Green Building Handbook for South Africa
Chapter: The environmental impacts of construction materials use: a life cycle perspective

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Introduction

In its creation and use, the built environment consumes inordinate quantities of resources. An additional issue of grave concern are the impacts of industrial emissions and wastes on the aspects of the environment which society wishes to protect and conserve.

The main focus of improvement efforts are the building assessment and rating systems of the green building movement which have yielded considerable success. Energy and water consumption have been reduced considerably. However, these efforts are informed by perceptions rather than scientific facts. Materials selection has remained a particularly difficult and contentious issue. For instance, the use of wood from well-managed forests reduces the consumption of non-renewable resources but the fertilisers, pesticides and herbicides used in crop production processes contain heavy metals which may end up in the food chain. Current approaches also encourage problem shifting. For instance, construction is one of the largest users of energy, raw materials and water. However, energy efficiency and water conservation are prioritised on the green agenda while the key environmental impacts associated with materials use, namely, depletion of resources; and releases of solid and liquid wastes and toxic emissions to air are barely addressed.

Key features of the Life Cycle Assessment concept

To place construction on a truly sustainable path the green building movement needs a method which goes beyond subjective checklists of green features. Such a method must provide objective guidelines for a comprehensive assessment of the environmental impacts of a product (or service). The Life Cycle Assessment (LCA) concept previously known as Life Cycle Analysis has emerged as one of the most appropriate tools for assessing product-related environmental impacts and for supporting an effective integration of environmental aspects in industry, business and the economy. LCA is distinguished from Life Cycle Costing (LCC) in that whereas the former involves environmental accounting the later is concerned with economic value.

LCA describes the entire industrial system involved in the making of a product (or delivery of a service). This approach provides a systematic opportunity to anticipate problems and their solutions all along the life cycle from “cradle-to-grave”, namely, from the acquisition of raw materials, manufacture of the product, distribution, use and maintenance to disposal of the used product (Figure 1). Identified problems are also traced through all environmental media, namely, air, water and soil. The systems perspective of LCA avoids problem shifting from one life cycle stage to another, from one type of problem to another and from one location to another (UNEP, 1996).

The LCA procedure investigates a wide range of environmental impacts associated with industrial products, for instance, Climate Change, Acidification, Ozone depletion and Human toxicity. Although the main driver for LCA is sustainable development, the methodology does not as yet incorporate criteria for measuring the social and economic dimensions. All aspects of the environment, namely, human health, ecological health and natural resources are however considered in a comprehensive manner. Potential environmental trade-offs can thus be identified and assessed. The LCA procedure is standardised under the ISO 14040 sub-series *Environmental Management Life Cycle Assessment*.

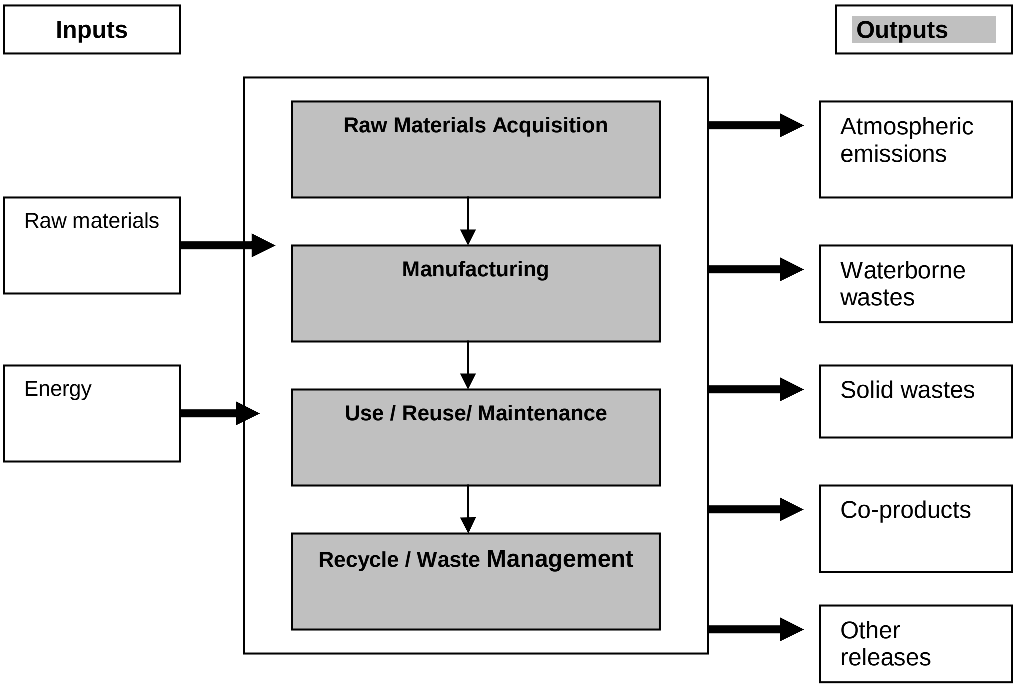

Figure 1: The generic life cycle stages of an industrial system (Source: USEPA, 2006)

Applications of Life Cycle Assessment

The first LCA study was commissioned by the Coca Cola Company in 1969. The study compared glass and plastic coke bottles by quantifying the raw materials and energy used, and the releases to the environment from the manufacturing process for each container. The study resulted in a switch in packaging from glass to plastic bottles. The development and spread of applications was possibly driven by public concerns over the limitations of raw materials and energy resources arising from the seminal *Limits to Growth (1972*) and the Oil Crisis of the 1970s. The concept has become well-known and is used in various ways by a wide range of societal actors including economic regions, national governments, industry, business, NGOs and consumers to integrate environmental concerns into economic activity.

More recently, the United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC) launched the UNEP/SETAC Life Cycle Initiative to encourage new applications of the LCA concept through Life Cycle Thinking (LCT) and Life Cycle Management (LCM). The essence of LCT is that key actors in a product value chain cannot strictly limit their responsibilities to those phases of the life cycle of a product, process or activity in which they are directly involved. National governments and other regulatory bodies in the developed countries are increasingly leveraging their purchasing power through new environmental policy instruments rooted in LCT to reduce the life cycle environmental impacts of industry and business. A notable example of this trend is the European Union's (EU) Integrated Product Policy (IPP).

Life Cycle Management is an integrated framework of concepts, programmes and techniques for improving organisations and their respective goods and services. A key application of LCM in the context of the EU is the environmental design of products known variously as Eco-design or Design for Environment (DfE). Typically, companies respond to the new, LCA-based policies, for instance, the EU's end-of-vehicle life policy or Germany's Extended Producer Responsibility (EPR) by designing their products for ease of disassembly, ease of recycling and free of hazardous substances and materials. Industry sectors currently applying new LCA-based approaches to "green" their supply chains include the electronic, electrical and chemical sectors and vehicle manufacturers.

The development of design and decision-support tools has become an important area for LCA applications in the construction industry. Construction-specific tools which have been developed for ease of use by non-LCA experts comprise building rating and certification systems, whole building tools and tools for assessment of construction materials and construction components. The building rating and certification systems are distinguished from well-known rating systems such as LEED in that they focus on true environmental performance measures which include but are not limited to acidification, climate change, ozone depletion, human and ecological toxicity and resource depletion. A whole building tool is applied at the concept design stage to the building in its entirety or to an assembly. The aim is to compare how substituting different materials and components in a design affects its overall environmental impacts. Tools for assessment of construction materials and components are applied at the specification stage of a project to guide the final selection of materials and components which have the least environmental impacts. All tools incorporate generic inventory datasets which are representative of average technology in the given region or nation. To avoid uncertainty of results, datasets need to be localised prior to international use.

Table 1: Construction-specific LCA tools (adapted from Trusty & Horst, 2005)

Tool	Country	Comments
Material and component tools		
BEES	USA	Combines LCA and life cycle costing (LCC). Includes both brand-specific and generic data.
LCAiT	Sweden	Streamlined LCA tool for product designers and manufacturers.
TAKE-LCA	Finland	LCA tool for comparison of HVAC products, including energy content of the product and energy consumption.
Whole building tools		
Athena Environmental Impact Estimator (EIE).	Canada/USA	All of these tools use data and incorporate building systems that are specific to the country or regions for which they were designed.
BRI LCA (energy and CO2)	Japan	
EcoQuantum	Netherlands	
Envest	United Kingdom	
Green Guide to Specifications	United Kingdom	
LISA	Australia	
LCADesign (under development)	Australia	
Rating and certification systems		
BREEAM	United Kingdom	Uses LCA results from whole building tools
GBTool	International	Experimental platform that accepts LCA results or performs rudimentary LCA calculation using built-in calculators.
Green Globes	Canada/USA	Assigns a high percentage of resource use credits based on evidence that a design team has conducted LCA using a recognised whole building or material and component assessment tool

Construction materials and the environmental impacts of built facilities

The primary application of LCA in the built environment professions is to inform design decisions, in particular, provide quantitative data to guide the selection of construction material, construction component and building system combinations which will reduce the life cycle environmental impacts of a built facility. While the decisions made throughout the building life cycle will influence the impact it can have on the environment, materials choices made in the pre-use phase commit the major environment impacts which occur in the use phase. Environmental concerns, for instance potential contributions to Climate Change must therefore be addressed side by side with more traditional concerns such as thermal comfort, health, safety, cost and maintenance from the planning and design stages. Studies have shown that the opportunities to reduce the environmental impacts of a built facility decrease substantially after the pre-use phase (Lloyd et al, 2005). A barrier to incorporation of environmental concerns is however the time required for exploring various options to capitalise on the environmental benefits; and the initial cost of the building is typically higher (Janssen, 1999).

1	2	3	4	5
Material extraction and processing	**Construction material fabrication**	**On-site construction**	**Facility operation and maintenance**	**End-of-life**
Forest products coal and petroleum, plastic products, natural gas, iron, copper, zinc, aluminium, sand, stone, limestone	Timber products, fibreboard, cellulose products, steel, aluminium frames, appliances, wire, paint, solvents, plate glass, carpet	Foundation and site earthwork, concrete pouring, structural framing, roofing, mechanical and electrical systems, painting and cleanup	Space and water heating, space cooling, appliances, lighting Facility improvement and maintenance materials	Stripping reusable materials, knock-down, site clearing, disposal
PRE-USE PHASE			**USE-PHASE**	**EOL**

Figure 2: The generic life cycle stages of a built facility (adapted from Keoleian et al, 2001)

Pre-use phase environmental impacts

The pre-use phase of the building life cycle may account for 10-20% (Keoleian et al, 2001; Adalberth et al, 2001) of the total life cycle environmental impacts of a built facility. This phase of the life cycle is dominated by environmental impacts due to the extraction and processing of raw materials, construction materials production, transportation in between processes and on-site installation of materials.

The extraction of virgin raw materials from the earth contributes to a loss of biodiversity and destroys natural habitats. Large portions of forests are cleared each year, resulting in the extinction of 20 000 species a year (Edwards, 2002). The creation of timber products for use in the construction sector is responsible for most of this loss. Extraction activity such as mining, growing/harvesting quarrying and felling is a source of air pollutants, solid waste, polluted water run-off and noise, vibration and odour. The processing of raw materials, for instance, copper and zinc ores may result in emissions of toxic substances which can enter the food chain – it is estimated that the body of the average person today carries several hundreds of chemicals that were not present in previous generations.

The fabrication of construction materials from virgin raw materials is an energy intensive process. However using embodied energy as a basis for green materials selection overlooks significant energy related impacts which occur in the use phase. Energy consumption releases the air pollutants carbon dioxide and sulphur dioxide which contribute to Climate Change and Acidification respectively. Embodied energy, which is the energy used in the processing of raw materials as well as the fabrication and installation of materials in a built facility (Treloar, 2001) is therefore widely cited when considering impacts due to construction materials use. However, in reality, a construction material forms an integral part of a building system, component or assembly and environmental performance must be measured at the systems level (Graveline, 2005). In a review of 100 material LCAs the European Commission concluded that LCA comparisons performed at the materials level provided misleading results. Further to this, LCA literature has established the dominant role of use phase energy consumption in the total environmental impacts of a built facility thus providing a logical basis for building designers to focus their efforts more on selecting materials which will contribute to energy efficiency in the use phase and less on issues around embodied energy. For instance, heavy walls (bricks, concrete) are higher in embodied energy. However, the high mass is a critical component which is used to advantage in passive building design leading to long-term savings in energy consumption during the use phase of a building.

The focus on embodied energy may also mask the presence of toxic substances in the construction materials life cycle. For instance, factory workers in the brick production sector may continue to suffer from working environment problems such as hearing impairment and respiratory problems despite successful cuts in energy consumption. Similarly, efforts to reduce the environmental impacts of concrete are focussed on energy efficiency strategies. However, in the production of concrete heavy metals are emitted which can potentially damage ecosystems and enter the human food chain.

The environmental impacts of the on-site construction life cycle stage comprise transportation of materials to site, use of construction equipment on site, use of energy in materials installation processes and the transportation of construction waste to a landfill (Junnila et al, 2006). Transportation, equipment use and energy use contribute to Climate Change and Acidification. Of additional concern are toxic emissions of carbon monoxide and particulate matter which reflects the dust common to construction sites.

Use phase environmental impacts

The use phase may account for 70-90% (Keoleian et al, 2001; Adalberth et al, 2001) of the total life cycle environmental impacts of a built facility. The environmental impacts of the use phase are primarily due to energy consumption for purposes of heating, cooling, lighting and operating domestic or commercial appliances; and materials use for purposes of facilities maintenance/upkeep. In the area of building and construction LCAs there is consensus that use phase impacts are dominated by energy consumption, Climate Change and Acidifying emissions.

There is a strong correlation between materials used for the building envelope and intensity of impacts. A study compared three homes of equal floor area designed primarily in wood, steel and concrete over the first 20 years of their lifespan. Relative to the wood design, the steel and concrete designs (Wood Promotion Council, 2006):

- Release 24% and 47% more air pollutants
- Emit 34% and 81% more greenhouse gases
- Consume 26% and 57% more energy.

The contribution of a material to use phase impacts is directly related to the quantities used during construction and maintenance. Due to the very large quantities used the three categories of construction materials which contributed the most to environmental impacts measured during the use phase of 25 commercial buildings located in Hong Kong were concrete, steel reinforcement and the combination of plaster, render and screed (Chau et al, 2006). The contributions of these top three to total environmental impacts varied between 46-65%.

Table 2: Environmental impacts of commercial buildings - the ten most influential building materials (adapted from Chau et al, 2006)

Ranking	Building material	% contribution to overall environmental impacts of building
1	Concrete	21.3
2	Reinforcing bar	16.0
3	Galvanised steel	11.4
4	Plaster, render and screed	10.9
5	Tiles	7.6
6	Stones	5.2
7	Aluminium	5.0
8	Structural steel	4.3
9	Access floor panel	4.1
10	Stainless steel	4.1

The extent of environmental impact of a material has nothing to do with its contribution to the total weight of a built facility. In the Hong Kong study building services components such as power cables and busbar trunking accounted for about 27% of environmental impacts but typically contributed only 2% to building weight. The severity of impacts was attributed to the presence of copper which has a very high environmental impact per kilogramme. In contrast to this finding, concrete accounted for 14% of impacts but on the average contributed 74% of building weight.

Table 3: Environmental impacts of commercial buildings – the ten most influential building services components (adapted from Chau et al, 2006)

Ranking	Building service system or component	% contribution to overall environmental impacts of building
1	Power cable	25.2
2	Busbar trunking or busduct	24.1
3	Chiller	5.7
4	Air conditioning ductworks, fittings and insulation	5.6
5	Chilled water systems including pipework, excluding chiller	4.6
6	Mcb and mccb distribution board	4.4
7	Sprinkler systems including pipework	3.8
8	AHUs/PAUs	3.8
9	Submain conduits and trunking	2.8
10	Luminaries	2.4

Construction materials which need frequent replacement can contribute significantly to use phase environmental impacts. Built facilities have a service life which is a function of design and material durability. The service life of a facility is typically specified in the range of 50-100 years and reflects the durability of structural elements which do not require replacement. In contrast to this, the total impact due to non-structural elements is substantially increased due frequent replacement. In the Hong Kong study non-structural elements, for instance, carpets were found to have impacts 1.4 to 1.6 times higher than structural elements when assessed over a service life of 50 years. The replacement of materials and components, such as interior furnishings also accounted for up to 33% of total environmental impacts assessed over a 50 year lifespan. Similarly, a comparative LCA of various commercial roofing systems concluded that relative to a building with a 75-year service life, a roof assembly with a 15-year life expectancy had roughly four times the Climate Change impacts of the roof with a 30-year life expectancy (Graveline, 2005). Selection of replacement materials and assemblies during the use phase of a facility is therefore as important as the selection process in the pre-use phase.

End-of-life phase

When assessed in the context of a whole building LCA, end-of-life activities, namely, the use of demolition equipment and the transportation of demolition waste to landfills contribute marginally to the total life cycle environmental impacts of a built facility (Junnila et al, 2006; Adalberth et al, 2001). However, in the context of waste disposal it is apparent that the end-of-life management of construction materials contrasts sharply with the principles of sustainable development. Globally, construction consumes at least 40% of all raw materials extracted from nature - due to the conventional open loop industrial system, virtually the same quantity of materials end up in landfills worldwide as construction and demolition (C&D) waste (Koroneos et al, 2006). The rates of resource extraction are estimated to be substantially higher than nature’s capacity to replenish stocks, thus the high rates of disposal by landfill give great cause for concern. The embodied energy of millions of tonnes of C&D waste discarded annually represents potential energy savings for the benefit of future generations. The ever growing landfills contribute to land competition, in particular, conflicts in respect of agricultural land and conservation and protection of natural habitats.

Other large industry sectors, notably, vehicle, electronics and chemical manufacturing have already made significant progress by adopting closed loop industrial systems which divert waste away from landfills and into reuse and recycling. A closed loop industrial system optimises materials use and avoids pollution because by convention, the environmental impacts due to secondary materials (reuse and recycling) are considered to be nil as the impacts are assigned to the primary (raw) material. Increasingly, the adoption of closed loops is moving from voluntary to mandatory as nations respond to the 2002 World Summit on Sustainable Development (WSSD) call to create a “life cycle economy”. A key aspect of the new, LCA-based policy environment which has implications for C&D waste management is the concept of “product take back” or extended producer responsibility (EPR) which make producers responsible for their products after their useful lives. The success of loop closing in industry is however premised on a shift in design mentality. A product needs to be deliberately redesigned for disassembly to facilitate recovery of potentially reusable or recyclable parts (Schultmann et al, 2007). To further increase waste recovery efficiency the energy value of residual materials may be recovered by incineration or combustion.

Green building rating and certification systems make provision for construction materials optimisation, for instance, LEED awards credits for deconstruction, recycling or reuse of building components at end-of-life. However, green buildings are not designed for disassembly and many construction materials are difficult to recycle. Construction also has a history of cheap resources and low waste disposal costs (Kibert et al, 2000). Thus in the absence of environmental policy interventions such as EPR the rates of recycling and reuse of construction materials is low and is driven by economic value rather than product stewardship, for instance, steel and concrete are subject to high rates of recycling and timber beams are frequently reused. Closing the construction materials loop is dependent on a paradigm shift in the entire construction supply chain. Manufacturers of construction materials, components and building systems on the one hand and building teams on the other hand would need to apply DfE principles to allow disassembly and reuse or recycling of materials and components.

The green construction materials selection process is a complex process requiring major shifts in approach to the planning, design, operation and disposal of built facilities. In the context of the green building movement there is a tendency to simplify this process by selecting materials on the basis of a single environmental attribute or on the basis of perceived rather than actual environmental benefits. The essence of LCA is that it captures the full life cycle profile of a construction material on the basis of objective data thus facilitating well informed decisions which can increase the environmental performance of built facilities.

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