Consultancy Agreement No. CAO L013 –

Consultancy Study on Life Cycle Energy Assessment of Building Construction

An Introduction to Life Cycle Energy Assessment (LCEA) of Building Developments
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Preface

Life cycle assessment (LCA) is a quantitative method for assessing the environmental impacts of products including buildings, from cradle-to-grave. Informed by LCA results, manufacturers or contractors can identify areas of improvement on their production processes for minimizing environmental impacts.

Different measures may be used to reduce the environmental impacts of a building but each may require a different cost and may lead to different results. Therefore, investing into improvement measures must consider their cost-effectiveness. This requires the use of life cycle costing (LCC), which is a quantitative method for assessing the economic or financial viability of investments, to inform selection of the most worthwhile options. LCA and LCC methods are increasingly used to underpin investment decisions in the interest of sustainable development.

Modern buildings, which are products of construction processes, are resources intensive to build, operate and maintain. Construction and demolition of buildings generate huge amount of solid wastes and various kinds of emissions. Furthermore, buildings will continue to incur substantial environmental impacts until they are demolished, mainly due to the intensive use of energy for running the services plants in the buildings.

Because buildings can incur large environmental impacts throughout their life cycle, improving the sustainability of building development is a key means to achieving sustainable development in modern cities, which needs to be underpinned by LCA and LCC methods. Whilst LCC may be frequently applied to construction projects, LCA application remains embryonic in the construction industry.

For promoting sustainable building development in Hong Kong, this book targets at building professionals who are keen to make building developments more sustainable. Readers are introduced to the relation between sustainable development and LCA and LCC, the fundamental principles of LCA and LCC, and the standard framework and procedures of using LCA and LCC to quantify environmental and financial performances of buildings. The contents should allow readers to appreciate the extent to which LCA and LCC can underpin sustainable building design, the limitations of the state-of-the-art LCA and LCC methodologies and the currently available supporting data.

Building designers need to be equipped with an appropriate tool and the necessary data to enable them to conduct LCA and LCC for a design as complex as a commercial building. As a means to promote sustainable building development in Hong Kong, the Electrical and Mechanical Services Department (EMSD) of the Hong Kong SAR Government has recently made available a LCEA tool for use by persons who are interested in using LCA and LCC to assess designs of commercial buildings in Hong Kong. A brief introduction to this tool is also given in this book. Descriptions on the tool emphasize on how such a tool can be utilized in the design process to improve the environmental and financial performances of building developments.

Additionally, the prospects of benchmarking and voluntary assessment of building performance based on LCA and LCC are discussed. The book concludes with a bibliography that guides interested readers to find further information about LCA and LCC.
is hoped that when equipped with the LCEA tool, building designers will be able to turn out more sustainable building developments in Hong Kong.
1 Introduction

1.1 Buildings and sustainable development

Buildings are meant for providing people with indoor environments that are habitable or are suitable for various kinds of social and economic activities. Metropolitans in different parts of the world are invariably densely populated with buildings. The quantity and quality of buildings in a city, especially sky-scrapers, are often regarded as a sign of the prosperity of the city. In Hong Kong, the quantity of properties transacted in the market each year is perceived as the barometric pressure that reflects Hong Kong’s economic climate.

However, modern buildings are resources intensive to build, operate and maintain. Production and transportation of the enormous amounts of materials needed for construction of buildings consume huge quantities of natural resources and energy, and incur various kinds of adverse environmental impacts. During the construction of a building and while a building is demolished at the end of its life, large quantities of solid wastes and various types of emissions, such as particulates, noise and various kinds of effluents, are generated.

In a modern city, the energy use for operating buildings accounts for a substantial portion of the city’s overall energy use. The energy use also leads to pollutant emissions due to combustion of fossil fuels, either directly in buildings or indirectly for producing the energy commodities (electricity, gas, etc.) that are consumed in buildings. Furthermore, the physical existence of buildings means that alternative uses of the land occupied by the buildings, including habitat for plants and animals, are forsaken. Buildings also impact the environment in their vicinity.

Continuing with using conventional design approach and construction methods to produce buildings to meet the development needs of mankind will exacerbate environmental problems like depletion of natural resources, global warming, ozone depletion etc., which is now well recognized to be unsustainable. Therefore, sustainable building development is an indispensable part of sustainable development in general, especially in modern cities. This is manifested by the publication of Agenda 21 on Sustainable Construction in 1999 by CIB, an international research organization focusing on buildings, to help realize the objectives of Agenda 21, which is a global action plan emerged from the 1992 Rio Earth Summit, for achieving sustainable development.

1.2 Buildings in Hong Kong

The stock of buildings in Hong Kong has been growing rapidly over the past several decades (Figure 1.1), and the trend is expected to continue. The large stock of existing buildings, in conjunction with their high energy use intensity, makes buildings the dominant energy consumer in Hong Kong (Figure 1.2). Furthermore, there is an urgent need to reduce the amount of solid wastes generated by construction and demolition of buildings (Figure 1.3), due to the limited capacity of existing landfills but suitable new landfill sites are increasingly difficult to find within the territory of Hong Kong.

In the past, stakeholders of the construction industry of Hong Kong paid little attention to the environmental performance of buildings. What building end-users concerned most was property prices, which were influenced primarily by location, size and aesthetic appearance
of building premises. Building developers’ main concern was to produce buildings to meet market demand so as to reap the greatest profit within the shortest time possible, with high operation and maintenance costs and poor indoor environmental quality left as afterthoughts.

More recently, greater attention has been given to environmental performance of buildings, especially in aspects of energy efficiency and indoor environmental quality. This may be ascribed to the increased awareness of the general public about the importance of environmental protection, the seriousness of fossil fuel depletion and the health impacts of poor indoor air quality. Initiatives have been taken by various stakeholders in the building construction industry, including the Government, private developers, professional and academic institutions and individual practitioners, to promote and enhance environmental performance of buildings.

![Figure 1.1 Building stock in Hong Kong: a) number of residential units; b) floor area of office/commercial buildings (Data from Rating and Valuation Department)](chart.png)
Figure 1.2 Electricity use in the commercial, residential and industrial sectors of Hong Kong

Solid Waste Disposal Quantities

- **Year 1986**: 9,000 tpd
- **Year 2000**: 17,900 tpd
- **Year 2015**: 37,200 tpd (predicted)

Figure 1.3 Growth of solid waste disposal quantities in Hong Kong (Source: Environmental Protection Department)

Relevant initiatives that have been taken include making available voluntary building environmental performance assessment schemes in Hong Kong, such as:

- The Energy Efficiency Registration Scheme for Buildings of the Electrical and Mechanical Services Department (EMSD);
- The Indoor Air Quality Certification Scheme of the Environmental Protection Department (EPD); and
- The Hong Kong Building Environmental Assessment Method (HK-BEAM), which is a private sector initiative.

Furthermore, a Comprehensive Environmental Performance Assessment Scheme (CEPAS) has been developed by the Buildings Department, but how the Scheme is to be implemented is still under review.
Although not directly relevant to building performance, EMSD has launched voluntary energy efficiency labelling schemes for various kinds of equipment and appliances, many of which can be found inside buildings.

All the available schemes relevant to building developments, however, lack a scientific method for assessing sustainability of buildings. Life cycle assessment (LCA) and life cycle costing (LCC) are methods that can fill this gap.

1.3 Realizing sustainable building development

Sustainable building development is unattainable without conscientious design. Being quantitative methods for assessing the life cycle environmental impacts and costs of products, LCA and LCC can be applied to buildings, especially for informing selection among design options for optimizing the environmental and financial performances of buildings.

However, embracing LCA in building designs is, as yet, an emerging practice to construction industries worldwide. As few building professionals have had experience with using LCA, introducing the method to practitioners in the industry is the first step to take to widen its application, so as to promote sustainable building development.

Designing more sustainable buildings demands for much greater efforts of the designers, because it entails a wide range of complicated analyses, including energy simulation, LCA and LCC, etc. The evaluation has to be rigorous and holistic, embracing the technical feasibility and environmental and financial impacts of a wide range of alternatives, to provide a sound basis for decision making.

Being cradle-to-grave assessments, conducting LCA and LCC of a building development is a demanding task. LCA requires resources consumption and emissions data for each of the processes involved, including the production and transportation of the required materials; construction, operation and maintenance of the building; and finally demolition of the building at the end of its useful life. It also involves considerable amount of efforts for gathering the required data and performing the required calculations.

The complicated analyses may deter building designers from attempting to embrace the analyses in the design process. They may instead use qualitative or subjective methods, conduct just partial studies ignoring aspects that are complicated to evaluate, or even avoid conducting any in-depth studies. Therefore, attempts to improve sustainability of building developments will remain limited, or will be in vain, unless adequate tools are made available to facilitate building designers to properly conduct the required studies within affordable time and effort.

Lacking the required information, e.g. values of parameters essential to the studies, will be another hurdle. This highlights that making available effective enabling means to the building industry, including the required tools and data, is a crucial step to take in implementing policies for the promotion of sustainable building development.

For this purpose, the Electrical and Mechanical Services Department (EMSD) of the Hong Kong SAR Government commissioned a consultancy study, which had the objective to develop a LCEA tool suitable for application to commercial buildings in Hong Kong. The tool development work included establishment of the required data to support LCA and LCC.
calculations. The tool and the associated databases are now ready for use by any person interested in applying LCA and LCC to building designs.

In addition to making available a suitable tool and the associated databases, reference materials have been provided to introduce LCA and LCC methods to local building professionals, and to provide them with guidance on proper use of the tool. These include a User Manual and an Application Example for the LCA and LCC tool, and other reference materials, including pamphlets and this book.

Interested persons can download the LCA and LCC computing tool, the databases and the supporting documents from EMSD’s website below:

2  Life cycle assessment (LCA)

This chapter provides readers with a general introduction to life cycle assessment (LCA). The relation between LCA and sustainable development is first discussed. An illustrative example is described to highlight the functions of the standard steps involved in a LCA study. The historical development of LCA is outlined, followed by an introduction to the LCA framework and procedures stipulated in the 14040 series of ISO Standards. A brief review of the current direction of LCA development and the limitations in application of LCA to buildings is given at the end of the chapter.

2.1  The function of LCA and the steps involved

2.1.1  LCA and sustainable development

Since life cycle assessment (LCA) is meant to support pursuits for sustainable development, it is instrumental to introduce here what sustainable development is about, and the relation between sustainable development and LCA. The following is the most widely quoted definition of sustainable development:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Developments of any kind require input of resources and existence of favourable environmental conditions. First and foremost, human beings require clean air, water and food, and a habitable environment to survive. Any economic activities we carry out involve consumption of resources, such as materials and energy for producing goods and services. While we obtain resources from the natural environment to meet our development needs, all the activities we carry out generate wastes, which we dump back to the natural environment.

However, many natural resources on earth are becoming increasingly scarce. Furthermore, the ability of the natural environment to assimilate the wastes we generate is limited without affecting its ability in supplying resources for our consumption. Any natural resources consumed and emissions discharged to the natural environment impact the environment's capacity to supply environmental goods and services, which include life support services (e.g. supply of clean air and water), natural resources (e.g. fossil fuels and minerals), waste assimilation, and environments for our amenities (e.g. rivers, lakes and scenic sites). Hence, from the perspective of sustainable development, consumption of any natural resources and discharging any emissions are regarded as environmental impacts.

The severity of the impacts of resources consumption is dependent on whether the resources consumed are renewable or substitutable. The environmental damages incurred by emissions are more detrimental if the damages are irreversible. The impacts are severer the more non-renewable and non-substitutable resources are consumed and the more damages are incurred to the natural environment, which may endanger human health and the survival of other biological species, which are irreversible.

As already mentioned in the Preface, LCA is a quantitative method for assessing the environmental impacts of products, from cradle-to-grave. Being able to quantify the
environmental impacts incurred by human activities is the pre-requisite to making decisions on what measures to take or avoid in striving for sustainable development. LCA is, therefore, an indispensable tool for underpinning pursuits for sustainable development.

In assessing the impacts of a product on sustainable development, it is essential to embrace the environmental impacts it would incur throughout its entire life cycle. A LCA is complete only if the natural resources taken from the earth and consumed, and the emissions to air, water and land incurred during the production, transportation, consumption and disposal of the product are all accounted for. Leaving out the impacts incurred by a product in any stage within its life cycle will result in a biased quantification, which can be misleading, especially if the LCA result is relied upon in making purchasing or improvement decisions.

![Life cycle of buildings](image)

**Figure 2.1** Stages in the life cycle of a building

### 2.1.2 An illustrative example: a simple wood shed

Life cycle assessment (LCA) involves a number of steps that serve different functions. To illustrate why these steps are needed, the discussion is based on a hypothetical case of constructing, using and demolishing a simple wood shed, by assuming that we are interested in quantifying the environmental impacts incurred in the life cycle of the wood shed. The problems that will be encountered in this exercise and how these problems can be dealt with are discussed. For the sake of brevity, we assume that all the materials required for constructing the wood shed are just some wood planks and nails.

Before the shed can be constructed, wood planks have to be produced. Hence, the first process to be undertaken is felling trees in a forest. The tree felling process, illustrated in Figure 2.2, requires resources input, which includes the trees in the forest and the fuel input for the tool used, e.g. a chain saw powered by a small petrol engine. The output of the
process includes logs, which are the wanted output, and tree branches and sawdust left in the forest and emissions from the chain saw, which are the by-products.

![Diagram showing the tree felling process and the inputs and outputs of the process](image)

Figure 2.2  The tree felling process and the inputs and outputs of the process

The logs, which are the output of the tree felling process, need to be transported to a sawmill, where the logs will be sliced into planks. Transportation of the logs requires the use of a truck, which consumes diesel. The inputs to the transportation process (Figure 2.3), therefore, include the logs and the diesel for the truck while the outputs are the delivered logs and the emissions from the truck during the transportation process.
The inputs to the next process, sawing, include the logs and the electricity used by the rotary saw. The sawing process (Figure 2.4) produces the planks as well as bark and sawdust as by-products.

The tree felling, log transportation and the sawmill processes described above are each regarded as a unit process. For each unit process, there are inputs, such as natural materials or products of other processes, and outputs, which may include the wanted output and by-products, some of which are emissions that adversely impact the environment. The three unit processes are connected in series, as the output of one unit process is an input of the next process.

The other unit processes embraced by the life cycle of the wood shed are:
- Transportation of the planks and nails (an input product brought from the market) to the site, which requires fuel input and incurs truck emissions;

- Assembly of the shed, which involves energy use for powering the required tools – after this process, the shed can be occupied;

- Using the shed, which, for this simple case, would incur insignificant impacts;

- Demolition of the shed at the end of its life and disposal of the waste materials; this involves the energy use of the tools for demolishing the shed and transporting the waste materials to an incinerator or a landfill site for waste treatment; and

- Treatment of the wastes. This will incur emissions and may require certain resources inputs.

### 2.1.3 Implications of the wood shed example

In order to provide a complete account of the environmental impacts that the wood shed would incur in its life cycle, all the natural materials (e.g. trees) and products (e.g. nails, petrol, diesel, electricity, etc.) input into the various unit processes involved, and all the outputs of the unit processes must be accumulated (Figure 2.5).

![Figure 2.5 Accumulation of inputs and outputs of unit processes](image)

For the product inputs (e.g. nails), all the natural resources consumed and the emissions incurred in the processes for their production (e.g. extracting iron ore, refining the ore into steel, drawing and cutting steel wires and pointing the wire rods to make nails) should also be made known and accounted for. Backward tracing of the upstream unit processes involved in producing each of the input products (e.g. fuels and electricity used in the steel refinery) should continue, until all the associated natural resources inputs and all the emissions are identified and accounted for. Otherwise, the account of the life cycle impacts of the wood shed will remain incomplete.

The abovementioned process of accounting for the natural resources and emissions incurred for a product is called **life cycle inventory (LCI) assessment**. The data obtained at the end will be a long list of quantities of various types of natural resources consumed and chemicals emitted to air, water and land, which are called **life cycle inventory (LCI) data**.
The extent to which the backward tracing exercise needs to be carried out is dependent on the goal and scope of the LCA study and their significance (cut-off criteria). For instance, whether parts of the life cycle impacts of the chain saw for tree felling, the sawmill for producing planks from tree logs, the trucks used in transportation, etc. should be accounted for in the life cycle impacts of the wood shed is dependent on the share of these impacts by the wood shed; these impacts may be discounted if the wood planks used is but a minute fraction of the life cycle outputs of these tools, equipment, plants and other related capital assets (e.g. factories for manufacturing trucks).

It can be seen from the above discussions that life cycle assessment on a product, here the shed, requires knowledge about all the processes involved in its life cycle, including the production, use and end-of-life treatment processes. This embraces all the inputs and outputs of each process involved, including those for the production of each input product (e.g., petrol, diesel, electricity or nails). Where some of the wastes generated can be used to serve a purpose (e.g. wood as fuel for generating heat), the effects (e.g. use of other fuel avoided) should also be accounted for.

From the above description, it is evident that a comprehensive life cycle inventory (LCI) assessment can be an intricate task. We may know the processes directly involved in producing a specific product (e.g. those discussed above for the shed), but we may not know all the processes involved in producing the input products (e.g. petrol, diesel, nails, etc.), or in treating the wastes. We may know the by-products (sawdust, bark) and wastes (wood, metal) generated in the life cycle of our product, but we may not know the whole range of emissions that would be generated, including those due to the input products used and the waste treatment processes.

The above discussions highlight that numerous data are needed for a LCA study, even for a product that is as simple as the wood shed described above. If all the required information needs to be found from scratch, LCA will be a formidable task even to LCA experts. However, LCI assessment can be made much easier if LCI data for the basic processes and the input products are already available. LCI databases are intended to be a source of such data from which data for a range of basic processes, such as electricity generation, transportation and production of some materials and products can be found.

However, the environmental impacts that will be incurred in the production of a specific product are dependent on many factors, such as the type of fuel used or the fuel mix used in generating the electricity used in the manufacturing processes, and the sources from which the input materials were obtained for producing the product. Therefore, the LCI data obtained from manufacturing plants in a particular region can differ significantly from those obtained in other regions. Hence, the data in a LCI database are applicable only to the specific region for which the data were assembled but not generally for other places.

Impact categories and classification

As discussed above, the inventory data that a LCI assessment yields are a very long list of quantities of substances that flow into and out of the unit processes involved in the life cycle of a product, but such a quantities list (Figure 2.6) will not make much sense to many. This entails the question of whether there are flows that would incur environmental impacts of the same nature. If there are, grouping them together will ease understanding and interpretation of results.
The process of grouping the in and out flows by the type of environmental impacts that the flows will incur is indeed a necessary step to take in a LCA study, which is referred to as classification. For example, emissions of CO₂, NO₂, CH₄, CFCs, HCFCs, CH₃Br, etc., would all lead to global warming, and thus can be classified under one category: global warming.

It follows that before classification can be performed, one has to define the range of impact categories to be considered. The following lists a few impact categories that are embraced by most LCA studies:

- **Greenhouse effect or global warming** – increase in earth surface temperature due to release of carbon dioxide, methane, CFCs, etc., which in turn causes polar melt, soil moisture loss, forest loss, etc.
- **Ozone depletion** – release of CFCs destroys stratospheric ozone layer, leading to higher ultraviolet radiation and in turn to decrease in harvest crops, skin cancer, etc.
- **Acidification** – release of sulphur dioxide and nitrogen oxides leads to acid rain, resulting in dying of forest, damages to nutrients in soils, damages to buildings, etc.
- **Eutrophication** – air pollutants, waste water and fertilization in agriculture enriches nutrients in water and land, resulting in algae growth in waters, thus fish dying due to lowered oxygen concentration, and plants prone to diseases and pests, and other problems.
- **Photochemical smog** – release of volatile organic compounds and oxides of nitrogen produces compounds that react with sunlight to produce photochemical smog, which in turn leads to harmful impacts on human health and vegetation and reduced visibility.

Other impact categories embraced in most LCA studies include depletion of resources and eco-toxicity in various aspects that endanger human health and various biological species on lands or in waters.
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<table>
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<tr>
<th>Impact category</th>
<th>Unit</th>
<th>IVAM</th>
<th>China</th>
<th>Australia</th>
<th>Hong Kong</th>
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<td>abiotic depletion</td>
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<td>0.00255</td>
<td>0.0106</td>
<td>0.00349</td>
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<td>1.43</td>
<td>0.553</td>
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<td>ozone layer depletion (ODP)</td>
<td>kg CFC-11 eq</td>
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<td>1.97E-08</td>
<td>1.79E-06</td>
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<tr>
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<td>kg 1,4-DB eq</td>
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<td>0.421</td>
<td>0.725</td>
<td>0.456</td>
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<tr>
<td>fresh water aquatic ecotoxicity</td>
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<td>marine aquatic ecotoxicity</td>
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</tbody>
</table>

Figure 2.6.2 The LCIA profiles for 1 Kg of brick produced in various countries compared to data in IVAM database.

Characterization

Although emissions can be classified into a range of impact categories, the degree of significance of different kinds of emissions in the same category are different, e.g. the release of 1kg of CO2 and 1kg of NO2 would lead to different degrees of global warming effect. The method used to deal with this problem is to pick one of the emissions as a reference emission and evaluate the quantity of the reference emission that will lead to the same effect when a unit quantity of another emission in the same category is released. The equivalent quantity of the reference emission per unit quantity of emission of a different kind in the same category is called a characterization factor and one such factor is needed for each kind of emission embraced by an impact category (Figure 2.7).

Figure 2.7 Characterisation factors for various kinds of emissions

With the characterization factors, an equivalent total amount of the reference emission can be determined and used to represent the total impact of all kinds of emissions in the same impact category. For example, each greenhouse gas emission can be converted into an equivalent amount of CO2 that would lead to the same degree of global warming effect, and the total impact on global warming can be expressed as the sum of the equivalent amounts.
of CO₂ emitted. This process of evaluating the equivalent total impact for different emissions in an impact category is referred to as characterization in LCA.

Normalization

In the characterization process, numerical values are determined for the impact categories embraced in a LCA study, which are taken as the impact indicators. There will be as many impact indicators as the number of impact categories included in the study, which may be up to 10 or more. Furthermore, each impact indicator carries a unit of measurement that is used to quantify the equivalent total amount of a specific substance emitted or consumed, e.g. a certain number of kg of CO₂ equivalent for the global warming category.

The set of impact indicators is similar to the set of marks attained by a student in a range of subjects, which reflect the academic performance of the student (see Figure 2.8). The subject marks for a multitude of subjects, however, are difficult to use to compare the overall performance of the student against another student. Likewise, the results of characterization remain difficult to comprehend to non-LCA experts, and are difficult to use for comparison of the results with those of other products that serve the same purpose.

The LCA results can be made more comprehensible through normalizing the impact indicators for a product by the corresponding impact indicators of a reference case. This process is referred to as normalization in LCA. Typical reference impact values, referred to as normalization factors, that are commonly used include the total emissions and resources use of:

- The whole world, a continent, a country or a local region;
- Same as above on per capita basis;
- A reference case (e.g. a reference building); etc.

Figure 2.8  Scores of five students: (a) individual subject and (b) total of all subjects
The need for normalization can be explained by referring again to the case of assessing the overall performance of students. Because the spread of marks in individual subjects can differ from one another, to better reflect the performance of individual students, their subject marks can be normalized by the corresponding subject marks of an average student in the class (or simply the class averages of corresponding subjects, see Figure 2.9). The ratio of the mark of a student to the class average mark for a subject will reflect if the student is above (if the ratio is greater than 1) or below average (if the ratio is lower than 1). By examining the normalized marks of a student across different subjects, whether the student is strong or weak in individual subjects will become evident.

![Normalized scores of five students](image)

**Figure 2.9** Normalized scores of five students: (a) individual subject and (b) total of all subjects

In LCA, the normalization step can also help remove the influence of the choice of a reference substance for each impact category for characterization of impacts. Through normalizing the impact indicator for an impact category by the impact indicator of the reference case for the same impact category, with both quantified using the same method and in the same unit of measurement, the normalized result becomes a dimensionless, relative measure which is independent of the chosen reference substance. Without normalization, it will be difficult to compare the impacts of different products in a specific impact category when they are quantified in terms of the equivalent amount of different substances (e.g. in kg of CO2 or in kg of methane for global warming).
Weighting

A further step can be taken to yield an overall impact indicator to aid interpretation and comparison of LCA results. This step computes a weighted sum of the normalized impact indicators for all the impact categories. A weighted sum is needed because the consequences of the impacts in different impact categories may be perceived to be of different seriousness. For example, global warming may be perceived to be more important than ozone depletion due to the serious consequences of climate changes that the former can lead to. The process of determining a weighted sum to reflect the total impacts for all the impact categories in a LCA study is referred to as weighting.

The function of the weighting step can be appreciated by referring once again to the case of student assessment. If the subjects taken by the students include two language subjects and three science subjects while it is thought that language and analytical abilities are equally important, the overall performance of each student can be determined by assigning a weighting factor of 1.5 to each language subject and a weighting factor of 1.0 to each science subject such that the weighted sum of the normalized subject marks will include contributions of equal weights from the language and science subjects, and thus can be taken as an overall indicator of the all round academic performance of individual students (see Figure 2.10).

![Figure 2.10 Weighted scores of five students: (a) individual subject and (b) total of all subjects](image)

As yet, there are no scientifically sound methods for determining the weights among impact categories for use in LCA studies. The method most widely used for determining the weights is based on subjective judgments on the relative importance of the impacts of individual...
categories, which are typically solicited from a panel of experts or from a representative cross-section of stakeholders.

**Interpretation of results**

The results from a LCA may be used to study which unit process contributed the greatest impact and if any abatement measures can be taken; or to compare the impacts of a product with another that serves the same purpose. The results can be examined in greater detail to see which impact categories are the more problematic such that measures that can pinpoint at the problematic impact types can be devised to mitigate the problem.

Since LCA results can be strongly influenced by the normalization and weighting factors used in the study, note should be taken in the interpretation of LCA results of the reference condition and the relative importance among the impact categories that are represented by the employed factors. Therefore, presentation of LCA results must include details about the normalization and weighting processes implemented.

**2.2 A brief history of LCA**

Reportedly, Coca-cola conducted a multi-criteria study in 1969 to compare between using glass and plastic bottles, which is believed to be the first LCA study ever conducted. More active development of LCA methodologies took place in the late 1980’s and in the early 1990’s, during which the efforts made by the Society of Environmental Toxicology and Chemistry, widely known by the acronym SETAC, have been instrumental. SETAC defined LCA as:

"LCA is an objective process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and material uses and releases to the environment, and to evaluate and implement opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing materials; manufacturing, transportation and distribution; use, reuse, maintenance; recycling and final disposal. The life cycle assessment addresses only environmental impacts and not other consequences of human activities such as economic and social effects."

An international standard framework for LCA studies has been developed toward the late 1990’s, which is covered in a series of ISO Standards, and is currently the authoritative standard LCA framework.

Subsequent to the 1992 Earth Summit in Rio de Janeiro, the United Nations Environment Program (UNEP) has been implementing programmes for promoting sustainable consumption and production. UNEP and SETAC have joined forces to facilitate the use of LCA and to promote life cycle management for both businesses and governments.

Uptake of LCA has been most active in the manufacturing sectors in West Europe, North America, Australia and Japan, and is emerging in other countries. Besides internal audits of environmental performance in individual companies, one of the major applications of LCA is for environmental performance declaration for products, i.e. eco-labelling. Application of LCA in building construction is a relatively recent move.
2.3 **Standardized LCA framework and procedures**

The set of international standards that provides a structured framework for LCA includes:


ISO Standard 14040 stipulates that a LCA shall comprise the following four phases:

1. Definition of goal and scope;
2. Inventory assessment;
3. Impact assessment; and
4. Interpretation of results.

Rather than a series of consecutive processes, the four phases of a LCA are interrelated, as depicted in Figure 2.11.

![Figure 2.11 Phases of a LCA (adapted from ISO Standard 14040)](image)

According to ISO Standard 14042, the life cycle impact assessment (LCIA) phase includes the following steps:

- Categorization (classification)
- Characterization
- Normalization
- Grouping
- Weighting

Note that in ISO Standard 14042, categorization and characterization are regarded as mandatory steps in a LCIA process but the other steps listed above are only regarded as optional.

Except for grouping, the functions of each of the above listed steps have been discussed in the preceding parts of this chapter. The optional grouping step allows impact categories to be aggregated into one or more sets to ease interpretation of results.
It should be noted that the LCA framework stipulated in the ISO Standards does not govern the more detailed procedures and methods and the choices of reference parameters for LCA calculations. For instance, there is no specification on which impact categories are to be embraced in a LCA study; how emissions are to be allocated to various impact categories; the substance to be used as the reference for characterization; the choice of normalization factors; the choice of weighting factors; etc. Hence, different life cycle impact assessment (LCIA) methods have been developed, which may lead to different results for the same product.
2.4 **Current and future LCA developments**

Rather than a mature method that is well-established, standardized and universally accepted, LCA methodologies are still undergoing rapid developments. An active development direction is toward the use of the endpoint approach. The distinction between the midpoint approach and the endpoint approach is depicted in [Figure 2.12](#).

As [Figure 2.12](#) shows, the midpoint approach stops at the stage when the chemicals that contribute to a specific impact category have been quantified. Further steps of life cycle impact assessment (LCIA), including characterization, normalization and weighting, will be based on the quantities of the chemicals determined.

The endpoint approach goes one step further to quantify the damages incurred by the chemicals released, and further LCIA steps will be based on the quantified damages. Conceptually, the endpoint approach is better than the midpoint approach as the quantification of impacts is in terms of the end effects of the impacts. However, this approach is at present limited by availability of scientifically sound methods for quantification of the damages.

---

**Figure 2.12** Distinction between midpoint and endpoint approaches for LCA: (a) with reference to ozone depletion; and (b) a general illustration.
One of the most significant hurdles to widespread application of LCA is the lack of LCI data for processes and products needed in LCA studies. Since the applicability of LCI data is region specific while making available LCI data requires input of ample amount of resources and cooperation of material and product manufacturers, regional or national efforts have to be made to make available the needed data for open access. This, indeed, is one of the major initiatives taken by governments of various countries to support pursuits for sustainable development.

At present, LCI data are available only for a very limited range of building materials. There are hardly any LCI data for building services equipments. However, we should not simply ignore LCA in building design based on this reason, because the required data will not be made available unless there is a demand. Such a demand will emerge and strengthen only if more designers are interested in applying LCA.

Marked by the launching of the LCEA tool, EMSD has taken the initiative to promote application of LCA to designs of commercial buildings in Hong Kong. Further development of the tool and the databases will be made if the tool is well-received by stakeholders in the local construction industry.

### A note on using abbreviations

The abbreviations to be used to denote terminologies of life cycle assessment are defined in the ISO Standards. LCA is to be used to denote life cycle assessment. LCI should only be used to denote life cycle inventory but should not be used to denote life cycle impact or any other terms. LCIA is reserved for life cycle impact assessment and should not be used to denote life cycle inventory assessment, etc. This convention is adhered to throughout this book.
3 Life cycle costing (LCC)

This chapter provides a concise description about life cycle costing (LCC), the key parameters that affect LCC results and application of LCC in conjunction with LCA.

3.1 The function of LCC

As stated in SETAC’s definition (see Section 2.2), LCA does not address economic impacts. However, in the pursuit of minimizing life cycle impacts on the environment, one cannot ignore the life cycle costs of the required improvement measures, as this is a key factor that influences whether or not such measures would be taken on-board. Obviously, people would not (and should not) be driven by environmental considerations to the extent that they would pay any costs, no matter how high, to achieve environmental improvements.

Far more often than not, there are alternatives that could lead to similar environmental improvements but would incur different costs. The cost-effectiveness of the options, therefore, should be evaluated to allow the target environmental improvement to be achieved in the most economical manner. Knowledge about the relative cost-effectiveness of different options would allow the options to be prioritized such that the budget, which is always limited, could be spent only on those options that would lead to the greatest environmental benefit, and hence the best result per dollar invested.

Life cycle costing (LCC) is a quantitative method that can be used to inform investment decisions, e.g. to tell whether it would be worthwhile to make an investment now for reductions in future expenditures and/or to borrow now for an investment with the loan paid back in the future. The method allows alternatives (options) that involve different time scales, and incomes and expenditures that take place at different time instants, to be brought to a common basis, the present value, for comparison.

LCC underpins systematic economic and financial ranking analyses which are needed for selection among mutually exclusive alternatives. In such analyses, the life cycle benefit and life cycle cost of each alternative can be evaluated using LCC method, which will allow the net pressure worth (NPW) or benefit-cost ratios (B/C) for each alternative to be evaluated. The NPW is an economic indicator that tells if an investment can lead to economic benefit while the benefit-cost ratio is a financial indicator that equals the return per dollar invested. A project will be worth undertaking provided its NPW is greater than zero or its benefit-cost ratio is greater than one.

3.2 A brief history of LCC application to buildings

Life cycle costing (LCC) is based on the theory of interest in economics, and has been in use for a much longer time than life cycle assessment (LCA). The first documented record on the use of LCC by the US government can be traced back to 1933. However, it was not until mid-1960s that LCC became a subject of considerable interest. The technique was initially more widely used in North America while interest in the technique in UK started in the 1950s, as the Building Research Establishment undertook a research on cost-in-use.

For application to evaluation of investments into building assets, LCC is defined in the 1995 edition of the National Institute of Standards and Technology (NIST) Handbook 135 as:
“The total discounted dollar cost of owning, operating, maintaining, and disposing of a building or a building system over the appropriate Study Period. The Study Period is the length of time period covered by the economic evaluation, which includes both the planning/construction period and the service period.”

Standard practice for measuring life cycle costs of buildings and building systems is defined in the ASTM Standard E917-99. In fact, LCC can be implemented at any level of design process for controlling the initial and the future costs of building ownership. It can also be an effective tool for evaluation of a full range of new and existing projects, from an entire site complex to a specific building system component.

Triggered by the energy crisis of the 1970s, it has been made a legislative requirement in the US, under the National Energy Conservation Policy Act, that a LCC assessment must be performed for energy conservation and renewable energy investments in existing and new federally owned or leased buildings. A manual was published in 1980 by the then National Bureau of Standards (NBS Handbook 135) to guide the LCC studies, which had been superseded by later versions. The latest version is the abovementioned 1995 edition of NIST Handbook 135, published by the National Institute of Standards and Technology.

The usefulness of a LCC assessment in assisting the decision maker depends on whether accurate estimates can be made of the initial and future costs, the period of time over which these costs are incurred (the study period), as well as the discount factor for converting the future costs to present values. In the NBS Handbook published in 1980, the discount rate (see later descriptions about its meaning) was fixed at 7% per annum, inflation rate inclusive. The initial energy cost and prediction of energy price growth, however, should be determined based on data provided by the US Department of Energy (US DOE). Furthermore, the study period was fixed at the lesser of 25 years or the expected lifespan of the system.

Starting with 1991, US DOE sets the discount rate each year on 1st October for the upcoming fiscal year rather than using the same discount rate each year. In addition, NIST has also made available a Building Life Cycle Cost (BLCC) program, which can be downloaded from the DOE website (http://www.eren.doe.gov/femp).

Nowadays, the concept of LCC is a part of most textbooks on engineering economics and is accepted by the engineering communities throughout the world. The CIBSE (Chartered Institution of Building Services Engineers) Guide includes a section on owning and operating costs. The Institute of Industrial Engineers includes a short section on life cycles and how they relate to life cycle costs in the Handbook of Industrial Engineering. Also, LCC of highway schemes is now accepted by the World Bank. More recently, LCC has been extended to embrace optimal design, maintenance, refurbishment and management of buildings, highways, defence facilities and health services facilities and, in conjunction with the use of probabilistic concepts, to deal with aspects of reliability and maintenance planning.

### 3.3 LCC calculation method

Life cycle costing (LCC) is based on the concept of discounting future worth of money to present value. For example, by making an investment of $P_0$ dollars at present, which will
generate interest at the rate of \( r \) per annum over a total period of \( N \) years, the return at the end of the \( N^{th} \) year, \( P_N \), will be:

\[
P_N = P_0 (1 + r)^N
\]

\( P_N \) is, therefore, the future worth of \( P_0 \) at the end of the \( N^{th} \) year for an annual interest rate of \( r \), with interest payable at the end of each year which will also generate interest at the same rate (i.e. compound interest). Conversely, \( P_0 \) is the present value of \( P_N \), which can be determined by discounting the future value \( P_N \) based on the interest rate \( r \) and the years of investment \( N \), as follows:

\[
P_0 = \frac{P_N}{(1 + r)^N}
\]

Hence, the total present worth (\( P \)) of an investment that will lead to an annual income of \( A \) dollars over \( N \) years at the interest rate of \( r \) per annum can be determined, as follows:

\[
P = \sum_{i=1}^{N} \frac{A}{(1 + r)^i} = A \left( \frac{(1+r)^N-1}{r(1+r)^N} \right)
\]

A \( P \) value that is greater than the total present cost of the investment implies that the investment will be worth making.

![Figure 3.1 Determining present worth of a uniform series of future incomes by discounting](image)

Note that if a person expects that by investing \( P_0 \) dollars now, the interest receivable will be at the rate of \( r \) per annum, which will result in a return of \( P_N \) dollars \( N \) years later (e.g. by purchasing US Treasury Bonds), in considering investing \( P_0 \) into something else, the investment will only be made if the interest rate for that investment exceeds \( r \). The interest rate \( r \) becomes the interest rate that will make spending \( P_0 \) now or spending \( P_N \) only \( N \) years later indifferent to that person.

If, within the investment period (e.g. \( N \) years), there is inflation at the rate of \( r_{inf} \) per annum, instead of the nominal interest rate \( r \), the real interest rate, more commonly referred to as
the real discount rate, \( d \), is to be used to determine the present worth of future incomes, which can be evaluated from:

\[
d = \frac{1 + r}{1 + r_{inf}} - 1
\]

Monetary values that have the effect of inflation adjusted are referred to as ‘constant dollars’. In the above formula for calculating the total present worth of a series of incomes, each being \( A \), if \( A \) is in constant dollars, \( r \) in the formula has to be replaced by \( d \); likewise for the other formulae for conversion between present and future values.

The principle above for discounting future incomes to present values applies equally to future expenditures. For instance, if an environmental improvement measure would incur a first cost \( C_0 \), and then a recurrent cost \( C_i \), in constant dollars, for each year during its life span of \( N \) years, and would have a residual value of \( R_N \) at the end of its life, also in constant dollars, the life cycle cost (LCC) of the measure can be computed as follows:

\[
LCC = C_0 + \left( \sum_{i=1}^{N} \frac{C_i}{(1 + d)^i} \right) - \frac{R_N}{(1 + d)^N}
\]

If the recurrent cost includes the energy expenditure the price for which is subject to an escalation rate different from the general inflation rate, the real energy price escalation rate, \( e \), can be determined from the nominal escalation rate, \( E \), as follows:

\[
e = \frac{1 + E}{1 + r_{inf}} - 1
\]

It can be seen from the above formula that if the nominal energy price escalation rate (\( E \)) equals the inflation rate (\( r_{inf} \)), the value of the real energy price escalation rate (\( e \)) will be zero.

Assume that implementing an energy saving measure will lead to an annual energy cost saving \( A \), which is evaluated at the present energy price, the life cycle energy cost saving, or benefit (\( B \)), over a life span of \( N \) years, taking into account the real discount rate (\( d \)) and real energy price escalation rate (\( e \)) can be determined as follows:

\[
B = A \cdot \sum_{i=1}^{N} \left( \frac{1 + e}{1 + d} \right)^i
\]

which can be simplified to:

\[
B = A \frac{(1 + e)}{(d - e)} \left[ 1 - \left( \frac{1 + e}{1 + d} \right)^N \right]
\]

The above formula cannot be used to determine \( B \) if the real discount rate equals the real energy price escalation rate (i.e. \( d = e = 0 \)) but, in this case, the value of \( B \) is simply:
If the life cycle cost of the energy saving measure is \( C \), the net present worth of the measure (\( NPW \)) and the benefit-cost ratio (\( B/C \)) of the energy saving measure will be:

\[
NPW = B - C \\
B/C = \frac{B}{C}
\]

It will be worth investing into the energy saving measure if its \( NPW \) is greater than zero, or the benefit-cost ratio is greater than one.

When different mutually exclusive options are available, selection among the options should be based on the \( NPW \) of the options, i.e. the one that will lead to the greatest \( NPW \) should be selected, as it will yield the greatest economic benefit. Note that the option selected on this basis could be different from the one that will lead to the greatest benefit-cost ratio. The benefit-cost ratio is just a financial indicator that reflects the return per dollar invested whilst investing more may still lead to greater economic return, and thus should not be discarded.

### 3.4 Sensitivity of LCC result to exogenous factors

The result of a LCC assessment can be strongly influenced by the choice of values for the exogenous factors involved, which include the nominal interest rate (\( r \)), the inflation rate (\( r_{\text{inf}} \)), and the energy price escalation rate (\( E \)). Varying the value of either \( r \) or \( r_{\text{inf}} \) changes the value of the real discount rate (\( d \)), and the latter will also affect the value of the real energy price escalation rate (\( e \)).

The influences of these exogenous factors to the LCC result are illustrated below with reference to a hypothetical case. The case is about an investment that would involve an initial cost of 100 units of money and a recurrent cost of 10 units of money per annum, in constant dollars, over a period of 50 years. The investment will lead to an energy cost saving of 20 units of money per year, which is evaluated at the current energy price.

The reference condition assumed is that the nominal interest rate is 5% per annum while both the inflation rate and the energy price escalation rate are 3% per annum. Accordingly, the life cycle energy cost saving (\( B \)) will be 636 units of money while the life cycle cost (\( C \)) will be 418 units of money. The net present worth (\( NPW \)) of the investment is therefore 218 units of money. Hence, the investment is worthwhile. However, the \( NPW \) of the investment can vary significantly with changes in the interest, inflation and energy price escalation rates, which may make the investment not worthwhile.

#### 3.4.1 Nominal interest rate

Figure 3.2(a) shows the changes in the \( NPW \) of the investment as the nominal interest rate (\( r \)) varies from 2% to 14% per annum, while the inflation rate and the energy price escalation rate remain unchanged.
Under the same inflation rate, the real discount rate \( (d) \) will rise with the nominal interest rate \( (r) \). Since the present worth of a future income will drop with rises in \( d \), the \( NPW \) of the investment diminishes with increases in the nominal interest rate. Figure 3.2(b) shows the relation between the \( NPW \) and the real discount rate \( (d) \) for this case. It can be seen from these figures that when \( r \) exceeds 13% or when \( d \) exceeds 10% per annum, the investment will become economically unviable.

### 3.4.2 Inflation rate

An increase in inflation rate \( (r_{inf}) \) impacts both the real discount rate \( (d) \) and the real energy price escalation rate \( (e) \), and hence the \( NPW \) of the investment. For the case where the nominal interest rate \( (r) \) and the nominal energy price escalation rate \( (E) \) are fixed respectively at 5% and 3% per annum, varying \( r_{inf} \) from 1% to about 5% per annum will lead to a drop in the \( NPW \) of the investment as shown in Figure 3.3(a). Corresponding to this change in the inflation rate \( (r_{inf}) \) is a drop in the real discount rate \( (d) \) from about 4% to nearly 0% per annum, as shown in Figure 3.3(b).

It can be seen that, rather than dropping with increases in \( d \), the trend of \( NPW \) is reversed in this case. Explanation for this observation is given below.
Recall that the life cycle energy cost saving ($B$) due to an annual energy cost saving evaluated based on the current energy price ($A$) is given by:

$$B = A \cdot \sum_{i=1}^{N} \left( \frac{1 + e}{1 + d} \right)^i$$

Furthermore, both the real discount rate ($d$) and the real energy price escalation rate ($e$) are determined from the inflation rate ($r_{inf}$) in the same manner as shown below:

$$d = \frac{1 + r}{1 + r_{inf}} - 1$$

$$e = \frac{1 + E}{1 + r_{inf}} - 1$$

![Graph (a)](image1)

![Graph (b)](image2)

**Figure 3.3** Variations in the net present worth of the investment with: (a) inflation rate; and (b) real discount rate when the nominal interest rate is fixed at 5% per annum and the energy price escalation rate at 3% per annum

It can be seen that $B$ is unaffected by the changes in $r_{inf}$ provided the nominal interest rate ($r$) and the nominal energy price escalation rate ($E$) both remain unchanged, as shown below:
However, the life cycle cost of the investment (C) will increase with reductions in the real discount rate (d), because a future money outlay of the same amount will become greater in present value as d drops. With B unaffected but C rises, the NPW of the investment will drop with increases in the inflation rate (r_{inf}), because the latter will lead to reductions in d.

### 3.4.3 Nominal energy price escalation rate

![Figure 3.4 Variations in the net present worth of the investment with the nominal energy price escalation rate when the nominal interest rate is fixed at 5% per annum and the inflation rate at 3% per annum](image)

Figure 3.4 shows the variations in the NPW of the investment with increases in the nominal energy price escalation rate (E) from 2% to 14% per annum, when the nominal interest rate and the inflation rate are both fixed respectively at 5% and 3% per annum.

The increases in the nominal energy price escalation rate mean that the energy cost saving (B) will become increasingly large. Therefore, given a fixed inflation rate, the NPW of the investment will be higher the higher the nominal energy price escalation rate.

### 3.5 Integrated LCA and LCC applications

Given that the majority of the decisions related to environmental performances will inevitably involve economic considerations, there is always an interest to combine environmental performances (as reflected by the LCA results) with economic performances (as reflected by the LCC results) into a single index or score to ease decision making. If there are reliable methods that would allow environmental impacts to be quantified in monetary values, the whole process of LCA and LCC can boil down to just a LCC assessment. Unfortunately, monetarization of environmental impacts remains difficult and imprecise and thus the present way of dealing with the problem is to have the two aspects of performance evaluated separately and combined through subjective judgements.
Initiatives have been made to develop subjective importance weights to aggregate these two types of performances into a single index or score. However, it is crucial that even if weights for the environmental and economic performances are available, separate assessment results should remain available for interpretation.

The concept of LCC is easy to apply but the result can be imprecise as its determination is dependent on a number of factors that are difficult to quantify precisely. The unit costs of various materials and components for building construction may be obtainable from data in recent returned tenders and taken as a reflection of recent market prices for such materials and components. However, the variety of materials and components in buildings is extremely wide, and their unit costs are dependent further on the methods and labour involved, which vary from one component to another. For instance, the unit price for cement, sand and aggregates for making concrete and that for steel reinforcement bars may be found but the costs for constructing different reinforced concrete elements, such as a column and a floor slab, could not be precisely determined from the quantities of the ingredients consumed. However, to produce a detailed unit cost database that can embrace all types of building components for all possible shapes, sizes and construction methods will require a prohibitively high cost to be paid.

Even with such a comprehensive unit cost database, the cost data may still fail to reflect the market rates as the prices for materials and labour vary. Prediction of price escalation is dealt with through the use of an inflation rate that covers all types of materials and components, which is just an approximation. Furthermore, the choice of a specific inflation rate that may seem reasonable now may become too high or too low in the future and this may happen many times given the long life span of buildings. Likewise, the nominal interest rate and the nominal energy price escalation rate are difficult to predict, but the values for these exogenous factors used in the LCC calculations are influential to the result, as shown in the preceding section.

It can be seen from the review described above that there are good resource supports to LCC in the US, which can greatly facilitate LCC studies. Similar supports are, however, lacking locally. This may explain, at least in part, why LCC is not yet widely practised in the local construction industry. In Hong Kong, there is no standardized method for evaluating economic viability of investments and various methods like payback period, internal rate of return and life cycle costing may be used. The key parameters, such as nominal discount rate, inflation rate, study period and energy price escalation rate, and the method for estimating costs, can vary from one study to another, largely up to what are perceived to be reasonable by the investigators.
4 A LCEA tool for commercial buildings in Hong Kong

In this chapter, readers are introduced to the life cycle energy assessment (LCEA) and life cycle costing (LCC) tool recently made available by EMSD. The introduction describes briefly the functions that the tool is intended to serve, the methods and data used in the LCA and LCC calculations, the processes through which the tool and its associated databases were developed, and some key features of the tool. More detailed descriptions about the features of the tool and the procedures of using it to perform LCA and LCC for buildings are described in the User Manual and exemplified in the Application Example, which are distributed together with the tool.

To allow readers to appreciate the way in which the tool can support designs of more sustainable building developments, the questions that designers may raise, and how the tool can help the designers address such questions are discussed in this chapter. In the discussion, readers' attention is also drawn to the tool's limitations.

4.1 Introduction to the LCEA tool

4.1.1 The main function of the tool
The LCEA tool is a computer program meant to facilitate building designers to predict the life cycle environmental impact and life cycle cost of commercial building developments in Hong Kong. It is intended to serve as an enabling means, to support designs of more sustainable commercial building developments in Hong Kong.

The LCEA program was written in Microsoft Visual Basic. This is a computer programming language that allows a programmer to incorporate into the program being developed various user interfaces that are familiar to users of application programs that run on the platform of Microsoft Windows, which is currently the most widely used operating system for personal computers. The present version of the LCEA program requires the use of a personal computer that uses Microsoft Windows XP as the operating system.

The present version of the LCA and LCC program is applicable only to commercial buildings, which is the dominant type of buildings in Hong Kong in respect of the environmental impacts that the buildings would incur. Compared to other types of buildings, commercial buildings are more extensively provided with building services installations and consume more energy.

Because buildings are complex artefacts that comprise a wide variety of components in large quantities, considerable amount of data have to be gathered and input into the program by the user before the program can predict the energy use and to perform LCA and LCC calculations for a building. User input data are required for defining the relevant design characteristics of the building, including its foundation, structural frame, envelope, internal and external finishes as well as the major services installations in the building. Admittedly, collecting and entering the large volume of data can be rather taxing.

In order to reduce the burden on the users, efforts were made in the development of the program to keep the amount of input data required to the minimum; to provide users with
facilities that can help simplify the data entry process; and to allow the users with the greatest degree of flexibility in preparing input data for modelling a building. There are front-end modules in the program with which the user can perform the data entry process conveniently (Figures 4.1 and 4.2 show a few examples). Other necessary data for performing LCA and LCC calculations have either been embedded into the program as default data or have been compiled and lodged into the accompanying databases. The tool also allows the users to make changes to default parameters used in the calculations, or to change its energy use and cost predictions, if deemed appropriate.

Figure 4.1  User interfaces for defining construction components and elements
Figure 4.2 User interfaces for defining building and plant characteristics for energy use prediction
The LCEA program has been incorporated with calculation routines that enable it to predict:

- The annual operating energy use of a building for running the major building services systems in the building, which include air-conditioning and mechanical ventilation systems, lighting installations and other electric appliances, lifts and escalators, fire services, plumbing and drainage installations, and where applicable, gas consuming equipment in the building; and

- The life cycle environmental impacts and life cycle cost due to consumption of materials and energy for construction, operation, maintenance and demolition of a building.

Additionally, the program will calculate:

- The life cycle energy use of a building, which includes the energy used during the production and transportation of the consumed materials, and the energy use during the operating stage of the building. The former type of energy use is referred to as the ‘embodied energy’ of the materials.

- The amount of solid wastes that will be produced during the construction and demolition of the building and due to replacement of components throughout the operating stage of the building.

The program will output the following results:

- The life cycle environmental impacts of the assessed building, quantified by a set of 10 impact indicators, one for each of the 10 impact categories embraced by the adopted life cycle impact assessment (LCIA) method. All results calculated after the characterization, normalization and weighting steps of the LCIA process will be shown.

- The weighted sum of the impacts of the 10 impact categories, as an all-embracing environmental impact indicator.

- The life cycle energy use and solid waste production of the assessed building, as two supplementary impact indicators (see later discussions in Section 4.1.2.1).

- The life cycle cost of the assessed building and energy consumption.

- An overall performance indicator that represents the environmental-cum-financial performance of the assessed building.

- Breakdowns of the life cycle impact, cost, energy use and solid waste production of the assessed building by different composing parts of the building and by different stages in the life cycle of the building.

The main result output form in the program is shown in Figures 4.3(a). Figure 4.3(b) shows the graphical output form in the program that allows the user to view the assessment results for different composing parts or life cycle stages. Figure 4.4 illustrates the relations among the user input data, the databases that supply the program with pre-calculated data and the life cycle energy, LCA and LCC calculation processes implemented in the program.

Besides using the LCEA program to quantify the life cycle impact and life cycle cost of a specific design for a building, the user can make changes to the characteristics of the building design to visualize how effectively different design features can help enhance the performance of a building. This will enable the designer to select the optimal combination of design features for adoption, which is perceived as the most important function that the LCA and LCC program is intended to serve.
Figure 4.3 Main output and graphical output forms in the LCA and LCC program
Figure 4.4 Relations among processes implemented within the LCEA program

4.1.2 Methods and data for LCA and LCC calculations

Impact categories and impact profiles of materials

The LCA calculations implemented in the program are based on pre-calculated impacts data for materials (Figure 4.4), which were evaluated using the CML 2 Baseline 2000 life cycle impact assessment (LCIA) method. This LCIA method embraces the 10 impact categories listed below, which are regarded as ‘must include’ in most LCA studies.

1. Abiotic depletion
2. Global warming
3. Ozone layer depletion
4. Human toxicity
5. Fresh water aquatic ecotoxicity
6. Marine aquatic ecotoxicity
7. Terrestrial ecotoxicity
8. Photochemical oxidation
9. Acidification
10. Eutrophication

The CML 2 Baseline 2000 method is a well-established and well-documented LCIA method which adopts the mid-point approach (see Section 2.4). In this LCIA method, the 10 impact indicators determined after the characterization step are the equivalent total quantities of the reference natural material consumed (for the abiotic depletion category) or the reference emissions released (for the other 9 categories) for the respective impact categories.
For each kind of material, the impacts in the above 10 impact categories that would be incurred due to the consumption of a unit quantity of the material are collectively referred to as the impact profile of the material. The impact profile for each material was expanded to include also the embodied energy and unit price of the material, which are the needed data for the program to determine the life cycle energy use and life cycle cost of a building.

Impact profiles for the materials were pre-calculated and lodged into the databases that accompany the LCEA program (Figure 4.4). To allow the program to determine separately the impacts that will be incurred due to treatment of construction and demolition wastes, a separate database was established which contains the impact profiles for just the landfill processes for the materials.

The program will evaluate the impacts, embodied energy use and cost incurred due to consumption of materials within the life cycle of a building based on the quantities of various materials involved and the respective impact profiles of the materials. Determination of material consumption includes those incurred due to replacement of building and services components within the life cycle of a building, and any auxiliary materials used and wastage incurred during the construction and replacement processes. The solid waste product calculation is based simply on the total quantities of all kinds of materials used, which will finally be disposed of.

Note that the two supplementary impact indicators for life cycle energy use and solid waste production are excluded from the normalization and weighting processes for calculation of the overall impact indicator, to avoid double counting. This is because depletion of fossil fuel reserve and the emissions resulting from burning of the fuels for electricity or heat generation have already been accounted for, under the impact categories of abiotic depletion, global warming, acidification, etc., within the 10 impact categories embraced by the LCIA method. The impacts of solid waste disposal have also been accounted for by the landfill processes included as the end-of-life treatment process for various types of materials and products, which would also contribute to the relevant impact categories.

Establishment of impact profiles for materials

The impact profiles that the program uses for LCA calculations were established from life cycle inventory (LCI) data sourced from proprietary LCI databases procured for use in the tool development work. Those LCI data, however, can only reflect the environmental impacts incurred due to consumption of the materials in the specific regions for which the proprietary databases were established, which are different from the places of origin from which materials are imported into Hong Kong for building construction. Differences in the incurred impacts exist when different mixes of energy sources are used in the production of the materials. Transportation of the materials to Hong Kong would also incur significant extra impacts. Therefore, adjustments had to be made to the LCI data obtained from the proprietary LCI databases in order to produce LCI data that can reflect the impacts that will be incurred by consuming the materials in Hong Kong.

The LCI data adjustment process made reference to the following information:

• Import statistics, which included data about the quantities of materials imported from various countries into Hong Kong;

• The transport distances between those countries and Hong Kong; and
• The energy mixes used in those countries for electricity generation.

The LCI data adjustment work was performed through the use of a generic, proprietary LCA program. The same program was used to perform the characterization step of the life cycle impact assessment (LCIA) process to yield an impact profile (which includes impact values for the 10 impact categories; embodied energy and unit cost data were appended later to the impact profile) for each material, which became the contents in the impact profile database.

Obviously, it is impossible to establish impact profiles for the very wide range of materials that can possibly be found in commercial buildings in Hong Kong. The two major constraints were the time and effort required for the LCI data adjustment process, which was a demanding task; and the very limited life cycle inventory (LCI) data for construction materials that could be sourced from the proprietary LCI databases.

In order to keep the database development work manageable and to ensure the database can cover those materials that dominate the life cycle impact of commercial buildings in Hong Kong, a survey of materials used in local commercial buildings had been conducted. The survey was based on the bills of quantities of 28 projects. The assessment unveiled that for the commercial buildings surveyed, 99.5% of the total environmental impacts due to material consumption was contributed by 20 kinds of materials while LCI data for these materials could all be found from the proprietary databases. The current version of the impact profile database covers 41 materials, including the 20 kinds of dominant materials.

Normalization factors

The normalization factors (see Section 2.1.3.4) embedded into the LCEA program are the impacts due to consuming 1TJ (Tera-Joule) of electricity locally in Hong Kong. This choice was made because of the following considerations:

1. Commonly used normalization factors are the total impacts incurred in a year in the geographical region concerned (e.g. in a country or a continent or in the whole world), which may also be scaled down to impacts per capita. However, sufficiently detailed and comprehensive data embracing all sorts of socio-economic activities for evaluation of the total impacts under each of the ten impact categories, as would be incurred in the whole Hong Kong were unavailable.

2. Electricity generation is responsible for a large proportion of pollutant emissions in Hong Kong (for around 86% of SO2, 60% of CO2, 43% of NOx and 37% of particulate matters). Therefore, as a basis for impact quantification, the impacts due to electricity use are a good substitute of the city-wide total impacts. Furthermore, for typical commercial buildings in Hong Kong, their operating energy use, which is predominantly electricity, usually dominates the life cycle impact of the buildings.

3. The reference impacts are domestic, which are therefore more relevant than applying impact figures available in the literature for other countries, continents or for the whole world.

4. The life cycle impact of a building quantified on this basis will assist comprehension, as the value of the building’s impact can be interpreted as equivalent to that due to consumption of an equal number of TJ of electricity in Hong Kong.
5. With the impacts of a building normalized based on the impacts of consuming 1TJ of electricity in Hong Kong, normalizing the life cycle cost of a building by the price of 1TJ of electricity will provide a consistent basis for the two aspects of assessment.

6. Referencing the life cycle impact of a building to electricity use also provides a good basis for considerations of trade-offs between life cycle impact and life cycle cost. Where improving the design of a building would yield a reduction in its life cycle impact by an amount equivalent to that due to a reduction in electricity use by a certain amount, the cost of the reduced amount of electricity use may be regarded as a return to the investment made in the measures that would lead to the reduction in the impact of the building. The investment could be considered worth making if the life cycle cost of the measures is lower than the electricity cost saving.

Since the impacts and the cost of consuming 1TJ of electricity may both change with time (the impacts are dependent on the fuel mix used in Hong Kong for electricity generation, e.g. the shift from coal to natural gas as the main fuel will lead to reduced emissions), the normalization factors for impacts and cost will need to be updated when substantial changes in the fuel mix for electricity generation and/or the electricity price take place.

Users can view the normalization factors used in the program by calling up the relevant form (Figure 4.5), but they are not permitted to change the normalization factors.

![Weighting Factors](image_url)

Figure 4.5.1 Normalisation and weighting factors used in the LCA and LCC program

**Weighting factors**

Given that there are still limited scientific evidence to support derivation of objective weighting factors for the categorized impacts and for impact and cost, the weighting factors used in the LCEA program were derived from subjective valuations, as expressed by a
group of stakeholders who were invited to unveil their valuations on the issues through responding to a questionnaire at the end of a forum. In the forum, an introduction to LCA and LCC was given, the need for normalization and weighting in LCA and LCC of buildings was explained and the ten impacts for which the respondents were required to judge their relative importance were introduced, before the questionnaire survey was conducted.

Since weighting of LCA and LCC results is subjective, the set of weighting factors derived from the questionnaire survey was only used as default data. Users of the program are allowed to define weighting factors of their choice for the program to use in the LCA and LCC calculations. The form shown in Figure 4.5 can be called up to view the default weighting factors, or to define the weighting factors preferred by the user.

**Decomposing a building for modelling**

To facilitate systematic handling of the user input data and the calculation processes and to permit outputs of results for different parts and life cycle stages of a building, the program adopts a specific method to model a building. The method used involves disaggregating a building into smaller and smaller parts by several levels.

At the first level, a building is broken down into three Portions, namely the Foundations, Floors and Services Portions. In the next level, each Portion is broken down into a number of Component Groups. For example, each floor in the building may be a Component Group of the Floors Portion and each discipline of services installations, e.g. HVAC or electrical and lighting, may be a Component Group of the Services Portion.

![Figure 4.5.2 Three Building Portions](image)

Decomposition of the building goes further with dividing the Component Groups into Components and further subdividing the Components into Elements. For example, each layer of material in a composite wall may be an Element of the wall, which is regarded as a
Component of the Floor Component Group. As a result, a hierarchy of objects is defined, with an object at one level being made of a number of objects at the level below.

Calculation of impacts and costs due to consumption of materials will be performed at the Elements level but, according to the defined hierarchy, the results for the Elements can be aggregated to permit results for objects at each of the upper levels to be evaluated and reported. Through this method, the program is able to output LCA and LCC results separately for the foundation, structural frame, envelope, other materials, such as partitions, false ceilings, etc. on individual floors, and for each of the services systems.

**Standard and generic elements**

To ease preparation and entry of user input data into the program for modelling a building, models for a range of building and services system elements have been prepared and lodged into a set of data libraries. This allows the user to select appropriate element models from the libraries such that a building model can be conveniently assembled from these element models for LCA and LCC evaluation.

In each element model, the types of materials that make up the element, the types of auxiliary materials that would also be used in construction of the element, the portions of the materials that would become wastes during the construction stage, and the life expectancy of the element are assigned with default values in the model, which may be altered by the user. The input data that the user has to provide are thus limited to parameters (e.g. dimensions) that determine the quantity of each type of material that would be consumed. Figure 4.6 shows a few examples of those elements for which element models are available from the libraries accompanying the LCEA program.

A generic element model is also included such that where an element falls outside the coverage of the element models in the libraries, the generic model may be used to model the element provided all the composing materials of the element are available from the impact profile database. The user can select the types of materials and specify the quantity, wastage rate and life expectancy of each material using the generic element model to build a model for the element concerned (Figure 4.7).
<table>
<thead>
<tr>
<th>Description</th>
<th>Required input data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rectangular reinforced concrete column</strong></td>
<td>W: Width of column cross-section (m)</td>
</tr>
<tr>
<td></td>
<td>D: Depth of column cross-section (m)</td>
</tr>
<tr>
<td></td>
<td>H: Height of column (m)</td>
</tr>
<tr>
<td></td>
<td>m_S: Mass of steel per unit volume of component (kg/m³)</td>
</tr>
<tr>
<td>[Diagram of rectangular reinforced concrete column]</td>
<td></td>
</tr>
</tbody>
</table>

| **Reinforced concrete beam**                              | W: Width of beam (m)                                                               |
|                                                          | D: Depth of beam (m)                                                               |
|                                                          | L: Length (span) of beam (m)                                                       |
|                                                          | m_S: Mass of steel per unit volume of component (kg/m³)                            |
| [Diagram of reinforced concrete beam]                     |                                                                                     |

| **Reinforced concrete wall and partition**                 | T: Thickness of wall (m)                                                           |
|                                                          | W: Width of wall (m)                                                               |
|                                                          | H: Height of wall (m)                                                             |
|                                                          | w: Width of opening (m)                                                           |
|                                                          | h: Height of opening (m)                                                          |
|                                                          | m_S: Mass of steel per unit volume of component (kg/m³)                            |
| [Diagram of reinforced concrete wall and partition]       |                                                                                     |

Figure 4.6  Examples of standard element models in the element libraries
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Figure 4.7 Selection of generic model for an element and data entry for the element

Because services equipment are complex assemblies of a vast amount of different materials, services element models were established on the basis of typical designs of the respective types of equipment. Equipment of the same type but of different capacities are regarded as different elements. This means that each equipment model is assumed to be made of a pre-assigned range and quantities of materials, which cannot be altered by the user, and the entire piece of equipment is modelled as if it is a ‘material’. Nonetheless, a few services elements, such as light troughs, duct and pipe insulations, etc. are modelled by standard elements, which would require user input data about their dimensions.

4.1.3 Methods and data for predicting annual energy use
The choices of component types and system designs for fabric construction and services installations in a building affect not only the impacts due to consumption of resources for production, construction and installation of the materials and components in the building, the heat gains of air-conditioned spaces and the energy use for air-conditioning in the building...
can also be significantly affected. Therefore, the use of a low impact, low cost component may not necessarily be a desirable choice, as it may result in an increase in energy use and, in turn, higher overall impact and cost, and vice versa. Therefore, life cycle assessment (LCA) and life cycle costing (LCC) of a building must take a holistic approach; ignoring the influences of building and system designs on the energy use of a building will lead to wrong decisions. Such influences, however, are complicated and their prediction requires the use of detailed simulation methods.

One of the key features that distinguish the present LCEA tool from other available LCA and LCC tools is that it includes a detailed building energy simulation model for prediction of the hourly space cooling load and air-conditioning energy use of a building. This permits an assessment of the impacts of using alternative building and system designs to take account of not only the use of different materials and equipment in the alternative designs, the consequential effects on the building cooling load and air-conditioning energy use due to the use of the alternative designs can also be assessed through the use of the same tool.

The air-conditioning energy use prediction model

The air-conditioning energy use prediction model in the LCA and LCC program includes:

- A finite difference model for simulation of heat transfer through the building fabric;
- A heat balance model for prediction of cooling load due to heat gains in a space; and
- Steady-state plant models for prediction of energy use of air-conditioning plants.

The selection of modelling methods took into account the rigor of the methods, and the time and effort required in developing the required computer codes.

Since the application of the energy prediction model will be confined to commercial buildings in Hong Kong, the year round hourly weather conditions as well as the usage characteristics were pre-defined and embedded into the simulation program as default data, thus largely reducing the amount of input data to be prepared and entered by the user. Pre-defined characteristics of premises inside commercial buildings include occupancy patterns, lighting and small power patterns and air-conditioned hours for offices, retail shops, restaurants and hotel guestrooms, which have been embedded into the program for prediction of the space cooling loads and energy use of lighting and appliances in these types of premises.

Furthermore, some parameters, such as the solar intensity incident upon a surface facing a specific direction, can be pre-calculated and used as default data, to speed up the calculation. Using pre-calculated solar irradiance on surfaces, however, requires limiting the exposure directions of envelope components in a building to a few pre-determined values. Hourly solar intensities upon surfaces exposed to the eight principal directions for vertical components, namely N, NE, E, SE, S, SW, W and NW, and upon a horizontal surface were pre-calculated and the results were stored together with other climatic data, e.g. dry-bulb and dew-point temperatures, in a weather data file from which the program can retrieve the data for performing cooling load calculations.

To allow the cooling load calculation program to take account of the effects of shading devices, the calculation routine utilizes a set of data, referred to as a shading mask (Figure 4.8), to characterize the shading effect of such devices. Calculation routines are also
included to produce shading masks for relatively simple shading devices, such as an overhang or a side-fin or a combination of an overhang and one or two side-fins.

Models for the following major air-conditioning equipment have been incorporated into the program for prediction of their energy use for coping with the cooling requirement of the air-conditioned spaces:

- Air-cooled and water-cooled chillers, covering chillers that use centrifugal, reciprocating and screw type compressors;
- Cooling towers;
- Heat exchanges; and
- Pumps and fans, with and without variable speed control;

The chiller condenser heat rejection systems that can be modelled include (Figure 4.9):

- Direct air-cooled systems
- Direct seawater-cooled systems
- Indirect seawater-cooled systems
- Water-cooled systems with cooling towers
- Indirect water-cooled systems with cooling towers

The chilled water distribution systems that can be modelled include:

- Single-loop pumping system with differential pressure by-pass control (Figure 4.10); and
- Two-loop pumping system with and without variable speed secondary-loop pumps (Figure 4.11).

![Diagram of chiller plants](image)

**Figure 4.9** Schematic diagrams of chiller plants

![Diagram of single-loop chilled water pumping system](image)

**Figure 4.10** Single-loop chilled water pumping system

![Diagram of two-loop chilled water pumping system](image)

**Figure 4.11** Two-loop chilled water pumping system
The program can model any of the following air-side systems:

- Constant air volume (CAV) or fan-coil systems; and
- Variable air volume (VAV) with and without variable speed control

Fresh air supply for air-conditioned spaces can be from outdoor air drawn in by the air-handling units serving the spaces or from a central fresh air treatment plant.

**Energy use of other services systems**

Except for the central air-conditioning system, the annual operating energy use (AEC) of all types of services systems in a building will be estimated using a simplified approach, as follows:

\[ AEC = WD \times AOH \times LF \]

Where

- \( AEC \) = annual energy consumption (kWh)
- \( WD \) = power demand (kW)
- \( AOH \) = annual operating hours (h)
- \( LF \) = load factor (-)

The product of \( AOH \) and \( LF \) equals the annual equivalent full-load hours, which is also used for estimating the annual energy use of lighting and equipment in air-conditioned spaces. The annual equivalent full-load hours were determined based on the patterns of use of lighting and equipment in the respective type of premises, which are consistent with those used in determining the cooling load due to these internal sources for space cooling load prediction.

For gas consuming systems, the calculation will be based on the following method:

\[ AEC = RCap \times AOH \times LF / Eff \]

Where

- \( RCap \) = rated capacity (heat output, kW)
- \( Eff \) = efficiency (-)

All the annual energy use calculation results, including electricity and heat from gas, will be converted to values in MJ (1 kWh = 3.6 MJ), to match with the base unit of the impact profile figures used in the LCA calculations as well as the unit of embodied energy of materials.

**4.2 Making the best use of the tool**

To a building designer, the usefulness of a design tool depends on whether the tool can perform the required functions in the specific ways as he/she will want it to perform such that it can help him/her complete a design task, including finding solutions to specific
problems; the more comprehensive and versatile its functions, the more useful the tool. However, each building development project may have design objectives and may be subject to design constrains that are different from other projects. Therefore, specific design considerations need to be given by the designer to individual projects, who may turn out design solutions unique to each building development project.

Furthermore, how designers formulate approaches to solving problems is highly variable. Hence, even if the function is well-defined, e.g. the present program is dedicated to quantification of the environmental and financial performances of a building, it is impossible to produce a tool that can serve well every designer on every project.

Every design tool has limitations in its functional capabilities and the versatility in the ways that the tool can handle specific tasks. However, some such limitations can be overcome if the user understands well how the tool performs its functions such that, where needed, he/she can re-formulate the solution approach, and to appropriately adjust the input data to allow the tool to produce useful results. Therefore, how well a design tool can serve a designer is also dependent on whether the designer can make the best use of the tool.

4.2.1 Functional limitations of the tool

For the LCEA program, its databases and libraries can only cover a limited range of materials and element models. As mentioned in Section 4.1.2.2, the material impact profile databases cover only 41 kinds of materials, although they already include the 20 kinds that together dominate the life cycle impacts of commercial buildings in Hong Kong due to consumption of materials. If there are materials in a building that fall outside the range of materials covered by the databases, those materials will have to be left-out in using the program to perform LCA and LCC calculations.

In fact, provisions have been made in the development of the program and the databases such that the databases can be expanded to embrace more kinds of materials. However, no facilities have been incorporated into the program to allow users to insert new materials into the database because:

- Impact profiles for new materials can be produced only if appropriate LCI data for the materials are available. If the LCI data are not specifically for Hong Kong, the data need to be adjusted such that the resultant impact profiles can reflect the impacts due to consumption of the materials in Hong Kong. The LCI data adjustment work also requires the use of a generic LCA program that can implement the same LCIA method used for producing those impact profiles for materials already lodged into the databases. It is unrealistic to expect that target users of the program will be able to perform these complicated tasks.

- A consistent numbering convention has to have been used in the program to define material numbers which serve as pointers to the records for individual kinds of materials in the databases. This convention must be adhered to in expanding the databases. Otherwise, exchange of user input data will become problematic or LCA and LCC calculations will be in error.

The limitation in the coverage of the element libraries is less restrictive. Provided all the materials involved are covered by the impact profile databases, elements that fall outside the coverage of the standard element libraries can still be modelled through the use of the
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generic element model (see Section 4.1.2.6). In this case, the user will need to determine the quantities of each material involved and input the quantities together with the wastage percent and life expectancy of the element. Furthermore, user are permitted to make changes to the kinds of composing materials defined for the standard element models, including the auxiliary materials, if any, and to change the default life expectancy and unit cost for each material (see further discussions on this feature in Section 4.2.2 below).

The user input facilities and calculation modules in the program were devised to allow the user to model a building in detail, with the building and its services systems broken down into components and elements. For example, the user can define in the input data the dimensions of each beam, column, slab, etc. for the program to determine the quantities of different kinds of materials that will be consumed for constructing the components and elements, and the associated impacts. Similarly, the user can model services installations by inputting data about sizes of individual duct and pipe sections as well as capacity and size of major equipment of the building services installations.

However, before detailed architectural, structural and building services designs for a building are complete, detailed component and element data will not have been made available, but many design decisions have to be made before detailed designs can commence. How a building can be approximately modelled before detailed data are available is discussed in Section 4.2.3 below. Similar applies to the inputs required for space cooling load and air-conditioning energy use prediction, which is also discussed in that section.

The huge amount of user input data needed for modelling a building may also be considered too tedious by users. Several ways through which users may minimize the quantity of input data are described in Section 4.2.4. The data preparation and input task may also need to be shared by different parties in the design team, such as the architect, the structural engineer and the building services engineer. Section 4.2.5 describes the points that should be noted when users pass-on or exchange input data.

### 4.2.2 Assessing alternatives

A building can be constructed by using different designs, construction methods and materials. For instance, steel structural frames and metal decking may be used in lieu of reinforced concrete columns, beams and slabs for the building structure, or curtain walls may be used in lieu of windows and walls for the envelope. For alternatives of this nature, which differ substantially from one another in their designs or in the construction methods involved, each will have to be modelled separately for a comparison of the differences in the life cycle impacts and life cycle costs incurred when different alternatives are employed.

Many alternative designs or constructions can be dealt with at the component level, through assembling component models from different combinations of elements. If the difference between two alternative components is limited to addition, replacement or removal of one or a few elements, the first component model established may be re-loaded and edited for modelling an alternative component, by inserting, replacing or deleting the element models concerned. The *Application Example* document includes descriptions on examples of this method and the procedures involved.
Users may come across with construction methods and materials that require element models beyond those embraced by the libraries accompanying the LCA and LCC program. For instance, all reinforced concrete elements in the libraries assume that plywood formworks will be used in their construction but designers may consider using metal formworks instead. Some components may also be prefabricated off-site rather than being constructed entirely on-site.

The generic element model and the provisions made in the program to allow the user to change the default attributes of composing materials in a standard element model can be used to overcome the problem of lacking matching standard element models from the libraries. Figure 4.12 shows the forms through which the default attributes of standard element models can be modified.

For example, for the case of using metal formwork instead of plywood formwork, the type of material for the formwork can be changed from plywood to the metal being used, by selecting the specific metal on a list that can be called-up, which shows the materials embraced by the databases. The inputs for the thickness and the number of times that a formwork will be used before disposal can then be adjusted accordingly. If the component is pre-fabricated off-site, the wastage percent for the formwork and, where appropriate, for other composing materials may also be changed to a smaller number to reflect that this method can lead to less wastage.

![Figure 4.12 Change default attributes for elements](image)

Note that the changes made to the default attributes of an element apply only to the specific element concerned and will not affect other elements modelled using the same standard element model.
4.2.3 Assessing an entire building or a part of it

The scope and level of detail required of an assessment are dependent on the purpose of the assessment, which in turn dictates the type and amount of input data required in a simulation run. The LCEA program will calculate the impacts and costs for as many components and elements as the user has defined in the input data. The user may also select to skip any Portions, Component Groups, Components or Elements from a simulation (see Section 4.1.2.5 for meanings of these terms and Figure 4.13 for the provisions in the program for this purpose). Furthermore, calculation of operating energy use of all or individual services installations can be skipped if the impacts and costs due to the operating energy use of those services installations are irrelevant to the assessment.

![Figure 4.13 Controls for omitting parts of a building from calculations](image)

Therefore, for an assessment that targets only at comparing several alternative features for a specific part of a building while using any one of the alternatives will not affect the construction and performance of the other parts of the building, all the inputs for the other parts of the building can be omitted. For example, assessing the differences in the incurred impacts and costs due to the use of alternative foundation designs or alternative structural components can be done without inputs that describe the envelope and the services installations.

Although the program will determine the consumed quantities of materials and the associated impacts based on the user input data for individual elements, the user input data that describe the elements need not be congruent with the actual elements in the building in
every respect. For example, there will only be negligible differences, if any, in the predicted impacts and costs if a number of beams of the same width, depth and quantities of steel reinforcement bars per unit length are modelled separately by an equal number of elements or collectively by just one single element with a length that equals the total length of all the beams.

Alternative air-conditioning system designs may also be compared against one another without considering the impacts and costs incurred due to construction of the building. The results will be valid if the heat transfer characteristics of the building fabric and the internal heat gains in air-conditioned spaces remain unchanged throughout all alternative systems being assessed. This is possible because space cooling load prediction in the program is based on a set of building heat transfer characteristics data that is separate from that for evaluating the impacts and costs due to consumption of materials for building construction.

However, assessing alternative envelope designs cannot ignore the impacts on air-conditioning energy use in the building. Otherwise, the predicted benefits and costs of the alternatives will just be a partial picture, which can be misleading. Likewise, assessing alternative lighting installations must also account for the differences in the impacts on the air-conditioning energy use. Before sufficient data are available for modelling the air-conditioning system, system models may still be established based on ball-park figures, which can be refined later.

It can be seen that it is up to the user to determine the degree of detail of the data to be input for modelling a building or a part of it to meet a certain purpose. It will be more flexible to making future changes to the input data the more detailed the input data, but more efforts are also required for obtaining and inputting the greater volume of data. Prior to completion of detailed designs for a building, detailed data for many building and services components and elements would not have been made available but the program may still be used for assessing individual parts of the building.

Where an estimate of the impacts and costs are required for those parts for which detailed data are missing, the user may choose a simpler way of data input to enable approximate results to be obtained. The crude models can later be replaced by refined ones when more detail data become available. Thus, a building development is modelled in an iterative manner, with increasing level of details to match the needs at different stages in the design process, to assist the designers to make choices among alternatives that will improve the environmental and financial performances of the building.

### 4.2.4 Optimizing the amount of user input data

Specific considerations had been given in designing the program to minimize the required amount of user input data and to speed up the data entry process. The extent to which user input data can be reduced, however, is dependent on the way in which the user decomposes a building into components and elements.

For a building that comprises many repetitive parts, data input are required only for each unique part, plus a number that indicates the total number of parts that are represented by the data for the unique part. This applies to all Element, Component and Component Group
objects. For example, identical columns on a floor may be modelled by the data for just one column together with the total number of identical columns on the floor. Typical floors in a high-rise building can also be described by the data for one of the typical floors and the total number of floors identical to it. The same method is also used in handling data input for space cooling load predictions.

The program will save the user input data for individual objects, including Portions, Component Groups, Components and Elements, into separate files. The same file for a specific object can be used to model identical objects that form parts of other objects by selecting the file by its filename when data are being input for the objects.

For instance, when an Element model has been established to represent an internal finish layer in a wall (a Component), if there are other walls that are identical in area and have the same internal finish layer, the same data file can be used for modelling the finish layer in all these walls, even though these walls may be composed of different internal layers of materials and may have different external finishes. If there are differences in the attributes of the finish layers among different walls, e.g. different width, height and thickness, the file can still be loaded, but this time, the data will have to be modified and saved into another file with a different filename. Data files prepared for objects in a previous project may also be copied, modified if needed, and used for modelling objects in a new project.

For those parts of the building for which no alternative designs will need to be considered, they may be aggregated and modelled using fewer element models, which will help reduce the amount of data to be input and will also speed up the calculation (see the example described in the preceding section on using one element model to represent multiple beams).

By fully utilizing the features as mentioned above, a user can largely simplify the process of inputting data for modelling a building project, and will be able to perform data input more and more efficiently, as more and more component and element models have been established for previous projects or for the new project.

4.2.5 Exchanging input data among users

LCA and LCC study for a building has to embrace the entire building, which requires inputs from different members of the design team, including the architect, the structural engineer, the building services engineer and the quantity surveyor. Since the designs of different parts of a building can influence the performance of other parts, and thus the LCA and LCC results, e.g. the air-conditioning energy use of a building is subject to the influences of the envelope design and the lighting design, one of the design team members has to shoulder the responsibility of conducting the overall assessment. This gives rise to the need for passing back and forth data files among the design team members, especially when alternative design features are being explored for optimization of the building design.

To facilitate systematic data file management and exchange of data files among users, the LCEA program requires that all user input data files pertaining to a project are stored inside a dedicated file folder, which is used exclusively for the project. When the user creates a new project, the program will create a new folder for storing all the data files for the project. The program will also put all its output files for the project into the same file folder.
When individual members of a project design team start to prepare input data, each user will have created for the project a project folder inside the disk drive in his/her computer, and have the prepared data files stored inside the folder. When one receives data files from other design team members, he/she has to copy the received data files into the folder created for the same project such that the program can access data in those files. In this process, great care must be taken to ensure the same filename is not used for different object data files. He/she should also load the data supplied by others into the program carefully while assembling the data to model the entire building.

It is advisable to ask one of the members in the design team, preferably the building services engineer, to be responsible for coordination of the data files created by different design team members, to avoid confusion of files and loss of data, as well as for conducting the overall simulation. The building services engineer is nominated to be the coordinator because, in addition to the services system component and element data for determining material use of the systems, he/she will be responsible for the data input for prediction of the operating energy use, which will together amount to a dominant part of the total amount of input data for a project.

Once a whole building model has been established but files need to be passed back to design team members for preparing new data or editing existing data, it is advisable to have members working on the project in turn, one at a time. Furthermore, all data files pertaining to the project concerned should be passed-on from one design team member to the next, for making further changes to the data.
5 Prospect of application of LCA and LCC to support sustainable building development in Hong Kong

Aimed at promoting more sustainable commercial building development in Hong Kong, EMSD has made available a LCEA tool, which is meant to be an enabling means for realizing this aim. The tool may be used for different purposes, such as:

a) Simply as a design tool to support designers to optimize building designs by enabling them to quantify the environmental and financial performances of building designs; or

b) As a tool for quantification of the sustainability of building designs to support assessment, comparison and labelling of building developments.

The two purposes are not mutually exclusive but purpose b) further requires the co-existence of a relevant assessment scheme, which may be a mandatory or voluntary scheme. Besides assessment methods and procedures, benchmarks are to be defined in the assessment scheme for determining the assessment outcome, such as the threshold level for determining whether a building passes or fails the assessment, or the criteria for ranking the performance grade achieved by an assessed building. This chapter discusses these possible applications of the LCEA tool and the related concerns.

5.1 Possible applications

5.1.1 Simply as a design tool

If the LCEA tool is simply meant to be a design tool to facilitate building designers to turn out more sustainable commercial building developments in Hong Kong, making available the tool to local practitioners is the major work required, which has now been accomplished. How effectively the tool can help promote sustainable commercial building development is then dependent on how well-received is the tool by stakeholders in the industry, which, in turn, is dependent on whether the stakeholders will find the tool useful to them.

To widen the application of the tool, further efforts are needed to promote the tool to stakeholders and to continuously upgrade and expand the functional capabilities and versatility of the tool. Publication of this book represents a part of the promotion work. Whilst building designers can now use the tool to compare the performance of alternative designs for buildings, it will be useful to make available relevant benchmarks, to allow them to measure the performance of the buildings they designed against the benchmarks.

5.1.2 As a tool to support an assessment scheme

If a scheme is to be made available to assess the sustainability of building designs, the LCEA tool can serve as the quantification means for the scheme. In regard of realizing the aim of promoting more sustainable commercial building development in Hong Kong, the existence of such a scheme will be far more effective than just making available a design tool. This is because the assessment outcome can serve the function of an eco-label, to inform building end-users of the sustainability of buildings so that they can take this factor into account when they consider buying or renting building premises.
Since there are already building environmental performance assessment schemes in Hong Kong, e.g. HK-BEAM and CEPAS, enhancing an existing scheme to allow it to embrace LCA and LCC as a part of its assessment can be a more effective approach than establishing from scratch a brand new scheme. No matter which approach is taken, it is necessary to establish relevant assessment methods, procedures and criteria for the scheme. With regard to implementation, compliance with a minimum standard may be made either mandatory or voluntary, but each choice will entail significantly different considerations to be given in the development of the assessment scheme.

However, the establishment of benchmarks for LCA and LCC results of buildings is far from straightforward. Furthermore, the uncertainties in LCA and LCC results may undermine the robustness of the assessment, which is especially important if compliance with a minimum standard is mandatory. These problems are further discussed in the following sections.

5.2 Problems with benchmarking

Fair comparison of LCA and LCC results among different products is possible only if all the products being compared serve the same function. In the context of building developments, it is relatively straightforward to establish functional equivalence only for individual types of building or system components and elements. For example, comparison can be made between two floor slabs constructed from different materials if both are designed for the same load bearing capacity. Likewise, a water-cooled centrifugal chiller with a certain rated cooling capacity can be compared against another water-cooled chiller with the same rated cooling capacity but with a screw compressor.

However, commercial buildings are a highly complex type of products, which may differ largely from one another. Besides differences in the class and the total construction floor area of buildings, the mix of types of premises (e.g. offices, retail shops, restaurants, etc.), the building height, floor plate area and aspect ratio, orientation, fabric construction etc. may differ from one building to another, but all such factors are influential to the LCA and LCC results. Furthermore, the material use for constructing the foundation is highly variable, which depends strongly on the ground condition of individual sites and the type of foundation design that needs to be used. Therefore, strict equivalence among different commercial buildings can hardly be established.

Nevertheless, LCA and LCC benchmarks for commercial buildings can be determined only if a common basis has been established for assessing and comparing different buildings. In order to remove the disturbances due to factors that are beyond the control of the building designers, e.g. the ground condition for foundation design, the assessment may have to omit certain parts of the buildings. A method is also needed for the evaluation of a suitable denominator for normalization of LCA and LCC results of different buildings to facilitate comparison, such as the use of scaling factors for floor areas occupied by different types of premises.

Since a suitable assessment method is lacking, studies are needed to work out a proper method that can bring commercial buildings with different characteristics to a common platform for assessment. There is also a need for an investigation to find out the range of LCA and LCC results for a wide spectrum of buildings to support determination of the benchmarks.
The cost for performing an assessment is another factor to which attention should be paid. If the assessment is highly complicated and requires a lot of resources input, the high assessment cost will become a hurdle to penetration of the assessment scheme into the industry. Also, different benchmarks may be needed for different classes of buildings to ensure wide acceptance of the assessment scheme. Such benchmarks will be needed if certain classes of buildings, e.g. prestigious or special purpose buildings, may meet the general benchmark only if the provisions are downgraded, which could undermine the sales or rental values or the function of such buildings.

5.3 Mandatory or voluntary assessment

The major advantage of imposing a mandatory compliance requirement is that it can arouse the attention of all stakeholders. If the requirement is associated with a high penalty for violation, there will be few non-compliant cases. However, the enforcement of a mandatory requirement must be based on assessment methods and compliance criteria that are objective, unambiguous and consistent. Moreover, the compliance requirement cannot be set at a high standard. Otherwise, disputes or too many violations will arise rendering the control ineffective. Policing and prosecution of violations will also be costly. Therefore, only moderate improvements can be expected in taking this approach.

Up to the present, the available methods and data for conducting LCA and LCC of buildings are limited in various aspects, especially in the range of materials that can be covered, and the accuracy of the data and the results. As discussed in the preceding section, a proper method for establishing benchmarks for assessing buildings with different characteristics is yet to be developed. Furthermore, the result is dependent on the way in which a building is modelled.

The above discussion points to the fact that the state-of-the-art LCA and LCC methods are still unable to provide a sound basis to support imposition of a mandatory requirement on sustainability of building designs that is to be assessed based on LCA and LCC results. Having ruled out the possibility of mandatory implementation, the development of a LCA and LCC assessment scheme for commercial buildings in Hong Kong should target at voluntary participation. Further works are still needed to develop appropriate assessment methods and criteria for incorporation into such an assessment scheme. Meanwhile, the LCA and LCC tool can continue to serve as a design tool for use by building professionals.
6 Bibliography

Despite its relatively short history, LCA is currently seen as a key tool to the achievement of sustainable development. LCA has undergone rapid development in the Europe and North America and its application has spread from manufacturing industries to other industries, including the construction industry. Many books, reports, guides and academic articles about LCA have been written. There are also guides and other publications on LCC. This chapter lists a few selected examples to allow interested readers to source for additional references on these topics.

6.1 Relevant textbooks, standards and guides

A) Introductory materials about LCA:


B) Standards and guides:

6.2 General references

A) LCA methods


B) LCI data

C) LCA tools


D) Latest LCA development


E) LCC


