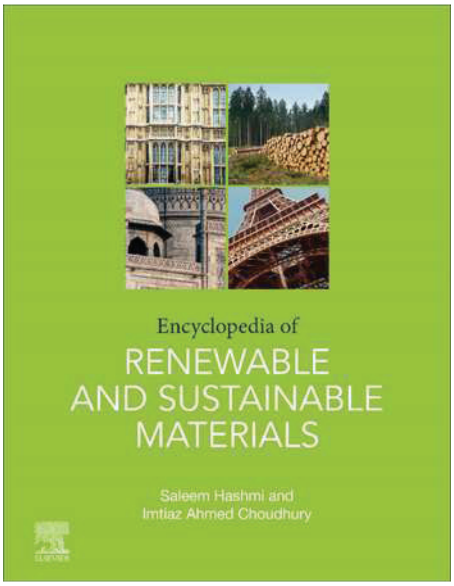

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Lifecycle Assessment of Building Materials – A Cradle-to-Gate Approach

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Introduction

In recent years the desire to quantify the impact of human activities on the environment has attracted attention around the world, in particular, the activities in the construction of buildings (Takano *et al.*, 2014). The construction of buildings utilizes about 40% of stone, sand and gravel, 25% of timber, 16% of water, and consumes an enormous amount of energy and emits 19% of global greenhouse gases (GHG) annually worldwide (Arena and de Rosa, 2003; IPCC, 2014; Hossain *et al.*, 2017).

In the past, research studies focused on improving operating efficiency as it was regarded as the stage that consumes most of the energy and generates most of the emissions during the building lifecycle. However, energy consumption and emissions due to building operation have been reduced progressively through shifting to the use of renewable energy, and the incorporation of technologies into the design and construction of sustainable buildings (Meggers *et al.*, 2012). The design and production of building materials have now attracted more attention.

To avoid the negative impact on the environment, it is important that the potential impacts of the design and production of building materials are taken into consideration on a lifecycle perspective. The consideration includes the consumption of resources and the damage to the environment caused by the extraction of raw materials, manufacturing and transportation of building materials. Also the recycle content and potential recyclable characteristic of materials should also be considered in the selection process of materials and products for buildings. The durability of the materials and their effect on the entire lifecycle of the building are also important considerations.

Government, industry and research organizations recognize the usefulness of lifecycle assessment (LCA) as a critical tool to identify the potential impacts of materials and products on the environment. The LCA approach is particularly important given the high volume of materials used and the growing importance of environmentally sustainable decisions. For a building, the commonly and traditional used materials are high impacts materials such as concrete, steel, plasterboard. Therefore improving material performance is paramount significant in reducing environmental impacts.

The goal of this article is to review the methodology of LCA of building materials for use in research, policy analysis and building code development. The article begins with a discussion on the importance of materials in a building's lifecycle and the selection criteria, followed by a discussion of the various initiatives and programs related to the evaluation of environmental impacts of materials. This article also reviews the LCA approach in the assessment of environmental impacts of materials on a cradle-to-gate system boundary and includes examples of LCA studies of commonly used building materials. The article ends with a discussion on strategies for reducing environmental load of building materials.

Importance of Sustainable Building Materials

Sustainable development is the foundation of environmentally sustainable practices in the construction industry and within which it provides a framework to develop strategies for buildings to be designed and built by shifting from the use of conventional resources to the use of renewable-based resources. The selection and use of materials in buildings have caused severe environmental impacts associated with the extraction and consumption of raw materials during the entire lifecycle of buildings. In achieving the goal of sustainable development in construction, the production and selection of low impact and environmentally friendly building materials are essential.

With the reduction of operating energy and emissions, the energy and emissions embodied in materials are now attracting more attention in research and development as they are permanent and take immediate effect from when the raw material is extracted and manufactured (de Wolf *et al.*, 2016). Huisingh *et al.* (2015) state that the emissions embodied in materials in the cradle-to-gate stage account for between 88% and 96% of the total lifecycle emissions. The increased attention on reducing energy and emissions in the material is challenging but can be achieved by shifting to the of use low impact materials and correspondently changing the perspective people have on these building materials (Meggers *et al.*, 2012).

The impacts of materials have on the environment depend on the length of the lifecycle studied, types of buildings, types of energy used and the related technologies employed within a building. According to Chau *et al.* (2015) conventional commercial buildings are about 10%–27% of the total energy use and carbon emissions with a lifespan of 50 years while residential buildings are about 15%–40%. They go on to state that the building structure is found to have a profound impact of the resources and emissions content due to the vast quantities of materials used in the construction. The percentage tends to become higher with a shorter studied lifespan.

Research studies shown that the material phase has more profound impact than operating phase on zero energy or zero emission buildings. Zero or low energy buildings consume less operating energy in the use phase due to the design and technological advancement (Basbagill *et al.*, 2013). Therefore it increases the importance of energy and emissions embodied in

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materials. According to Chau *et al.* (2015) the energy and emissions embodied in materials of net-zero energy buildings were found to have about 78% of the total in a building's lifecycle. The research further reveals that a passive house with photovoltaic installation was found to be 44% more than its operating energy in a 60 year lifespan and 56% for a 100 year lifespan. Thiel *et al.* (2013) analyze the environmental impact of a net-zero energy building and found that the most significant environmental impacts were in the structure made from concrete and structural steel. Haapio and Viitaniemi (2008) examine different structural design and material use of 78 single-family houses and results indicate that material production phase has the highest environmental impact for new buildings.

Presently, the construction industry is facing challenges regarding the delivery of sustainable buildings. Significant portions of a building's lifecycle impacts are determined by decisions made in the selection of materials at the early stage of design development. Therefore, choosing materials with low impacts at this stage has the potential to reduce the overall lifecycle impact significantly. For this purpose, it is crucial that both material manufacturers and designers take into account the potential effects and magnitude of the impact of materials on the environment at an early design stage of a building.

An LCA approach is particularly important in this respect as it provides a systematic assessment of the full range of impacts of materials on a lifecycle perspective. The aim of LCA in the first place is to compare the environmental impact of different raw materials and processes that have the same function but have lower impacts. LCA can be used as a decision-making instrument in the design and production of new materials. In choosing materials for buildings, the following criteria are to be taken into account in the design process:

(1) Materials with recycled content – The use of materials is closely related to the total embodied energy and emission during production processes. The use of materials with recycled content can potentially reduce embodied energy and emissions compared to the manufacturing of using new materials. Thormark (2002) conducts a research study of an energy efficient apartment building in Sweden for a lifespan of 50 years and research results indicate that the recycling potential can reclaim up to 15% of the total energy used.

(2) Low emission during manufacturing – Emissions are related to the manufacturing process of building materials that may have adverse effects on the environment. This will require the selection and use of building materials with the lowest negative impacts on the environment. Therefore, the environmental performance data of materials from the LCA results and eco-labeling can be useful and important in the selection processes.

(3) Low energy intensity – Energy is required in the entire supply chain in the production of materials. The production and use of energy affect both the natural and manmade environment through the resulting pollutants and depletion of resources. Therefore the consideration of low energy intensity materials is one of the most important criteria that should be taken into account in the design and construction of buildings.

(4) Biological content – The biological criterion takes into account the effects of materials on the health and wellbeing of users during the use phase of a building. The knowledge of the risks that old and modern building materials pose to health is essential to ensure the protection of the environment and users.

Initiatives, Certification Systems and Government Regulations for the Assessment of Environmental Performance of Materials

In response to the climate change and environmental degradation, governments and international organizations have developed policies, regulations and standards to reduce impacts of buildings on the environment. The European Union Energy Performance of Building Directive (Giesekam *et al.*, 2016) and the Australian National Construction Code Section J (ABCB, 2010) have been issued to regulate the improvement in the design and construction of building fabric performance for energy efficiency. However, these policies and regulations principally focused on the operating emissions associated with energy consumption for heating and cooling, lighting, and ventilation but have not been extended to the embodied energy and emission associated with the initial production of building materials and products.

The International Organization for Standardisation (ISO) standards is the most important one in providing consistency, transparency and credibility in the assessment, monitoring, reporting and verification of performance for buildings and materials (ISO, 2006a,b). The ISO 14040/14044 Standards focus on establishing principles and framework and providing requirements and guidelines for the LCA study (ISO, 2006a,b). The four steps of assessment in the LCA framework have been applied to standardize and quantify the environmental performance of materials (Finkbeiner, 2014).

In addition to the establishment of the ISO Standards, quantifiable impact such as carbon footprint (CF) and eco-labeling have also been developed as labeling systems to provide environmental performance data of materials and products. These systems are primarily voluntary but can raise awareness about environmental problems and leads to the competition in the material manufacturing industry. CF has been widely used to measure the total amount of GHG emissions of materials and products that both upstream and downstream emissions are accounted for. It is usually expressed in an equivalent value per mass of CO_2 for the GHGs such as N_2O and CH_4 in materials and products (Basu and Bidanda, 2014).

Eco-labeling for materials has been developed almost in every country now. The purpose of eco-labeling of materials is to promote the supply of materials with lower environmental impacts through verifiable and reliable information and to stimulate manufacturers to improve material performance environmentally. Eco-labeling was initiated by the Global Ecolabelling Network

Table 1 Three types of eco-labeling for materials and products

Type	*ISO*	*Example*	*Purpose*
Type I Third-party ecolabel	14024 (1999)	EU Eco-label, Nordic Swan (Nordic countries), Blue Angel (Germany), Environmental Choice (Australia)	To promote and identify products of the best environmental performance achieved in the market
Type II Self-declared environmental claims	14021 (1999)	In the form of written statements or symbols, e.g., CFC-free, recycled content	To provide environmental performance of products or services
Type III Environmental product declaration (EPD)	14025 (2006)	IBU-EPD Program (Germany)	• To provide independent verification of claims that contain relevant and verifiable LCA information based on the ISO 14040 series of standards • To facilitate environmental comparison between products that perform the same function

Sources: Vigovskaya, A., Aleksandrova, O., Bulgakov, B., 2017. Life cycle assessment (LCA) in building materials industry. MTEC Web of Conferences, 106, 08059, SPbWOSCE-2016 https://www.matec-conferences.org/articles/mateconf/pdf/2017/20/matecconf_spbw2017_08059.pdf. Logon: 15/7/2018.

in 1994 to improve and develop labeling systems of materials and products worldwide. According to the Global Ecolabelling Network (2018), there are more than 463 eco-labeling organizations in 199 countries in over 25 business sectors.

Table 1 summarizes the three types of eco-labeling for materials and products. The three types of eco-labels are developed in according to the ISO standards. Type III eco-label is particularly important as it has to be prepared in according to the rules and requirements of the Product Category Rules which are key part of ISO 14025 to enable transparency and comparability between environmental product declarations (Vigovskaya *et al.*, 2017). However, the exceedingly supply of eco-labels has abused and misused to claim environmentally friendly materials by manufacturers or suppliers. This is particularly serious for the Type II eco-labels as these labels are developed directly by manufacturers without the certification by a third-party. Some of these labels are based on the LCA approach but this information may not publicly available due to confidentiality (Basu and Bidanda, 2014).

The use of eco-labeling for the individual material may be informative but is particularly challenging to quantify the environmental impacts of building materials as building materials are functioned together to achieve the stated performance in the design. For example, the effective use of insulation in the building design can result in less energy consumption and better user comfort during the use phase, but its manufacture may involve the release of pollutants (Basu and Bidanda, 2014). Also building materials require transportation from distribution centres to site that the impact may be significant if sourced from overseas. However, locally harvested raw materials may affect the local ecological systems (Basu and Bidanda, 2014).

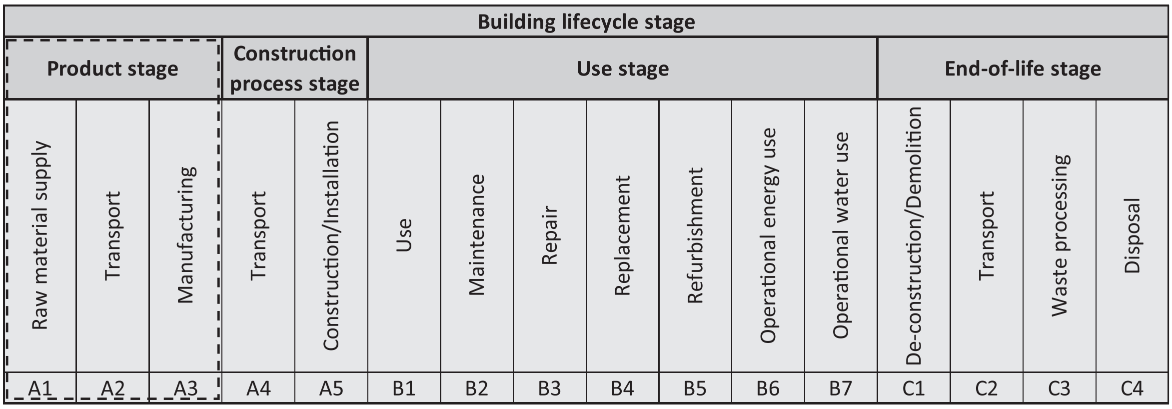
Life Cycle Assessment (LCA) for Building Materials

In the past, environmental studies have focused on the operating stage as this stage represents the majority of energy consumption and emission during a building's lifecycle. However, more attention has now been shifted to the environmental impacts of raw material extracting, manufacturing and transportation (de Wolf *et al.*, 2016). The assessment of the impact of building materials is similar to an LCA study of a building. The principal objectives of LCA are to quantify and evaluate the environmental performance of materials so that decision-makers can compare and select materials with the least impact on the environment. Additionally, LCA provides a basis for assessing potential improvements in the performance of materials to reduce their overall environmental impacts. This can be done in an overall sense or targeted to improve specific stages during the lifecycle.

Over the years LCA has been used to conduct detail analysis and comparison of the environmental impacts of numerous building materials. Cole (1999) conducts an LCA study on comparing the use of wood, steel and concrete structural assemblies and found that wood has the least impact compared to steel and concrete structure. Wei *et al.* (2008) use LCA to investigate energy and emissions for different building components while Goggins *et al.* (2010) investigate to replace Portland cement with blast furnace slag and results indicate a reduction of energy consumption and emissions in the production of concrete. Mao *et al.* (2013) study the use of industrialized methods of construction and found that prefabrication has lower emissions than traditional methods of construction.

The LCA Framework for Material Assessment

The lifecycle environmental impacts of building materials according to LCA is usually conducted on a 'cradle-to-gate' boundary as indicated in **Fig. 1** which presents a building lifecycle stages in according to the CEN 15978 (CEN, 2011). The LCA study for building materials based on a cradle-to-gate system boundary involves mainly the upstream processes of raw material extraction and associated processing activities (Hafliger *et al.*, 2017).



Building lifecycle stage															
Product stage			Construction process stage		Use stage							End-of-life stage			
Raw material supply	Transport	Manufacturing	Transport	Construction/Installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction/Demolition	Transport	Waste processing	Disposal
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4

Fig. 1 Lifecycle stage of buildings. *Source*: Adapted from CEN, 2011. Sustainability of Construction Works – Assessment of Environmental Performance of Buildings – Calculation Method. British Standard Institute.

The A1 stage in the CEN 15978 is the raw material supply stage. This stage includes the extraction of raw materials and the associated processing activities from the ground. The A2 stage is the transportation of the extracted raw materials to the factory gate either locally or overseas for the manufacturing of building materials and products. The manufacturing (A3) is the final stage of the Product Stage in a building's lifecycle. This stage involves the manufacturing of raw material into materials and products for buildings.

Energy is required at each stage of the Product Stage. Energy is consumed to operate machinery and equipment for the raw material extraction activities at the A1 stage and the manufacturing processes at the A3 stage. Energy is also required for the transportation (A2 stage) of raw materials and different transportation modes may require different fuel types. The energy consumption at these stages generates a significant amount of energy-related emissions and other pollutants such as dust, noise and contaminants which have a significant impact on the environment (Buyle *et al.*, 2013; Vigovskaya *et al.*, 2017).

LCA study for building materials ends at the production of materials and products at the factory gate and further downstream activities are not part of the cradle-to-gate boundary. Therefore the following stages are outside scope of the LCA study of building materials:

- Construction process stage (A4–5) – Transportation of finished materials and products between manufacturer and building site, and construction activities on-site.
- Use stage (B1–7) – This stage usually refers to the operating and use of buildings. Building materials and products may only be used during repair, replacement or refurbishment during the operating stage of a building.
- End-of-life stage (C1–4) – Similarly, this stage refers to the final stage of a building's lifecycle which may involve eventual demolition and disposal. Some of the salvaged materials may be recycled or reused in the manufacturing process of building materials or components.

The Application of the ISO Standard for the LCA Study of Building Materials

The ISO standard is central to the LCA study of building materials. **Fig. 2** illustrates the four steps of the LCA framework and the cradle-to-gate boundary of building material production (shown dotted lines). The four steps are generic for either a whole building LCA study or an LCA study of individual materials. According to the ISO 14040/14044 the LCA framework for material assessment begins with the goal and scope definition. This is the stage that objectives of the study are established so that boundary can be defined and functional unit to be set. For an LCA study of building materials the goal is to determine the environmental impacts from the production of materials and products and the scope of the study focuses on the raw material acquisition, processing and manufacturing.

The second step as indicated in **Fig. 2** is related to the development of the lifecycle inventory (LCI) of the material studied. The LCI activities include quantifying the input and output flows of raw materials and energy and analyzing environmental impacts to the production of material in the study. The usefulness of an LCA study is highly dependent upon the accuracy and comprehensiveness of the LCI. Without a reliable and broad LCI, the usefulness of an LCA study may endure and uncertainties may be introduced to the lifecycle impact assessment (LCIA) stage. As illustrated in **Fig. 2** the LCI stage of an LCA study of building materials includes identifying and collecting input and output flows in the supply chain of material production. The input flow involves the consumption of raw materials, energy and water. The output flow includes the production of the principal material and the generation of emissions, waste and by-products.

The compilation of data for the LCI can be developed using computer software such as GaBi, SimaPro for product comparison. Commercial and open access databases also exist and provide comprehensive information on environmental impacts of materials and products for developing the LCI. The databases that are commercially available include Ecoinvent or free access such as USDA, openLCA, NEEDS (NEXUS, 2018). However, base the study on different tools and databases may result in different outcomes.

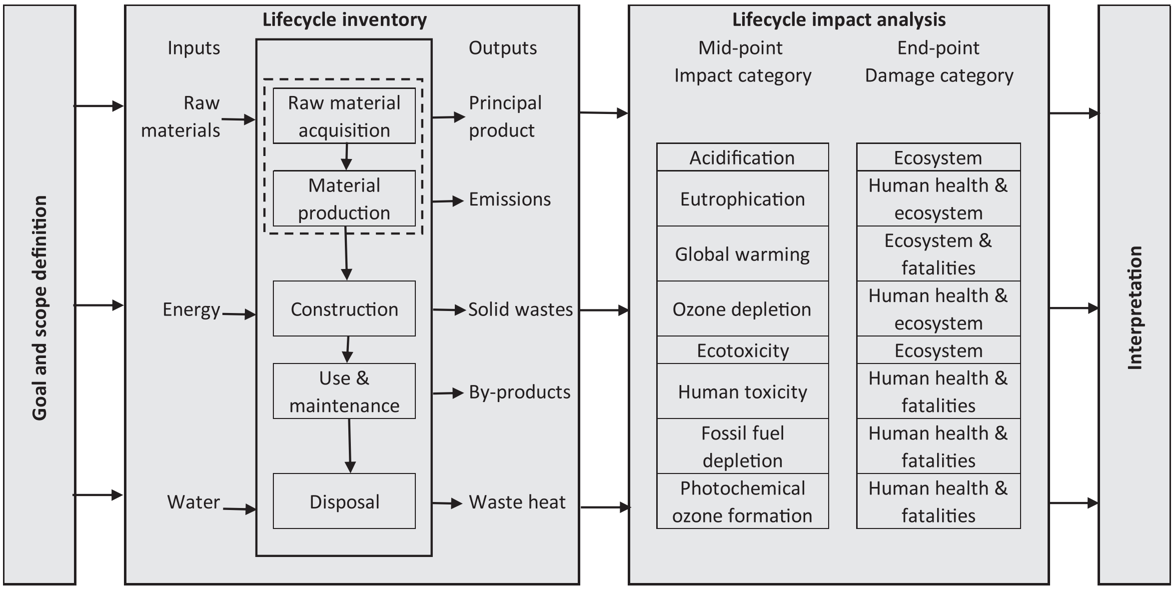


Fig. 2 ISO framework for the LCA study of building materials. *Source*: Reproduced from ISO, 2006a. ISO 14040: Environmental management – Life cycle assessment – Principles and framework. International Standards Organization, Geneva. ISO, 2006b. ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines. International Standards Organization, Geneva.

Table 2 Selected impact and damage categories in LCA study of building materials

Impact category	*Units*	*Damage category*
Acidification potential	$kgSO_{2\ eq}$	Ecosystem
Eutrophication potential	kgN_{eq}	Human health & ecosystem
Global warming potential	$kgCO_{2\ eq}$	Ecosystem & fatalities
Ozone depletion potential	$kgCFC_{-11\ eq}$	Human health & ecosystem
Ecotoxicity	$kgLC_{50\ eq}$	Ecosystem
Human toxicity	$kgLC_{50\ eq}$	Human health & fatalities
Fossil fuel depletion	MJ	Human health & fatalities
Photochemical ozone formation	$kgC_2H_{4\ eq}$	Human health & fatalities

Source: Adapted from IPCC, 2014. Climate change 2014: Impacts, adaptation, and vulnerability. In: Field, C.B., Barros, V.R., Dokken, D.J. (Eds.), Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Takano *et al.* (2014) conduct a research study to examine the numerical and methodological differences of five databases of GHG emission values in the material production phase of five housing projects. Research outcomes reveal that the databases generate different results but show similar trends and the same order of magnitude differences shown by all the databases. Therefore the selection of a database that is relevant to the regional condition and climatic similarity is critical.

The LCIA stage involves the classification and characterization of impacts identified in the LCI stage as illustrated in Fig. 2. The classification of impacts is to sort inventory parameters according to the type of environmental impacts they are contributed to (selected impact categories are included in Table 2), while characterization is to quantify intensity and degree of environmental impacts to each type of impacts such as global warming potential (GWP) is the total of all GHG emissions in materials. Table 2 extracts the common types of impact categories and the associated damage categories in relation to the production of building materials. At the LCIA stage for the LCA study of building materials the impacts are divided into mid-point and end-point category (Fig. 2). At the product stage of building materials the study may focus on all or some the mid-point or end-point impact categories.

The normalization may also be undertaken if impacts are to be standardized or ranked. However, normalization is an option only in according to the ISO 14040/14044. At the end of the assessment, the results are interpreted and conclusions are drawn for product improvement. The improvement can include changing the design and specification of the product to be more energy efficient and fewer emissions on the environment. The LCA results are capable of identifying the key areas for improvement.

Assessing Environmental Impact of Building Materials

Environmental impact (EI) at the product stage takes into account the extraction and consumption of raw materials from the ground and the associated energy in the manufacturing processes and transportation. The process of assessing the EI of individual building materials consists of identifying and collecting input flow of energy use, raw materials and other utilities, and the output flow of product, co-product emissions and waste. The amount and types of inputs used in the production of building materials are assessed according to the total quantity of raw materials needed to fit the functional unit adopted. The calculation of EI of individual building materials requires the quantities per functional unit such as 1 kg of steel, 1 m^2 of the gross floor area of a building, 1 m^3 of concrete. Therefore the calculation of EI of individual building materials is derived by multiplying the quantity of all the raw materials (including wastage) with corresponding EI data in the production of the building material per designated functional unit.

The amount of by-products and emissions associated with the production of building materials and products is highly dependent on the type and efficiency of machinery and equipment used in the extraction and manufacturing process (Chau *et al.*, 2012). The EI computation for energy consumption and emissions is calculated by summing up the duration of machinery and equipment used multiplied by fuel consumption per type and the associated emission coefficient of fuel consumption.

In addition to the energy required to operate machinery and equipment, raw materials are to be transported to the factory gate or finished products to the distribution centres by different modes of transportation. Raw materials transported to factories or distribution centres are delivered via trucks covering the outward trip (usually full load) and return trip (empty). The emissions about transportation are directly related to the efficiency, fuel type, number of truckloads, total distance travel (outward and return trip), fuel consumption and emission coefficient per fuel type (de Wolf *et al.*, 2016). There are various issues of transportation of raw materials that are not extracted locally which are often shipped or by rails from across countries or even from overseas. It is considered that the impact on cross-boundary air qualities and the estimation of EI are much more complicated.

Some Examples of LCA Studies of Building Materials

Cement Material

Cement is commonly used in the construction industry. It is an inorganic and non-metallic substance with hydraulic binding properties, and is used as a bonding agent in building materials. It is used as a component in concrete, mortar, stucco and grout. It is made by heating a mixture of limestone and clay to a temperature of about 1450°C. The product is then grinded to a very fine powder to become cement. During the heating process CO_2 is released from the limestone to produce cement.

The production of cement is an energy intensive process and adversely affects the environment in the form of GHG emissions (Basu and Bidanda, 2014; Hossain *et al.*, 2017). Half of the CO_2 emissions are from the manufacturing process through the combustion of fossil fuel and the rest comes from the calcination of limestone. According to Hossain *et al.* (2017), the production of cement in the world contributes to approximately 5%–10% of the total CO_2 emissions and consumes approximately 12%–15% of total industrial energy use. Overall, for the production of one tonne of Portland cement clinker approximately 0.87 tonne of CO_2 is released into the atmosphere (Hossain *et al.*, 2017). However, this value may vary with the location, technologies used, plant production efficiency, mix of energy sources used and the selection of kiln fuels (Josa *et al.*, 2007).

Fig. 3 summarizes inputs and outputs in the LCA study of the cement production. During the manufacturing process both direct and indirect impacts are considered in the LCA study. The inputs in the production of cement include lime, silica, iron, alumina and small amounts of additives. Approximately 1.6 tonnes of raw materials are needed to produce 1 tonne of cement primarily because of calcination of calcium carbonate, which typically comprises 75%–80% of the raw materials (Huntzinger and Eatmon, 2009). The composition of raw materials varies according to the required properties. The inputs also include the consumption of energy from the combustion of fossil fuels, e.g., coal, gas, oil and renewable energy sources may also be involved in the production processes.

The outputs of the product phase include the production of the cement or clinker. The production processes generate emissions to air, solid waste, waste heat and other by-products. Emissions are generated during the production of cement from the burning process and the diesel trucks. Other emissions include particulate matter from the point and fugitive sources and the combustion gases of CO_2, SO_2, NO_x, carbon monoxide, volatile organic compounds and methane. Solid wastes include cement kiln dust from the production of cement. According to Hossain *et al.* (2017), approximately 1.9 GJ of heat lost per tonne of cement produced. This is heat lost primarily in the kiln and cooler exhaust gases and also by radiation from the kiln shell and other hot surfaces.

The Portland Cement Associated initiated to develop LCA-based EPD for three types of cement and they are Portland cement, masonry cement and blended cement (Portland Cement Association, 2016a,b,c). The LCA results are summarized in **Table 3**. From the table the traditional Portland cement has the most significant impact in all categories and followed by blended and masonry cement. The blended cement is manufactured by mixing Portland cement with mineral admixtures such as fly ash, slag or silica fumes. The masonry cement is mixed with plasticizing materials and other performance-enhancing additions to form mortar for brick, concrete block and stone masonry.

Other LCA studies have also been undertaken to improve the environmental performance of traditional Portland cement. Huntzinger and Eatmon (2009) use LCA to evaluate and compare four cement manufacturing processes on a cradle-to-gate boundary. Research results show that replacing approximately 25% of clinker with natural pozzolans in the

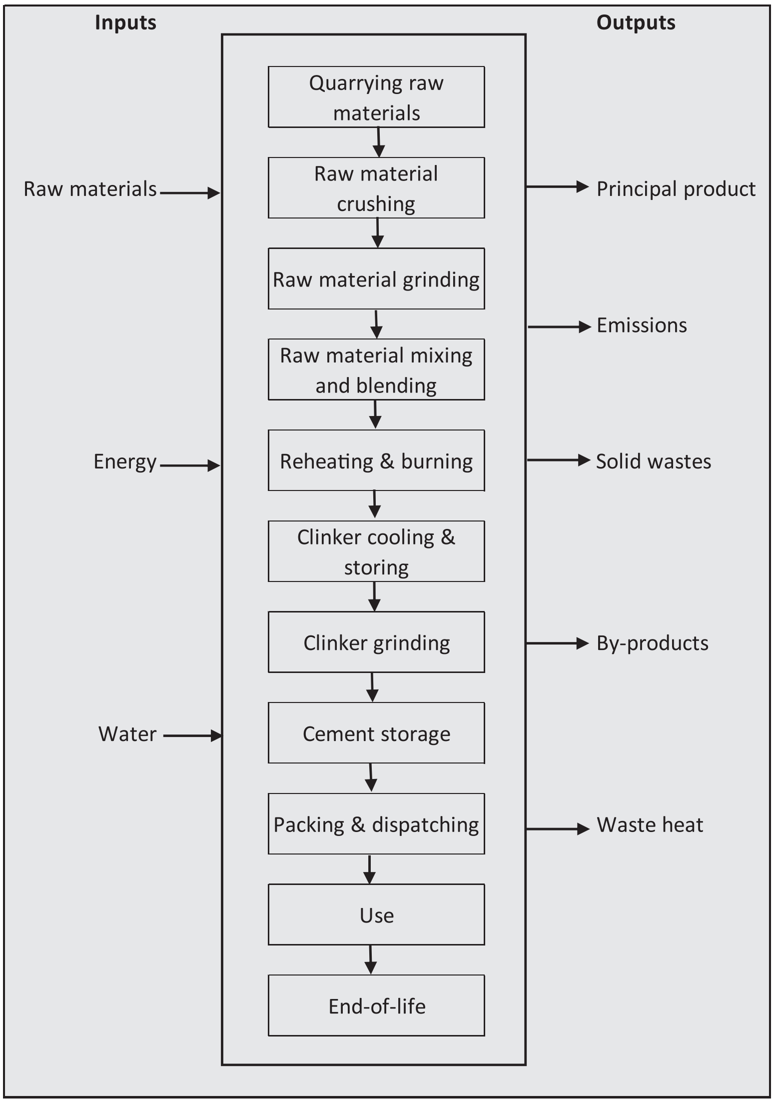


Fig. 3 LCA framework for the production of cement. *Source*: Adapted from Huntzinger, D.H., Eatmon, T.D., 2009. A life-cycle assessment of Portland cement manufacturing: Comparing the traditional process with alternative technologies. Journal of Cleaner Production 17, 668–675.

cement manufacturing process has effectively reduced the most substantial environmental impact process (the kiln or pyroprocessing step) by 22%.

Concrete Material

Concrete is a traditional heavy material used widely in buildings. Concrete is commonly used for load-bearing structures which are high in energy intensity and GHG emissions. Concrete is produced by mixing cement with aggregate, sand, water and other admixtures which are then poured into timber mould to form a designed structure. The characteristic and strength of concrete are controlled by the ratio of water to cement and the types of admixtures.

Concrete has a special characteristics to absorb CO_2 from the atmosphere. This is a process of carbonization that CO_2 diffuses back into the concrete and reacts with calcium dihydroxide (H_2CaO_2). The rate of carbonization depends on the CO_2 concentration and humidity in the ambient air. Since carbonization is gas diffusion the process is slower with increasing humidity. It also depends on the density of the concrete (water to cement ratio) and whether the surfaces coated such as painting or wallpaper that may reduce the rate of CO_2 diffusion into the concrete. According to Chau *et al.* (2015), the net CO_2 emission of concrete production after taking into account both calcination and carbonation was estimated to be 0.033 $kgCO_2/kg$ concrete.

The inputs and outputs in the LCA study of concrete are presented in **Fig. 4**. The inputs for the production of concrete require cement, sand, aggregates and admixtures. Cement is required as a bonding agent to bind all the resources together when mixed with water to form

Table 3 Environmental impacts of cement (1 tonne)

Environmental impact	*Portland cement*	*Masonry cement*	*Blended cement*
Global warming potential (100 year) (kg$CO_{2\ eq}$)	1040	692	892
Acidification potential (kg $SO_{2\ eq}$)	2.45	1.83	2.26
Eutrophication potential (kgN_{eq})	1.22	0.93	1.11
Ozone depletion potential (kg $CFC11_{eq}$)	2.61E-05	2.18E-05	2.48E-05
Primary energy consumption (MJ)	5887	4611	5243
Raw materials (kg)	1428	1259	1243
Fresh water (L)	9700	9330	9240
Waste generated (kg)	9.04	7.76	10.55

Source: Portland Cement Association, 2016a. Environmental product declaration (EPD 033) – Blended hydraulic cement. Skokie: Portland Cement Association. Portland Cement Association, 2016b. Environmental product declaration (EPD 034) – Masonry cement. Skokie: Portland Cement Association. Portland Cement Association, 2016c. Environmental product declaration (EPD 035) – Portland cement. Skokie: Portland Cement Association.

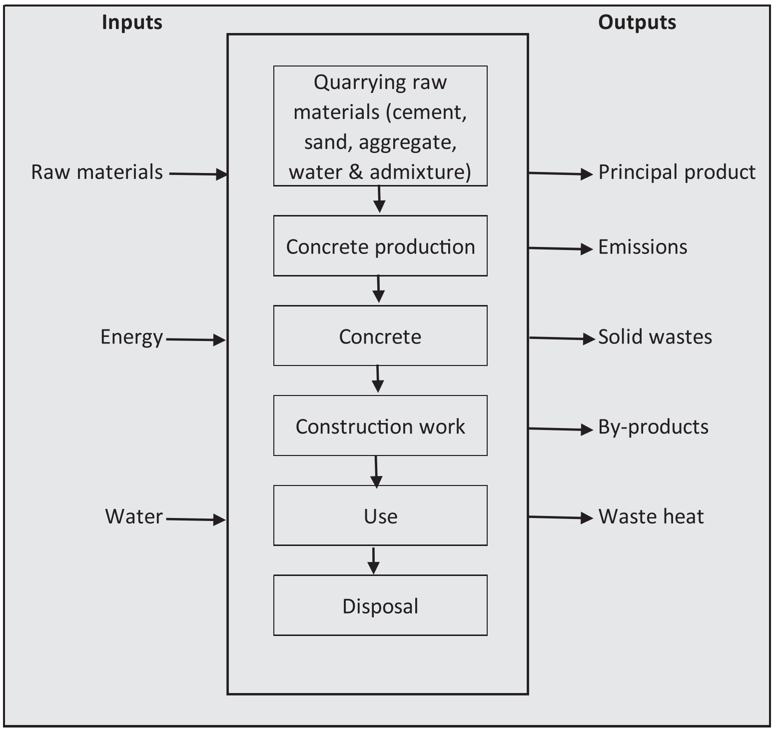


Fig. 4 LCA framework for the production of concrete. *Source*: Adapted from Chau, C.K., Hui, W.K., Ng, W.Y., Powell, G., 2012. Assessment of CO_2 emissions reduction in high-rise concrete office buildings using different materials use options. Resources, Conservation and Recycling 61, 22–34.

the designed structure in buildings. Sand and aggregates are produced from crushed stone and concrete mix determines the quantities of coarse and fine aggregates. Admixtures such as air entraining, water reducers, accelerators, superplasticizers are widely used in concrete to control the properties and performance but are usually below 1%. Water is needed in the production of concrete which may be affected by the type, location and size of the plant. Water is also used for truck wash out and off the site and the concrete plant.

Energy is used in the concrete plant that includes electricity and fuel used for equipment and heating. Energy is also required for the transportation of materials, e.g., cement, fly ash, aggregates from distribution centres to the concrete plant which can be by road rail or barge using diesel fuel or others.

The outputs at the concrete production stage include generating emissions in the making of coarse and fine aggregates from crushed stone, cement production and the final production of concrete. Emissions also generate from the consumption of diesel fuel by trucks and are calculated from the energy consumption in the same way as in the LCA study of cement in the previous section. Solid wastes are generated during the extraction of raw materials and the manufacturing processes. Waste heat is also produced in the manufacturing process of concrete.

The National Ready Mixed Concrete Association (NRMCA, 2014) developed EPDs for various types of concrete using an LCA approach and results are summarized in **Table 4**. The table presents the results of cradle-to-gate LCA results for two types of product

Table 4 Environmental impacts of concrete (1 m^3)

Environmental impact	*281.2 kg/cm² (27.6 MPa)*	*562.5 kg/cm² (55.1 MPa)*
Global warming potential (100 year) ($kgCO_{2\ eq}$)	432	633
Acidification potential (kg $SO_{2\ eq}$)	2.29	3.34
Eutrophication potential ($kgN_{\ eq}$)	0.068	0.094
Ozone depletion potential (kg $CFC11_{\ eq}$)	5.61E-06	8.27E-06
Primary energy consumption (MJ)	2646	3678
Raw materials (kg)	2449	2495
Freshwater (m^3)	21.2	17.6
Waste generated (kg)	0.73	0.73

Source: Adapted from National Ready Mixed Concrete Association (NRMCA), 2014. Environmental product declaration (NRMCA EPD: 10005) for concrete. Silver Spring.

Table 5 Percentage distribution of GWP and PEC by product lifecycle stage

Concrete strength	*Global warming potential (GWP) (100 years) %*			*Primary energy demand (PED) %*		
	A1	*A2*	*A3*	*A1*	*A2*	*A3*
281.2 kg/cm^2 (27.6 MPa)	93.7	4.0	2.4	89.3	6.8	4.0
562.5 kg/cm^2 (55.1 MPa)	92.7	4.4	3.0	83.9	9.7	6.5

Source: Adapted from National Ready Mixed Concrete Association (NRMCA), 2014. Environmental product declaration (NRMCA EPD: 10005) for concrete. Silver Spring.

mix designs considered within each compressive strength class on 1 m^3 of ready-mixed concrete. The LCA results show that the environmental impacts increase to the higher compressive strength of concrete.

Table 5 presents the results in percentage distribution by the three stages of the product phase for the compressive strength of 27.6 MPa and 55.1 MPa. The table shows that the percentage distribution of the raw materials production has the highest in both the global warming potential (GWP) and primary energy demand (PED) which agree with the research undertaken by Hafliger *et al.* (2017). Overall the upstream materials production accounts for approximately 93%–94% and 84%–90% respectively for GWP and PED associated with the production of ready-mixed concrete. The highest percentage in the A1 stage is due to the manufacture and use of Portland cement which is high in both emission and energy consumption. Materials transportation according to Vigovskaya *et al.* (2017) and **Table 5** contributes about 4% of the GWP and 7%–10% of primary energy consumption. The manufacturing stage according to Buyle *et al.* (2013) and **Table 5** contributes the least in both.

Steel Material

Steel is another commonly used material in the construction industry. Steel is combined with concrete to form a reinforced concrete structure for buildings. Steel can also be used as raw materials to make components such as window frames, pipes, machinery and household goods. Steel production is a high energy intensity and GHG emissions. The manufacturing processes of steel involve the extraction of iron ore from the ground which then goes through the melting process in a furnace with oxygen blowing through it to remove impurities and reduce carbon percentage to produce steel. The various industrial processes of iron, coke, sinter and steel production contribute to more than 60% of the total energy-related GHG emissions, of which iron production is the largest (74%) (Olmez *et al.*, 2016). According to Quader *et al.* (2016) one tonne of steel manufacturing emits approximately 1.8 tonnes of CO_2.

Improving efficiency in the manufacturing process of steel has been the focus of research and development. Steel has sustainable characteristics which can be recycled entirely and used infinitely. The production of steel can incorporate recycled content and reusing water for cooling purposes. Emissions to the air from the production can also be controlled through better design production technologies. Recycled steel (scrap steel) comes from demolished structures, end-of-life vehicles and machinery. According to World Steel (2018a), it was estimated that 630 million tonnes of scrap steel were recycled in 2017 and of this, approximately 560 million tonnes were used by the global steel industry.

The inputs and outputs in the LCA study of steel are presented in **Fig. 5**. The inputs in the production of steel include the use of 98% of iron ore, small amount of other elements such as manganese, carbon and coal as the primary energy sources. According to World Steel (2018b), the global steel industry used about 2.1 million tonnes of iron ore, 1.1 million tonnes of metallurgical coal and 560 million tonnes of recycled steel to produce about 1.7 billion tonnes of crude steel in 2017. The steel use is projected to increase by 1.5 times to meet the needs of population growth.

Steel production is energy intensive due to the chemical energy required to reduce iron ore using a carbon-based reducing agent. Iron ore and metallurgical coal are used mainly in the blast furnace process of ironmaking. Typically it takes about 1.6 tonnes of iron ore and around 400 kg of coke to produce one tonne of pig iron (World Steel, 2018b). Improvements in energy

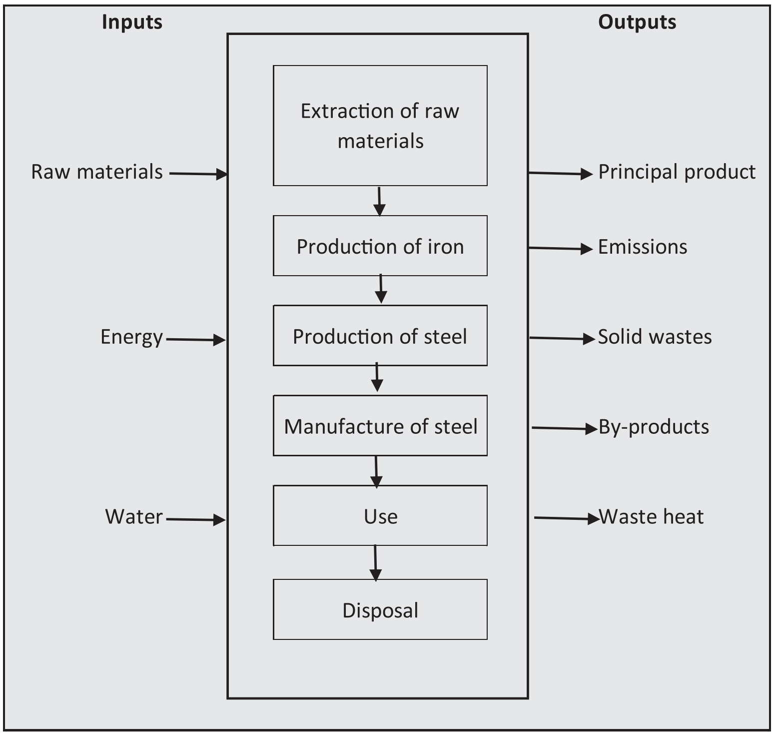


Fig. 5 LCA framework for the production of steel. *Source*: Reproduced from World Steel, 2018b. Life cycle inventory study, World Steel Association, Beijing, China.

efficiency have led to the reduction of about 60% in energy required to produce 1 tonne of crude steel since 1960. The energy efficiency of steelmaking facilities vary depending on production route, type of iron ore and coal used, the steel product mix, operation control technology and material efficiency.

The outputs at the product phase of steel production include the final production of steel but the processes generate various types of emissions, solid wastes, waste heat and other by-products. Similar to the production process of cement and concrete as previously discussed, emissions due to the combustion of fossil fuels in both the manufacturing processes and transportation are also included in the LCA study. The production of steel also generations by-products such as slags, dust and sludge. On average the production of 1 tonne of steel will result in 200–400 kg of by-products. About 90% of the by-products are slags which are solid wastes from the burning processes.

EPDs have been used to provide information on environmental impacts with regards to the production of steel. **Table 6** extracts and compares the EPDs for steel production of three different types of steels. The production of hot-dip galvanized steel generates the highest GWP and PDE and followed by hot rolled coil steel. The table also extracts the potential benefits of recycling of the steel at the end-of-life. According to World Steel (2018a), the rate of recycling of steel from the construction industry is approximately 80% which can be recycled as scrap steel in the production of crude steel. From the table hop-dip galvanized steel generates marginally better recycling benefit than the hot-rolled coil steel in both GWP and PED.

Sustainable Building Materials

The design and construction of buildings conventionally focus on using heavy materials such as steel, concrete and masonry but these materials are both high energy intensity and emission content. Therefore over the years research studies focus on using low impact alternative materials, improving technologies and practices to reduce the negative impact of materials on the environment.

Use Low Impact Materials

Construction materials are important for the survival of the industry. However, it is essential that the manufacturing processes of these materials be improved to reduce their impact on the environment. Low impact materials, therefore, play an important role and their selection at an early design stage should be undertaken as it will influence all downstream processes in achieving sustainability in buildings (Shen *et al.*, 2010). Majority of low impact materials are manufactured from the natural or renewable sources such as timber, straw bale and earth. These materials have low in energy intensity and emissions compared with conventional heavy materials. However, Giesekam *et al.* (2014) suggest that instead of just replacing conventional materials with

Table 6 Environmental impacts of steel (1 tonne)

Environmental impact	*Section*		*Hot-rolled coil*		*Hot-dip galvanized*	
	Cradle-to-gate	*Recycling benefit*	*Cradle-to-gate*	*Recycling benefit*	*Cradle-to-gate*	*Recycling benefit*
Global warming potential (100 year) (kgCO$_{2\ eq}$)	1.5	–0.3	2.2	–1.2	2.7	–1.3
Acidification potential (kg SO$_{2\ eq}$)	0.0042	–0.0006	0.0054	–0.0023	0.0065	–0.0025
Eutrophication potential (kgN$_{eq}$)	0.00032	–0.00005	0.00046	–0.00017	0.00059	–0.00018
Photochemical ozone creation potential (kgC$_2$H$_{4\ eq}$)	0.00064	–0.00015	0.00091	–0.00054	0.00101	–5.80E-04
Primary energy demand (MJ)	18.3	–2.8	23.3	–10.1	29.5	–10.7

Source: Adapted from World Steel, 2018b. Life cycle inventory study. Beijing: World Steel Association.

natural materials they can be combined to form low impact products such as panelized prefabricated timber and straw bale systems, lime and gypsum to replace convention cement plasters, timber and steel hybrid structures in buildings.

Advancement in the Material Production Technologies

Conventional heavy materials tend to have a long lifespan and require little maintenance and replacement throughout the building lifecycle. However, these materials are both high in energy intensity and emissions that are detrimental to the environment. There are research studies on the improvement of their manufacturing processes to reduce their impacts on the environment. Cement is a mostly used material in the construction of buildings. Gao *et al.* (2015) state that the production of cement is responsible for about 7% of total CO$_2$ emission globally. Ishak and Hashim (2015) further state that the clinker production generates about 90% of the CO$_2$ emissions in the production of cement. Therefore minimizing the need for carbon-intensive cement products is an essential part of reducing the embodied emissions of construction materials (Giesekam *et al.*, 2014; Gao *et al.*, 2015). The improvement in the production technologies of cement includes recovering waste heat, substituting fossil fuels with renewable energy sources, substituting low carbon cement by cementitious materials such fly ash, silica fume, slag, etc. (Crossin, 2015). Gao *et al.* (2015) further state that GHG emissions can be reduced by replacing carbonate-containing materials with non-carbonate materials and changing the clinker ratio in cement production.

Steel is another commonly used and high impact building material. Improvement in the steel production has attracted much attention to reduce the consumption of raw materials and emissions. Improvements include capturing and reusing gas and waste heat, collecting and recycling waste steel to reduce the use of virgin materials, improving the quality of steel products to maximize the lifespan, using energy-saving equipment, and improving the efficiency of energy conversion facilities (Quader *et al.*, 2016). In the production of concrete solid waste such as use waste glass cullet from waste glass bottles to substitute clinkers can be used to replace virgin materials to produce eco-glass cement. According to Hossain *et al.* (2017), eco-glass cement has about 16% energy consumption and 17% GHG emission compared to that of traditional Portland cement but comparatively similar strength.

Use Lightweight Building Structures

The design and construction of buildings can be shifted to focus on using lightweight materials (Meggers *et al.*, 2012). Meggers *et al.* (2012) go on to state that lightweight building designs can minimize the consumption of raw materials and the structural design of concrete with expanded aggregates can reduce the overall weight as well as improving insulation property of the building. Giesekam *et al.* (2014) further suggest to use lightweight design in conjunction with structural member optimization to minimize the excessive use of materials but this will require changes in design practices or innovative manufacturing processes. López-Mesa *et al.* (2009) compare environmental impacts between in-situ and precast concrete floors for two seven-storey residential buildings. Research results indicate that precast concrete floor with a longer span between beams reduces the size of columns and footings and thus reduces the total concrete used in the building which has about 12% lower environmental impact than in-situ concrete.

Use Alternate Fuels

Majority of the energy sources are fossil-based such as oil and coal which are high in emissions. Bio-based and industrial by-products such as waste plastics, scrap tires, wood residues, biomass wastes, wood chips, palm shells, saw dust and so forth can be used as alternative fuel sources in the production of building materials. These waste materials, on the one hand, can be used as fuel to replace fossil fuel, on the other can reduce waste to landfill sites. Hossain *et al.* (2017) conduct a research study to compare the manufacturing process of four different types of cement. Research results indicate that by replacing 10%–50% of coal with the biofuel produced from locally generated wood wastes, potentially 3%–14% and 6%–29% of total GHG emissions and non-renewable energy consumption can be reduced respectively in the production of one tonne of traditional Portland cement.

Increase Reuse and Recycling of Materials

The construction industry is an industry slow to change. Significant concept changes in the practices of the construction industry to facilitate the reuse and recycling of building materials can be made possible if they can be considered as early as possible in the design development. Such changes could be made to favour the disassembly of the construction materials at the end of their service life and by selecting materials for the recycled sources and assembly, techniques are significant in the reduction of GHG emissions (Bribian *et al.*, 2011). Giesekam *et al.* (2014) state that increased reuse and recycling will require design for disassembly and an increased focus on the end of life project stage during design. Proper early planning in the design and construction of buildings is essential.

Conclusion

Building materials are used for the initial construction of a building and will continue to be consumed during the use phase for maintenance and refurbishment. The production of building materials is both high energy intensity and GHG emissions throughout a building's lifecycle. The building materials while important for the construction industry they are also potentially significant in minimizing environmental loads as materials are used throughout the building lifecycle. To reduce the environmental impact of buildings, it is necessary to design and select and materials with low impact to reduce resources consumption and GHG emissions.

This article provides an overview of the importance of building materials and discusses the framework of LCA in the assessment of material on a cradle-to-gate boundary. LCA provides a systematic and transparent framework to generate data to assist the selection of environmentally friendly materials for buildings. Through the LCA analysis, all possible environmental loads of material are ultimately assessed and classified according to their contribution to the environmental impact and damage categories. While LCA can be applied to compare the environmental impact of different materials, it can also be applied to different production processes to determine the stages causing the most significant environmental harm for improvement in a lifecycle perspective.

Over the years significant research and development have been undertaken to improve the manufacturing processes of materials. The common suggestions are substituting high impact resources with more natural and renewable-based materials such as timber, straw bale, and earth in the construction of building materials. Research and development also focus on increasing the use of recycling materials to replace raw materials such as scrap steel, fly ash to produce building materials. Considering to improve the environmental benefits of material it is necessary to encourage more international collaboration and strengthen the policy aspects to promote the principal to reduce, reuse and recycle to reduce the consumption of virgin raw materials.

See also: A Comparative Life Cycle Assessment for Utilising Laminated Veneer Bamboo as a Primary Structural Material in High-Rise Residential Buildings

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