants, building designers, and some owner builders
Level:	2
Approach:	Bottom-up
Database:	-
Input:	Intuitive 3D CAD interface allows validation of the simplest sketch design to highly complex 3D models. Can also import 3DS and DXF files.

Output:	ECOTECT's own analysis functions use a wide range of informative graphing methods which can be saved as Metafiles, Bitmaps or animations. Tables of data can also be easily output. For more specific analysis or validation you can export to; RADIANCE, POV Ray, VRML, AutoCAD DXF, EnergyPlus, AIOLOS, HTB2, CheNATH, ESP-r, ASCII Mod files, and XML.
Remarks:	- It is mentioned as one of the few tools in which performance analysis is simple, accurate and most importantly, visually responsive. - It performs LCC.

ENVEST

Developer:	BRE, UK. http://envest2.bre.co.uk/
Aim of Application:	It is a software tool that simplifies the complex process of designing buildings with low environmental impact and whole life costs. It allows both environmental and financial tradeoffs to be made explicit in the design process, allowing the client to optimise the concept of best value according to their own priorities.
Availability:	Web-based (commercial) – a demo version is available on the internet.
Targeted users:	Architects, designers, environmental/energy consulting firms, authorities, clients, and research universities.
Level:	2
Approach:	Top-down
Database:	It contains the UK Database of Environmental Profiles of Construction Materials and Components
Input:	Simple data about building form, materials, components and operating systems are required.
Output:	The environmental performance measures are normalised, weighted, and aggregated to produce a single score, called Ecopoint. 100 Ecopoints are equivalent to the annual environmental impact caused by a typical UK citizen.
Remarks:	- It is a LCC/LCA tool. - Minimal data are required through the simple input screens. - Two versions are available: a) Envest 2 estimator, in which cost and replacement are prefixed, and cannot be seen or changed by the user; b) Envest 2 calculator, which allows the user to enter his own cost/replacement interval or use the defaults.

EQUER

Developer:	Centre for Energy and Processes, France. http://www-cenerg.ensmp.fr
Aim of Application:	EQUER is a life cycle simulation tool providing quantitative indicators of environmental quality to various actors. The tool is primarily intended to work at the whole building level,
Availability:	Windows (Commercial) – in French.
Targeted users:	Mechanical, energy, and architectural engineers, architects, consultants, utilities, federal agencies, urban designers, universities, and research laboratories.
Level:	2
Approach:	Bottom-up
Database:	The Swiss Oekoinventare database and other data collected in the European REGENER project are used for material fabrication and other processes (energy, water, waste, transport).
Input:	Building geometry, material characteristics, internal loads and schedules, climate, heating and cooling equipment characteristics are required. Water consumption, waste generation, and transport issues can also be taken into account.
Output:	The assessment results are represented by environmental indicators such as contribution to global warming, acidification, eutrophication, ecotoxity, and human toxicity for different phases or different alternatives of projects. The results can be presented in bar charts or radar diagram for comparing alternatives.
Remarks:	- Only the French version is available. - Readable, structured input file is generated by the PLEIADES (thermal simulation) and ALCYONE (2-3D modeller) user interface. - EQUER is linked to the energy simulation tool COMFIE.

GaBi 4

Developer:	University of Stuttgart and PE Europe GMBH, Germany. http://www.gabi-software.com/
Aim of Application:	It is a tool for building up life cycle balances. It provide supports with a large amount of data and within modelling of the product life cycle.
Availability:	Windows (Commercial)
Targeted users:	Consultants, designers, and researchers.

Level:	1
Approach:	Bottom-up
Database:	GaBi **4** professional ecoinvent contains GaBi 4 professional database plus Swiss ecoinvent database.
Input:	A balance (i.e. the results of a comprehensive balance) primarily consists of a list of all inputs and outputs which results from the life cycle of a product is modelled. The inputs and outputs in the balance are defined as flows.
Output:	The results can consist principally of every table cell of a balance in every conceivable constellation. Balance tables, balance columns, balance lines, size or evaluation, unit or normalisation, and also the aggregate level with LCC and life cycle working time value must be established to specify a result value. GaBi 4 provides several different Impact Methods including Ecoindicator 95, Ecoindicator 99, Ecological Scarcity Method (UBP), CML 1996 and CML 2001. In total, 63 environmental indicators are included.
Remarks:	- The assessment is based on ISO 14040. - It can perform SA, MCS and scenario analysis. - It provides the option for calculating LCC.

GBTool

Developer:	International Initiative for a Sustainable Built Environment (iiSBE) http://www.iisbe.org/
Aim of Application:	It is the software implementation of the Green Building Challenge (GBC) assessment method
Availability:	Spreadsheet in MS Excel (available for download)
Targeted users:	Designers, specifiers, builders, researchers, and policy makers.
Level:	3
Approach:	None
Database:	None
Input:	Module A includes Benchmarks and Weights, and is adjusted by credible third parties. The settings cannot be changed by users of Module B. Module B is for assessing a building. Parameters included in this module cover 3 areas: environment, social and economic sectors. The module can be used in 4 phases, i.e. pre-design, design, construction, and operation. The information of the building including number of floors, floor areas, floor heights is also required.
Output:	The relative performance results of the following issue areas are displayed in a scale of 0 (Acceptable Practice) to 5 (Best Practice): A)Site Selection, Project Planning and Development, B) Energy and Resource Consumption, C) Environmental Loadings, D) Indoor Environment Quality, E) Functionality and Controllability of Building Systems, F) Long-Term Performance, G) Social and Economic Aspects.
Remarks:	- Currently, more than 20 countries participate in this framework. - Similar to BREEAM, it is a performance assessment and rating system. - It allows users to assess the building against regional benchmarks.

GREENCALC

Developer:	Sureac Trust, Netherlands. http://www.greencalc.com/
Aim of Application:	It is a tool to assess and compare the environmental sustainability of buildings.
Availability:	Windows (commercial).
Targeted users:	Architects, designers, public authorities, constructors, and consultants.
Level:	2
Approach:	Bottom-up.
Database:	It uses its own LCA database, and also LCA databases from SimaPro, IVAM, and Eco-Invent.
Input:	The inputs for GreenCalc consist of all building sizes and installation types. To make faster calculations many pre-sets are implemented.
Output:	An environmental index that is computed by averaging the indices of the four modules.
Remarks:	- The environmental index is calculated using 'factor 20' based on 1990 as the reference year. A building with 1990 sustainability has an environmental index of 100. - A more environmental friendly building has a higher index value.

HQE Process

Developer:	HQE Association, France. http://www.assohqe.org (in French).
Aim of	The High Environmental Quality (HQE) process is first at all a process for project

Application:	management aiming at: - controlling environmental impacts of construction operations - creating healthy and comfortable living conditions. It covers the whole life cycle of the building, from the inception of the project up to its demolition.
Availability:	Guidelines (for French buildings)
Targeted users:	Owners and developers
Level:	3
Approach:	N/A
Database:	None
Input:	Environmental quality is defined by 14 issues/targets: 1: eco construction - harmonious relation between buildings and their close environment - integrated choice of construction processes and products - building site with low nuisance 2. eco management - energy management - water management - waste management - maintenance management 3. comfort - heat comfort - acoustic comfort - visual comfort - olfactory comfort 4. health - health quality of the areas - health quality of water - health quality of air
Output:	3 levels of performance (Basic, High and Very High) for each target. Certificates are given after passing the audits at three key steps
Remarks:	- It is a certification scheme including all the processes of the project and all the practitioners involved, and considering the environmental performances of the building. - It can be used for 4 types of non-residential buildings: offices, schools, hotels, and commercial centres. - It is conducted at 3 key steps: end of brief, end of design, and end of construction.

LCAid

Developer:	DPWS Environnemental Services (ES), Australia. http://www.projectweb.gov.com.au/dataweb/lcaid/
Aim of Application:	It is a user-friendly decision-making tool for evaluating the environmental performance and impacts of designs and options over the LCC of a building.
Availability:	It will be commercialised in the future.
Targeted users:	building designer, LCA practitioner, LCA researcher or building rating practitioners
Level:	2
Approach:	Bottom-up
Database:	It contains the DPWS LCI database, provides the ability to import LCA data from Boustead Model LCA software and has a template for data to be entered from other LCA packages such as SIMA-Pro. It also includes weather data for most parts of Australia used for thermal energy/thermal calculations and for water consumption calculations.
Input:	- By manually entering quantities and assigning materials from the LCAid library or; - By importing quantities generated by a 3-D architectural drawing and assigning materials to each building element (3-D model is not essential)
Output:	The output is currently calculated using Eco Indicator 95 with the additional reporting of water consumption and solid waste produced. A number of categorisations including the latest version of Eco-indicator (99) or the categories outlined in the Green Building Challenge are being considered for future versions of LCAid™. LCAid uses the categorisation of Eco Indicator 95 to provide global and some general environmental impacts. Eco-indicator 95 was produced for the National Reuse of Waste Research Programme (NOH) in the Netherlands and includes the following impact categories: Greenhouse effect, Ozone Depletion, Heavy Metals, Nutriphication, Acidification, Carcinogenesis, Summer smog and Winter smog. Additional indicators added to LCAid include energy and water consumption and solid wastes. This is to compare human consumption with the corresponding atmospheric and pollutant impacts. LCAid displays these categories under three headings: 1. Atmospherics are the Eco-indicators that affect the atmosphere including Greenhouse effect and ozone depletion.

	2. Resources are the Eco-indicators that describe what resources are used such as water and energy consumption. 3. Pollutants are Eco-indicators that include pollution impacts on air, water and earth.
Remarks:	- It can work on 3D models created in software such as ECOTECT or AutoCad. - It allows LCC.

LISA

Developer:	BlueScope Steel, BHP Billiton Technology **Task leader** Glen Dennison, University of Newcastle, Australia. http://www.lisa.au.com
Aim of Application:	LISA (LCA in Sustainable Architecture) is a streamlined LCA decision support tool for construction. It was developed in response to requests by architects and industry professionals for a simplified LCA tool to assist in green design.
Availability:	Windows (free).
Targeted users:	Architects, designers, and engineers.
Level:	2
Approach:	Bottom-up
Database:	Data and equations are provided by nominated users for the case studies.
Input:	User can flexibly define the inputs for Specification (analysis period, life expectancies, number of visitor per hour and so on), Construction (building elements, types and quantities of materials, or working hours required for different elements), Appliances, Fit Out, Utilisation, Decommissioning, and Material Transport.
Output:	The results contain detailed histograms of the various impacts, such as resource energy or greenhouse gas emissions. Two bars are graphed, the average NSW impact and the example set up by the user. Further, more detailed, breakdowns can be viewed by selecting options from the menu.
Remarks:	- Only case studies can be prepared by nominated developers. It does not allow users to add new case studies, or modify the existing ones. - Since it does not have a fixed format, it greatly depends on how the user define the inputs and equations he wants.

LEED

Developer:	The U.S. Green Building Council (USGBC). http://www.usgbc.org/LEED/publications.asp
Aim of Application:	It is a rating system awarding credits for each criterion met. Different levels of certification are awarded according to credits earned.
Availability:	Guidelines for different types of buildings are available for purchase.
Targeted users:	Public, investors, researchers, contractors, and consultants
Level:	3
Approach:	N/A
Database:	N/A
Input:	69 credit points are divided among 5 environmental impact areas - Sustainability Sites (SS), Water Efficiency (WE), Energy and Atmosphere (EA), Materials and Resources (MR), and Indoor Environmental Quality (IEQ); and the Innovation and Design Process (ID) activity. There are prerequisites in SS, EA, MR, and IEQ that every building must meet.
Output:	26 points (in addition to all the prerequisites) must be met to earn a LEED certification. A silver rating is achieved by earning 33 and 38 points, Gold between 39-51, and Platinum between 52-69.
Remarks:	

LEGOE

Developer:	Institut fur industrielle Bauproduction, Universitat Karlsruhe, Germany. http://www.legoe.de
Aim of Application:	It is a LCA tool integrated into normal work routines and tools used by architects and engineers. It measures the environmental performance of the designs in different life cycle phases.
Availability:	In German and Italy only.
Targeted users:	Architects, researchers, and consultants.
Level:	2
Approach:	Bottom-up or top-down
Database:	It contains the description of building elements (based on DIN 276), their life cycle cost based on DIN 18960 and the final report of EU-TG4 LCC in Construction. It is integrated with 4 software tools, each with its own database. The life cycle inventories are based on

	the Ecoinvent data and specific values from the Baustoff Okoinventare.
Input:	A building can be described alternatively with 15 macro elements, 40 complex elements, or approximately 150 simple elements.
Output:	It gives a complete, interrelated set of cost, energy, mass-flow and environmental indicators, such as eutrophication, ozone depletion, and primary energy consumption – renewable and non-renewable, in each life cycle phase.
Remarks:	- It is integrated with a CAD tool. - The environmental assessment comprises the material flows (input and waste), as well as an effect oriented evaluation based on ISO 14040 – 43. - The English and French versions are currently under development.

OGIP

Developer:	CRB, Switzerland. http://www.crb.ch
Aim of Application:	It enables the user to compare building projects in terms of construction and operating costs, the grey energy of structure, the operating energy, and the environmental impacts.
Availability:	Windows (commercial) – in Deutsche.
Targeted users:	Architects, designers, public authorities, constructors, and consultants.
Level:	2
Approach:	Bottom-up
Database:	It contains Ecoinvent life cycle inventory data, and information on building materials, fuels and processes.
Input:	Define the quantities of building element, based on the building element catalogue of CRB, and the energy in use.
Output:	Outputs include costs, embodied energy, Swiss ecopoints, and effect oriented categories.
Remarks:	- It can be linked to other standard tools developed by CRB. - Up to 5 buildings can be compared.

SimaPro 7.0

Developer:	PRe Consultants, Netherlands. http://www.pre.nl/pre/pre_consultants.htm
Aim of Application:	It is a tool for collecting, analysing and monitoring the environmental performance of products and services.
Availability:	Windows (commercial) – a demo version is available.
Targeted users:	Designer, manufacturers, researchers, and universities.
Level:	1
Approach:	Bottom-up
Database:	It contains some standard inventory databases for materials, energy, transport processing, and waste treatments. It also has databases specifically for Dutch, North America, and Europe. The Ecoinvent database containing life cycle inventory data for 2500+ process is also included.
Input:	Prepare an assembly process in a tree-like structure, and define the resources used in each part of the process. The information from the available library is utilised.
Output:	Bar chart indicating the level of land use, ecotoxicity, ozone layer depletion, minerals, radiation, climate change and others, are shown.
Remarks:	- Intuitive user interface according to ISO 14040 - MCS and SA are provided. - It can be connected to other tools using COM.

TEAM for Building

Developer:	ECOBILAN, France. http://www.ecobalance.com/index_uk.html
Aim of Application:	It evaluates the environmental performance of a building.
Availability:	Windows (commercial)
Targeted users:	Authorities, researchers, and consultants.
Level:	2
Approach:	Bottom-up
Database:	It consists of 309 different data modules.
Input:	For building description, the amounts of building components are defined. The data can be entered for all the components or only for the main ones. For operation, the annual consumptions of electricity, water, heating and etc. are required. For maintenance, the life time of the components and assumptions are required.
Output:	Different assessment methods are available for different levels: Inventory (particulate

	and waste for wood), Classification (resource depletion, greenhouse effection and others), and Evaluation – full aggregation (Eco-indicators 95, EPS and others).
Remarks:	- It allows the user to select the level of details for the building description, the life cycle stages under study as well as the environmental impact indicators. - It can perform SA.