CHAPTER II

THEORY AND RELATED LITERATURE REVIEW

The purpose of this chapter is to provide a concise demonstration of the necessary concepts in the techno-economic and environmental analysis of autoclaved aerated concrete, tobermorite, phase change materials, heat transfer, time lag and life cycle assessment. Furthermore, the review of previous works on autoclaved aerated concrete and phase change materials is presented.

Autoclaved aerated concrete (AAC) is also known by many names; autoclaved cellular concrete (ACC), autoclaved lightweight concrete (ALC), autoclaved concrete, cellular concrete, porous concrete, Ytong, Hebel Block, Aircrete, Thermalite, or BCA. It is a unique building material made from quartzite silica sand, water, lime, cement and anhydrite, which are processed with a gas-forming aluminium paste, to create a highly porous, lightweight, insulating mineral product. AAC can be used to produce such products as concrete blocks, wall panels, floor and roof panels and lintels.

History of the autoclaved aerated concrete

Lightweight aggregates and foaming agents have been employed to reduce the weight of concrete since Roman times. Whereas true aerated concrete relies on the alkaline binder (lime and cement) reacting with an acid to release gases, this differs from foamed or light aggregate mixes which directly employ foaming agents which remain entrained in the material. In 1889, the first attempt to produce aerated concrete was a method patented by a Czechoslovakian, Mr. E. Hoffman. The aeration was produced by carbon dioxide generated in the reaction between hydrochloric acid and limestone. In 1914, aluminium powder and calcium hydroxide powder were used as aeration agents in cementicious mixtures by Aylsworth and Dyer in the USA.

In 1917, a Dutch patent was registered using yeast as an aerating agent. Later patents involved the reaction between zinc dust and the alkalis in the cement mixture, hydrogen peroxide, sodium or calcium hypochlorite and air foaming. In 1919, the use of metal powders as a hydrogen gas forming agents was developed further by Grosahe in Berlin. Aluminium powder was settled upon as the medium which produced the most even, controllable aeration by the release of hydrogen bubbles in a consistent size range. However, most of these air cured aerated concrete methods resulted in low compressive strength, crumbly material, generally unfit for structural applications.

In 1923, the first documented attempt at autoclaving aerated concrete was in Sweden. The discovery was almost accidental. An architectural science lecturer, Dr Johan Axel Eriksson [35, 36], then assistant professor for Building Techniques at the Royal Institute of Technology in Stockholm, was working on a variety of aerated concrete samples. It went into production in Sweden in 1929 in a factory in Hällabrottet and quickly became very popular. In the 1940s, the trademark Ytong was introduced, and was often referred to as "blue concrete" in Sweden due to its blueish tinge. This Ytong was produced from alum shale, which was the combustible carbon content that made it beneficial to use in the production process. A competitive concrete brand, Siporex, was produced in Tuzla, Bosnia, and used raw materials other than those in the 'Ytong' brand product. "Ytong" subsequently acquired Siporex and today produces "Siporex" under the "Ytong" brand in the Tuzla, Bosnia factory. Unfortunately, the slate deposits used for Ytong also contained uranium, from which the material gave off radioactive radon gas in buildings constructed with this concrete. In 1972, the Swedish Radiation Safety Authority pointed out the unsuitability of the radon-emitting construction material, and the use of alum slate in the production of Ytong was discontinued in 1975. After 1975, Ytong has produced concrete which has used raw materials without the uranium content.

Autoclaved aerated concrete production in Europe has considerably decreased, while the industry is growing rapidly in Asia because of the strong demand in housing and commercial space. China, Central Asia, India, and the Middle-East are the biggest markets in terms of AAC manufacturing and consumption.

Materials Used in Manufacture

AAC is manufactured from sand, cement, lime, gypsum, water and an expanding agent. Quartz sand, lime, cement and water are used as a binding agent. Aluminum powder is used at a rate of 0.05–0.08% by volume (depending on the pre-specified density) [37]. After the AAC is mixed and cast in forms, several chemical reactions take place that give AAC its light weight (20% of the weight of conventional concrete) and thermal properties. The aluminum powder reacts with the lime (calcium hydroxide) and the water to form hydrogen. The hydrogen gas foams and doubles the volume of the raw mix (creating gas bubbles up to 3 mm (1/8 inch) in diameter). At the end of the foaming process, the hydrogen escapes into the atmosphere and is replaced by air. These chemical reactions processes are shown in (2.1)-(2.3).The formed AAC is then able to be cut into either blocks or panels, which are placed in an autoclave chamber for 12 hours. The temperature reaches 190°C (374°F) and the pressure reaches 8 to 12 bars. The quartz sand reacts with the calcium hydroxide to form calcium silica hydrate during the steam pressure hardening process as exhibited in (2.4).The calcium silicate hydrate crystals formed in this process are similar to volcanic rock, which is known in nature as Tobermorite. After the autoclaving process, AAC has high strength, is lightweight and has a highly porous structure (Approximately 80% of the volume of the hardened material is made up of pores, 50% being air pores and 30% being micropores). It also demonstrates lower thermal conductivity, higher heat resistance, lower shrinkage and is easier and faster to use in the construction process than traditional concrete [38-41].

$$\text{Cement} + H_2O \longrightarrow \text{C-S-H} + Ca(OH)_2 \tag{2.1}$$

$$CaO + H_2O \longrightarrow Ca(OH)_2 \tag{2.2}$$

$$2Al + 3Ca(OH)_2 + 6H_2O \longrightarrow 3CaOAl_2{\cdot}6H_2O + 3H_2 \tag{2.3}$$

$$5CaO + 6SiO_2 + 5H_2O \xrightarrow[180\text{-}190\ ^{\circ}C]{12\ h,\ 12\ bar} 5CaO{\cdot}6SiO_2{\cdot}5H_2O \tag{2.4}$$

Since 1980, there has been a worldwide increase in the use of AAC materials. New productions, which are composed of the plants, are being built in Australia, Bahrain, China, Eastern Europe, India, Israel, and the USA. AAC is increasingly used by developers, architects, and home builders worldwide [35, 36].

Quality classes of autoclaved aerated concrete [38]

Autoclaved lightweight concrete can be divided into 4 classes when considering the compressive strength property and 9 types when considering density, as shown in Table 1.

Table 1 Quality class based on the Thai Industrial Standard 1505-1998.

Quality class	Compressive strength ($x10^6$ N/m^2)		Type	Average volume density (kg/m^3)
	Average	Minimum		
G2	2.5	2.0	0.4	310-400
			0.5	410-500
G4	5.0	4.0	0.6	510-600
			0.7	610-700
			0.8	710-800
G6	7.5	6.0	0.7	610-700
			0.8	710-800
G8	10.0	8.0	0.8	710-800
			0.9	810-900
			1.0	910-1000

Tobermorite

Tobermorite is a calcium silicate hydrate mineral with chemical formula: $Ca_5Si_6O_{16}(OH)_2{\cdot}4H_2O$ or $Ca_5Si_6(O,OH)_{18}{\cdot}5H_2O$. It is naturally a rare mineral, but synthetic minerals of the tobermorite group are the main components in cement and lime-silica products and are produced during the binding process. Two structural varieties are distinguished: tobermorite-11 Å and tobermorite-14 Å. Tobermorite occurs in hydrated cement paste and can be found in nature as an altered mineral in metamorphosed limestone and skarn. It was first described in 1880 as occurring in Scotland, on the Isle of Mull, around the locality of tobermory [39].

In general, tobermorite has an orthorhombic structure which could be stable with Ca/Si ratio of 0.8~1.0 and the ambient temperature up to 150°C. It coexists within tetrahedral silicate layers and octahedral calcium layers [40]. A system of Calcium-Silicate-Hydrate (C-S-H system) can be formed as slurry phase by following a two-step process creating a hydrothermal reaction between SiO_2 and $Ca(OH)_2$. In the first step, calcium silicate hydrate gel (C-S-H gel) is generated on the surface of SiO_2which then reacts with $Ca(OH)_2$ to form a well-organized crystal line [41]. In the second step, the crystalline product is cured. There are two alternative curing processes which provide specimens with different properties. The first curing process made use of air to cure specimens, which creates the hydrogarnet crystalline structure, depending on the curing time period. The other curing process is the autoclave curing process in which high pressure and temperature is applied to the specimens in a heating and pressure chamber at a temperature of about 180°C to 190°C under pressure at 8 to 12 bars. The tobermorite is formed in the specimens in this curing process, as shown in Figure 1. The tobermorite structure model consists of Ca^{2+} ions which are entrapped in the protonated silicate ions [42]. So, the tobermorite crystal is stable to carbonation reaction under the condition of ambient temperature up to 650°C, at which temperature it will disintegrate. Pressure has no relevant affect in this process.

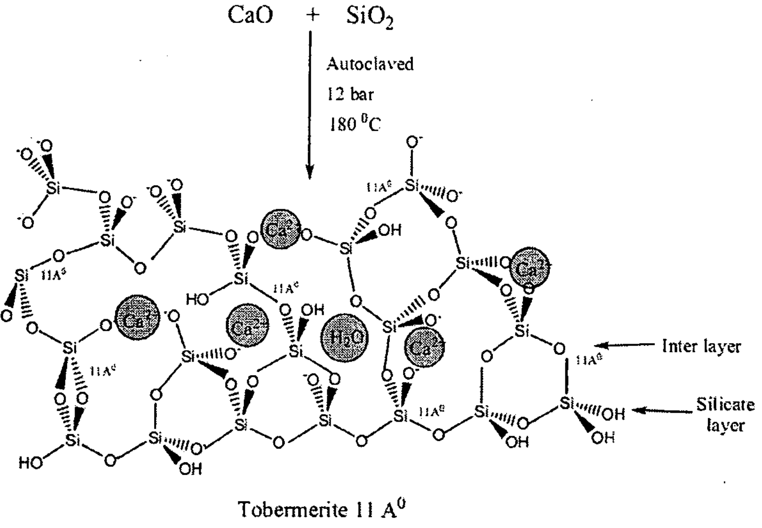

Figure 1 Model of tobermorite structure consisting of protonated silicate ions and water.

Phase change materials (PCMs)

Phase change materials (PCMs) are energy storage materials which have considerably higher thermal energy storage (TES) densities than sensible heat-sensitive storage materials. PCMs are able to absorb or release large quantities of energy at a constant temperature by undergoing a phase change [43]. Among the three ways to store energy, latent heat (LH) storage is the most attractive way since the heat can be stored and released as very large quantities of energy per unit weight of a PCM at a nearly constant temperature [44].The thermal energy transfer happens when the material changes from solid to liquid, or liquid to solid. Primarily, these solid–liquid PCMs function like conventional storage materials: their temperature increases when the phase change materials (PCMs) absorb the heat. Unlike conventional sensible storage materials, they absorb and release heat at a nearly constant temperature. PCMs store the heat around 5–14 times per unit volume greater than the sensible storage materials such as water, masonry, or rock. Many PCMs are known for melting with a heat of fusion in any required range. Nevertheless, these materials must show certain desirable thermodynamic, kinetic and chemical properties to be used as latent heat storage materials. Furthermore, the economic considerations and material availability must be investigated [45].

Classification

The numerous PCMs are classified as organic, inorganic and eutectic materials, which can be identified as a PCM from the view point of the melting temperature and the latent heat (LH) of fusion. Of these, PCMs with a melting point between 20°C –60°C are applicable to residential building using radiant floor heating systems.

Organic PCMs

The organic materials are further expressed as the paraffins and the non-paraffins. The organic materials offer the congruent melting, the self-nucleation and are usually non-corrosiveness to the container material. The organic PCMs have desirable cohesion, chemical stability, non-reactivity and recyclability as their advantages. Nevertheless, the organic materials have comparatively low heat conductivity in the solid state and a low latent heat capacity. The melting point and the latent heat of fusion of the organic PCMs allow them to be generally used for residential buildings, being used as radiant floor heating systems. PCMs of this type are listed in Table 2.

Inorganic PCMs

The inorganic compounds have a high latent heat per unit mass and a low volume cost compared to organic compounds. They are also nonflammable. Nevertheless, the inorganic compounds suffer from decomposition and super cooling that can further influence their phase change properties. The inorganic PCMs have high latent heat and high heat conductivity and are cheaper than the organic PCMs and the eutectic PCMs. Moreover, the inorganic PCMs are fire-resistant due to their nonflammable property. However, they need coagulants because of their large volume change when organic PCMs are changing to the opposite state. The melting point and the latent heat of fusion of the inorganic PCMs, listed in Table 3 , are normally applied in radiant floor heating systems in residential buildings.

Table 2 Organic PCMs for residential building using radiant floor heating systems [46]

Compound	**Melting point/°C**	**Heat of fusion/kJ kg^{-1}**
Paraffin C_{16}–C_{18}	20-22	152
Polyglycol E600	22	127.2
Paraffin C_{13}–C_{24}	22-24	189
1-Dodecanol	26	200
Paraffin C_{18}	27.5	243.5
Vinyl stearate	27-29	122
1-Tetradecanol	38	205
Paraffin C_{16}–C_{28}	42-44	189
Paraffin C_{20}–C_{33}	48-50	189
Paraffin wax	64	173.6

Table 3 Inorganic PCMs for residential building using radiant floor heating systems [46]

Compound	Melting point/°C	Heat of fusion/kJ kg^{-1}
$KF \cdot 4H_2O$	18.5	231
$Mn(NO_3)_2 \cdot H_2O$	25.8	125.9
$CaCl_2 \cdot 6H_2O$	29	190.8
$LiNO_3 \cdot 3H_2O$	30	296
$Na_2SO_4 \cdot 10H_2O$	32.4	254
$Zn(NO_3)_2 \cdot 6H_2O$	36	146.9
$Na_2S_2O_3 \cdot 5H_2O$	48	201
$Na(CH_3COO) \cdot 3H_2O$	58	226

Eutectics

A eutectic is a minimum-melting composition of two or more components. Each of the eutectics melts and freezes congruently forming a mixture of the components during crystallization [47]. Eutectic PCMs have a sharply formed melting point in the phase change and a measurement density which is similar to the melting point of the organic substances. Nevertheless, there has rarely been research undertaken to study their properties. The melting point and the latent heat of fusion of the eutectics (listed in Table 4) are also commonly applied in radiant floor heating systems in residential buildings.

Table 4 Eutectics for residential building using radiant floor heating systems [46]

Compound	Melting point/°C	Heat of fusion/kJ kg^{-1}
66.6% $CaCl_2 \cdot 6H_2O$ + 33.3%$MgCl_2 \cdot 6H_2O$	25	127
48% $CaCl_2$ + 4.3% NaCl + 0.4%KCl + 47.3% H_2O	26.8	188
47% $Ca(NO_3)_2 \cdot 4H_2O$ + 33%$Mg(NO3)_2 \cdot 6H_2O$	30	136
60% $Na(CH_3COO) \cdot 3H_2O$ + 40%$CO(NH_2)_2$	31.5	226
61.5% $Mg(NO_3)_2 \cdot 6H_2O$ + 38.5%NH_4NO_3	52	125.5
37.5% Urea + 63.5% acetamide	53	n.a.
58.7% $Mg(NO_3) \cdot 6H_2O$ + 41.3%$MgCl_2 \cdot 6H_2O$	59	132.2
67.1% Naphthalene + 32.9%benzoic acid	67	123.4

Transition of PCMs for building materials

Traditional PCM

Phase change materials (PCMs) have been developed for various applications because of their different phase change intervals: the materials which melt below 15°C are used to maintain a cool temperature in the air conditioning applications. While the materials that melt above 90°C are used to reduce temperature where there is a sudden increase in heat, thus avoiding ignition. The materials with the intermediate melting points can be applied in solar heating and for heat load leveling applications [48].

Phase change materials that have been studied over the last 40 years include the hydrated salts, the paraffin waxes, the fatty acids and the eutectics of the organic and inorganic compounds. Nevertheless, existing PCMs cannot be used in directly practical applications due to their weak thermal stability, high super cooling effect and low thermal conductivity. Thus, enhanced PCMs have been developed to overcome these difficulties. For example work reported by Kim et al. on the effect of exfoliated graphite nanoplatelets (xGnP) addition on the thermal properties of the paraffin wax/xGnP composite prepared as a form-stable PCM, which demonstrated that the thermal conductivity of PCM increased with increasing graphite mass fraction [49].

Encapsulated PCM

Phase change materials (PCMs) require special latent heat thermal energy storage (LHTES) devices in different shapes or elements such as shell and tube PCM heat exchangers or many cans to encapsulate the phase change materials. This is due to PCMs changing from solid to liquid during the energy storage period when applied to building materials. Even though the application of materials solves the difficulty of PCM leakage during the solid–liquid phase change, it increases not only the heat resistance but also the cost of the latent heat thermal energy storage system. Nonetheless, these problems can be overcome using micro/nano PCM capsules which can be fabricated by the encapsulation of PCM into a polymeric structure. Microcapsules are defined according to their parameters including particle diameter, shell thickness, thermal capacity, conductivity and durability. The thickness of the particle walls may be less than 1 μm, and the particle diameters vary within the range of less than 1 μm to more than 300 μm, which depends on the technique of the encapsulation, but are typically 20–40 μm. The PCM content of a capsule may be 80%–85% [50, 51, 52].

Microencapsulation is an important technique in the industrial, agricultural, and medical fields where a core material can be protected by a shell. Many substances have been encapsulated, including paint, liquid inks, toner, perfumes, pesticides, drugs, and phase change materials. Recently, this technique has been applied to expand the potential application fields of the phase change materials. Microencapsulated phase change material (MPCM) is a form of phase change material encapsulated in natural and synthetic polymeric capsules [53, 54].

Microencapsulated phase change materials (MPCMs) have been manufactured in various ways. One original MPCM slurry was prepared via a micro-encapsulation process and consisted of microencapsulated hexadecane ($C_{16}H_{34}$) particles and pure water which was made by Wang, et al. [55]. Microencapsulated paraffin, the most frequently used PCM with a melamine–formaldehyde resinous shell, was introduced by Diaconu [56].

PCM gypsum board, which consists of paraffin as a core material and polymer as shell, was made by Lai, et al. [57]. The phase change behavior of 65 mol% capric acid and 35 mol% lauric acid, calcium chloride hexahydrate, n-octadecane, n-hexadecane, and n-eicosane in spherical enclosures was investigated by Veerappan, et al. [58] to identify a suitable heat storage material. PCMs microcapsules were developed by two different methods by Baye′s-Garcıa, et al. [59]. The main difference between these methods was the shell composition which is composed of different coacervates; Sterilized Gelatine/Arabic Gum for the SG/AG method and Agar–Agar/Arabic Gum for the AA/AG method.

Microcapsules have the following advantages [60, 61]:

1. Protecting the PCM against the influences of the outside environment.
2. Increasing the heat-transfer area.
3. Permitting the core material to withstand changes in PCM volume, as the phase change occurs, because of the coating,
4. Allowing small and portable TES systems.

Many techniques have been developed for the microencapsulation of paraffins [62]. For example, the interfacial polymerization, the in situ polymerization, and the sol–gel, Melamine–formaldehyde, urea–formaldehyde and polyurethane are usually selected as microcapsule shell materials for the PCMs encapsulation [63, 64, 65, 66].

Shape-stabilized PCM

A new type of PCM called Shape-Stabilized Phase Change Material (SSPCM), which is composed of PCM and supporting materials, has been developed in recent years. Different PCMs should have congruent supporting materials. If the PCM is based on paraffin, the supporting material should have a similar skeleton, for example high-density polyethylene (HDPE), polypropylene (PP), and styrene–butadiene–styrene (SBS). Paraffin can be easily dispersed into the network formed by the supporting material. As long as the operating temperature is below the melting point of the supporting material, the SSPCM can maintain its shape even as the paraffin changes from solid to liquid [67].

Many Shape-Stabilized Phase Change Materials (SSPCM) have been successfully developed. A new kind of SSPCM plate was studied by Xu, et al., which consists of 70 wt% paraffin as the dispersed PCM and 15 wt% polyethylene and 15 wt% SBS block copolymer as the supporting materials. The thermal and physical properties of the developed SSPCMs were considered for the application as a walling product [68]. The SSPCM plate, which consists of 75 wt% paraffin as a dispersed PCM and 25 wt% polyethylene as a supporting material, can be used for heat storage by using cheap nighttime electricity and discharging the heat stored during the daytime [69]. The addition of graphite powder and expanded graphite can improve the thermal conductivity of shape-stabilized paraffin/HDPE composite PCM, which was reported by Cheng, et al. [70].

Heat transfer

In studying heat flow, it is customary to consider three distinct mechanisms of heat flow: conduction, convection and radiation. Heat is transferred by conduction in solids or fluids at rest. A medium is needed for Conduction to take place, whereas radiation can take place in a vacuum with no material carrier. Heat is transferred by convection in fluids in motion. In fact, conduction and radiation are the two basic modes of heat flow; convection can be regarded as conduction with fluid in motion [71].

In general, the temperature distribution in a medium is controlled by the combined effects of these different mechanisms of heat flow. It is not possible to completely isolate one from the others. However, when one mechanism is dominant, the others can be neglected.

Conduction

Conduction is the mechanism of heat flow in which energy is transported from the region of high temperature to the region of low temperature by the drift of electrons, as in solids. Therefore, metals that are good conductors of electricity are also good conductors of heat [71].

The conduction law is based on experimental observations made by Biot and named after Fourier. The Fourier law states that the rate of heat flow by conduction in a given director (the x direction) is proportional to:

1. The gradient of temperature in that direction, dT/dx
2. The area normal to the direction of heat flow, A

Then for heat flow in the x direction, we have

$$Q_x = -kA\frac{dT}{dx} \qquad W \qquad (2.5)$$

Where Q_x is the rate of heat flow in the positive x direction, through area A normal to the x direction, and

$$\frac{dT}{dx} = \lim_{\Delta x \to 0} \frac{\Delta T}{\Delta x} \qquad (2.6)$$

is the gradient of temperature in that direction. The proportionality constant k, called the thermal conductivity, is a property of the material.

To illustrate the application of this concept, we consider a slab (i.e., a plate) with a linear temperature distribution within the body, as shown in Figure 2.

Equation (2.5) becomes

$$\begin{aligned} Q_x &= -kA\frac{dT}{dx} \\ &= -kA\frac{T_2-T_1}{x_2-x_1} = kA\frac{T_1-T_2}{x_2-x_1} \\ &= kA\frac{\Delta T}{L} \end{aligned} \qquad (2.7)$$

Where $x_2 - x_1 = L$, the thickness of the slab, is a positive quantity.

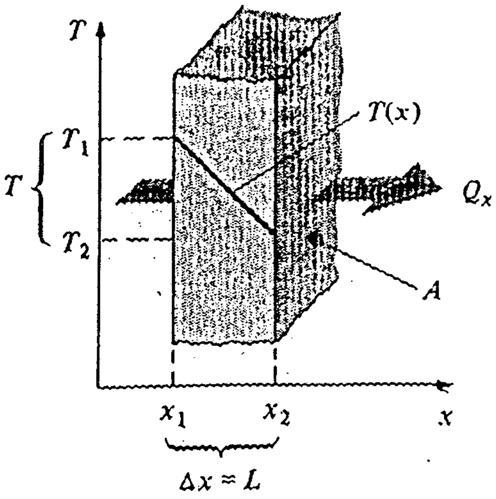

Figure 2 Temperature distribution T(x) and heat flow by conduction through a slab.

The heat flow rate per unit area is called the heat flux. Therefore, Q_x divided by the area A,

$$q_x = \frac{Q_x}{A} \quad \text{W/m}^2 \tag{2.8}$$

is the heat flux in the x direction. Thus q_x represents the amount of heat flow per unit area, per unit time in the x direction. When heat flow Q_x is in watts and heat flux q_x in watts per square meter, then the thermal conductivity k has the dimension W/(m ·°C) or J/(m·s·°C)

Plane wall

Consider a slab of thickness L, as shown in Figure 3. The boundary surfaces at $x = 0$ and $x = L$ are maintained at constant but different temperature T_1 and T_2, respectively. There is no energy generation in the solid, and the thermal conductivity is assumed to be constant. To develop the thermal resistance concept for this problem, the heat conduction problem is solved and the expression for heat flow is determined, then recast this result in a form analogous to Ohm's law in electricity in order to establish the equivalent thermal resistance [71]. The procedure is as follows.

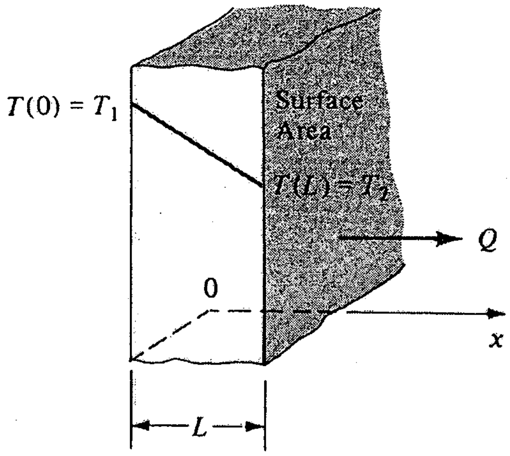

Figure 3 Temperature distribution for a slab with prescribed temperature at both surfaces.

The mathematical formulation of this heat conduction problem is given by

$$\frac{d^2T(x)}{dx^2} = 0 \quad \text{in} \quad 0 \square x \square L \qquad (2.9)$$

$$T(x) = T_1 \quad \text{at } x = 0 \qquad (2.10)$$

$$T(x) = T_2 \quad \text{at } x = L \qquad (2.11)$$

Then the solution becomes

$$T(x) = (T_2 - T_1)\frac{x}{L} + T_1 \qquad (2.12)$$

Equation (2.12) demonstrates that for one-dimensional steady heat conduction through a slab having a constant thermal conductivity and no energy generation, the temperature distribution T(x) is a linear function of x.

Knowing the temperature T(x), the heat flux through the slab is determined by Fourier's Law. The differentiation of Eq. (2.12) with respect to x gives,

$$\frac{dT(x)}{dx} = \frac{T_2 - T_1}{L} \qquad (2.13)$$

And from Fourier's Law,

$$q = -k\frac{dT(x)}{dx} \tag{2.14}$$

Then the heat flux becomes

$$q = k\frac{T_1 - T_2}{L} \quad W/m^2 \tag{2.15}$$

When $T_1 > T_2$, the right-hand side is positive, and hence the heat flow is in the positive x direction.

The total heat flow rate Q through an area A of the slab normal to the direction of the heat flow becomes

$$Q = Aq = \frac{T_1 - T_2}{L/Ak}. = \frac{\Delta T}{R_{slab}} \tag{2.16}$$

Where

$$R_{slab} = \frac{L}{Ak} \tag{2.17}$$

and $$T = T_1 - T_2$$

The quantity R_{slab} is called the thermal resistance for heat flow through the slab of thickness (L), area (A), thermal conductivity k and subjected to prescribed temperature boundary conditions at both surfaces.

Convection

When a fluid flows over a solid, and their temperatures are different, heat transfer takes place between the fluid and the solid surface as a result of the motion of the fluid. This mechanism of heat flow is called convection, since the motion of the fluid plays a significant role in augmenting the heat transfer rate. Clearly, if there were no fluid motion, heat transfer would be by conduction. If the fluid motion is caused externally by a forcing mechanism, such as a fan, blower, pump, or wind, the mechanism of heat flow is said to be forced convection. If the fluid motion is set up by the buoyancy resulting from density differences caused by the temperature difference within the fluid, the mechanism of heat flow is said to be free (or natural) convection. Here the word fluid is used to describe both liquids and gases; for example, air and water are both fluids [71].

In engineering applications, to simplify the heat flow calculation, a quantity called the heat transfer coefficient h is defined. To illustrate the concept, consider the flow of a cold fluid at a temperature T_f over a hot body at temperature T_w. Let q be the heat flux (in watts per square meter) from the wall to the fluid. Then the heat transfer coefficient h is defined as

$$q = h\,(T_w - T_f) \qquad (2.18)$$

If the heat flux is in watts per square meter and the temperature is in degrees Celsius (or Kelvins), then the heat transfer coefficient has the dimension $W/(m^2 \cdot {}^oC)$, and it is always a positive quantity.

If we rewrite Eq. (2.18) in the form

$$q = h(T_f - T_w) \qquad (2.19)$$

It implies that q is the heat flux from the fluid to the wall. The heat flow rate through area (A) becomes

$$Q_{conv} = qA \qquad (2.20)$$

Radiation

All bodies emit energy due to their temperature. The energy emitted by a body due to its temperature is called thermal radiation. The radiation energy leaving a body through its bounding surfaces actually originates from the interior of the region. Similarly, the radiation energy incident on the surface of a body penetrates into the depths of the body, where it is absorbed [71].

Different materials absorb thermal radiation in different amounts. If absorption of the thermal radiation takes place, then the body absorbing the radiation is said to be opaque to thermal radiation. For example, materials such as metals, wood, stone, paper, and numerous others are considered opaque to thermal radiation.

Where little or no absorption takes place, the material is considered to be transparent to thermal radiation. There are degrees of thermal transparency. A sheet of glass is said to be semitransparent to thermal radiation incident upon it because only part of the thermal radiation is absorbed. Part of the thermal radiation is reflected, and the remainder is transmitted by the glass.

Radiation propagation through a medium is weakened as a result of absorption. It is only in a vacuum that radiation propagates with no weakening (attenuation) at all. Therefore, a vacuum is considered completely transparent to radiation. Also, the atmospheric air contained in a room is considered transparent to thermal radiation for all practical purposes, because the weakening of radiation propagation in air is insignificant unless the air layer is several kilometers thick.

Emission of radiation

The maximum radiation flux emitted by a body at temperature T is given by the Stefen-Boltzmann law,

$$Eb = \sigma T^4 \quad W/m^2 \tag{2.21}$$

Where σ is the Stefen-Boltzmann constant [$\sigma = 5.6697 \times 10^{-8}$ W/(m^2·K^4)], E_b is the blackbody emissive power, and T is the absolute temperature in kelvins,

$$K = {}^{o}C + 273.15 \tag{2.22}$$

Only an ideal radiator or the so-called blackbody can emit the maximum radiation flux according to Eq. (2.21). The radiation flux q emitted by a real body at an absolute temperature T is always less than the blackbody emissive power E_b, and it is given by

$$q = \varepsilon E_b = \varepsilon\sigma T^4 \tag{2.23}$$

Where ε is the emissivity of the body, which is less than unity for all real bodies and equal to 1 only for a blackbody [71].

The heat flux time lag and decrement factor

The time lag (Φ_q) and the decrement factor (f) [72] are the parameters used to assess the thermal performance of a wall. The time lag is the time taken for the temperature wave to propagate from the outer surface to the inner surface. The decrement factor is the decreasing ratio of its temperature amplitude [73]. Therefore, the heat flux time lag and decrement factor are defined by the following equations.

$$\Phi_q = \tau_{qi,max} - \tau_{qe,max} \tag{2.24}$$

$$f = \frac{A_i}{A_e} = \frac{q_{i,max} - q_{i,min}}{q_{e,max} - q_{e,min}} \tag{2.25}$$

Where $\tau_{qi,max}$, $\tau_{qe,max}$ are the times that the interior surface heat flux and the exterior surface heat flux of the wall are at a maximum. A_i and A_e are the amplitudes of the wave on the inner and outer surfaces of the wall respectively. $q_{i,max}$, $q_{i,min}$, $q_{e,max}$, $q_{e,min}$ are the maximum and the minimum heat flux of the interior and exterior surfaces of the wall, respectively.

The schematic of heat flux time lag and decrement factor is shown in Figure 4. To clarify the assessment, the room temperature is assumed to be constant.

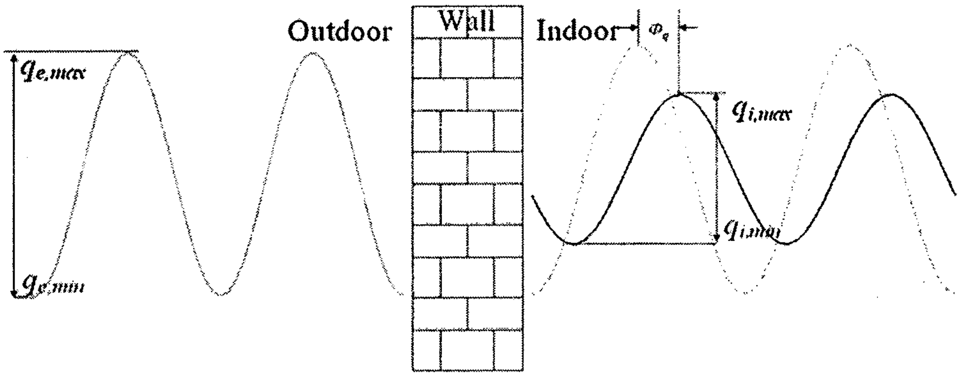

Figure 4 The schematic of heat flux time lag and decrement factor [72].

The heat transfer in the wall is assumed to be one-dimensional. The schematic of heat transfer in the wall is shown in Figure 5. The governing equation for the wall is

$$\rho c_p \frac{\partial t}{\partial \tau} = \lambda \frac{\partial^2 t}{\partial x^2} \quad . \tag{2.26}$$

The boundary conditions are

$$-\lambda \frac{\partial t}{\partial x} = h_e (t_{sa} - t_e) \quad (x = 0) \tag{2.27}$$

$$-\lambda \frac{\partial t}{\partial x} = h_i (t_i - t_{in}) \quad (x = \delta) \tag{2.28}$$

Where h_e, h_i are the exterior and interior surface heat transfer coefficient of the wall, respectively. t_{sa}, t_e, t_i, $t_{in}$are the solar-air temperature, the exterior surface temperature of the wall, the interior surface temperature of the wall and the indoor air temperature, respectively.

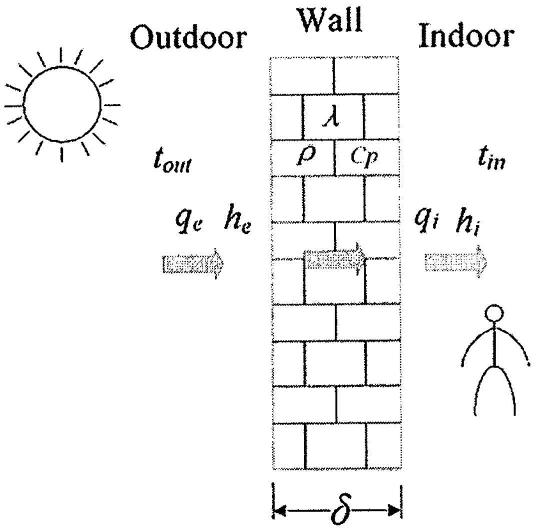

Figure 5 The schematic of heat transfer in the wall [72].

Life-Cycle Assessment

Life-Cycle Assessment (LCA), is also known as the life-cycle analysis, eco balance, and cradle-to-grave analysis [74], which is a technique to assess the environmental impacts that are associated with all stages of the life of the product from cradle to grave (as shown in Figure 6). This method considers all processes from obtaining the raw material extraction through materials processing, the manufacture, the distribution, the use, the repair and maintenance, and the disposal or recycling. LCAs avoid an unduly narrow outlook on the environmental concerns by:

1. Compiling an inventory of the relevant energy and material inputs and the environmental releases;
2. Evaluating the potential impacts associated with identified inputs and releases;
3. Interpreting the results to help make a more informed decision [74].

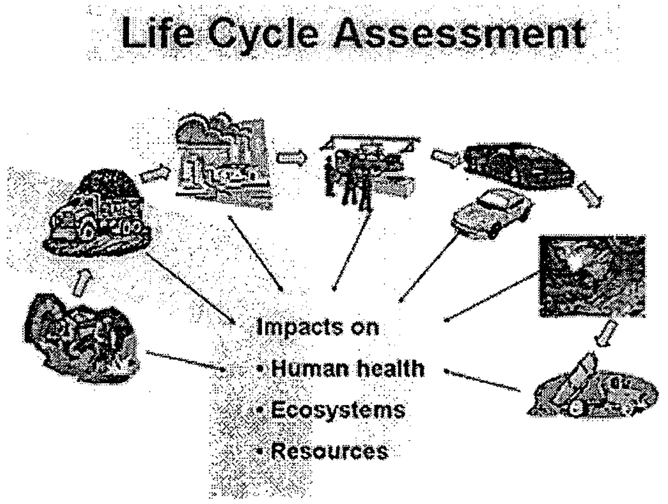

Figure 6 Life Cycle Assessment.

The goals of LCA include a comparison of the full range of environmental effects assignable to products and services in order to improve the processes, supporting policies and to provide the basis for informed decision making [75]. The holistic assessment of the raw-material production and the manufacture, distribution, use and disposal of the product, including all intervening necessary transportation steps, over the term of the life cycle is exhibited in Figure 7. The procedures of life cycle assessment (LCA) are part of the ISO 14000 environmental management standards: in ISO 14040:2006 and 14044:2006.

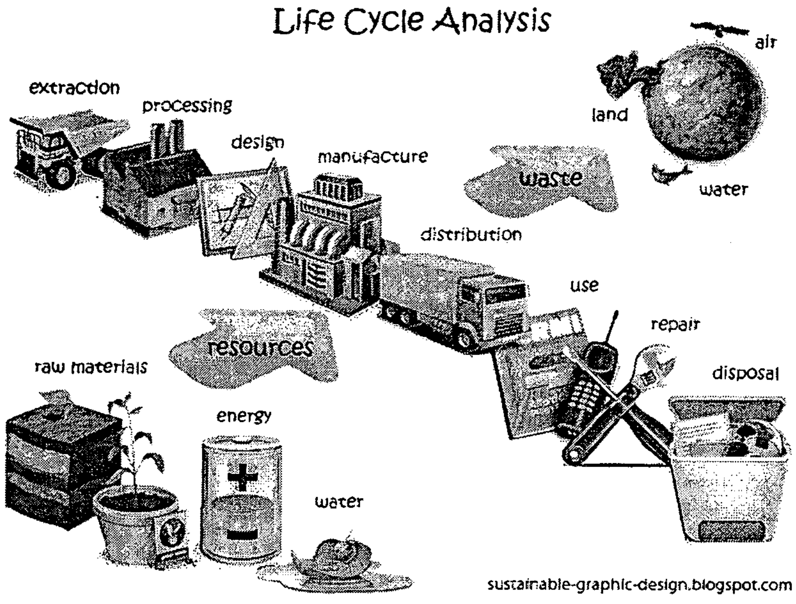

Figure 7 Life-cycle of product

Life Cycle Assessment is carried out in four major component phases according to the ISO 14040 [76] and 14044 [77] standards as illustrated in Figure 8.The phases are often interdependent where the results of one phase will depend on the outcomes of other phases.

1. Goal definition and scope

This study began with an explicit statement of the goals and scope, which set out the context of the study and explained how it was to be undertaken and the intended results. The formulation and presentation of this initial statement is an important step required by the applicable ISO standards which require that the goals and scope of an LCA be distinctly defined and consistent with the intended application. The goals and scope information thus includes the technical details that will guide subsequent work. This is enumerated here:

1. Functional unit, which defines precisely the study and quantification of the service that was delivered by the product system, providing a reference of the related inputs and outputs. It is a necessary basis that enables alternative goods, or services, to be compared and analyzed [78].
2. System boundaries
3. Any assumptions and limitations

4. Allocation methods for the partition of the environmental load of a process when several products or functions share the same process.
5. Chosen impact categories.

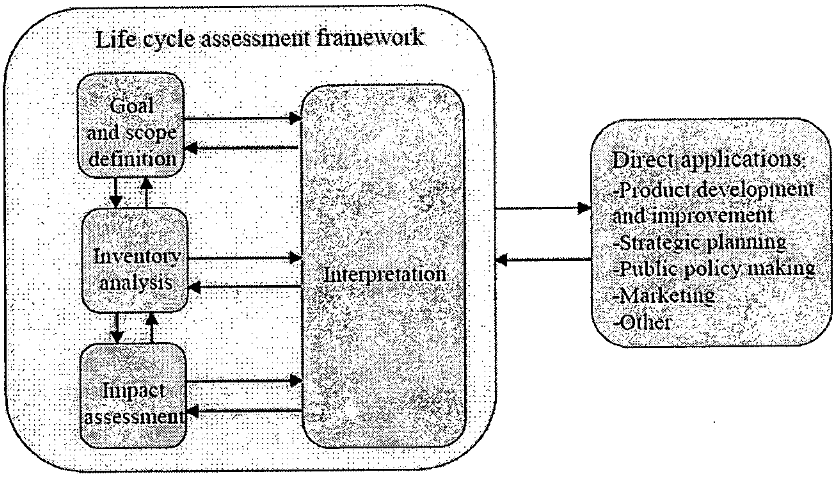

Figure 8 Illustration of LCA flame work

2. **Life cycle inventory**

Life Cycle Inventory (LCI) analysis includes an inventory of nature flows for a product system. Inventory flows comprise the inputs of water, energy, and raw materials, and the releases to air, land, and water as shown in Figure 9. The flow model of the technical system, which was created using data on inputs and outputs, is typically illustrated with a flow chart that includes the activities that will be assessed in the relevant supply chain and gives a clear picture of the technical system boundaries. The relevant flow model for this study is shown in Figure 10. The input and output data are necessary for the construction of the model, which are collected for all activities within the system boundaries, including from the supply chain. The data must be correlated with the functional unit that is defined in the goals and scope definition. Data can be shown in tables and some interpretations can be made already at this stage. The results of the inventory is an LCI, which provides information about all inputs and outputs in the form of elementary flows and from the environment to all the unit processes involved in the study.

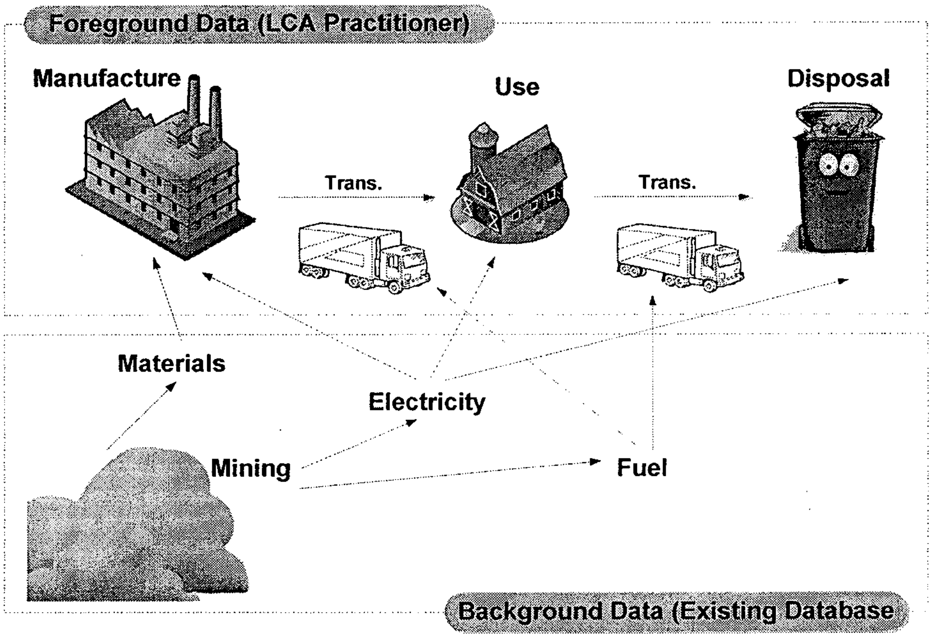

Figure 9 Data for LCA analysis

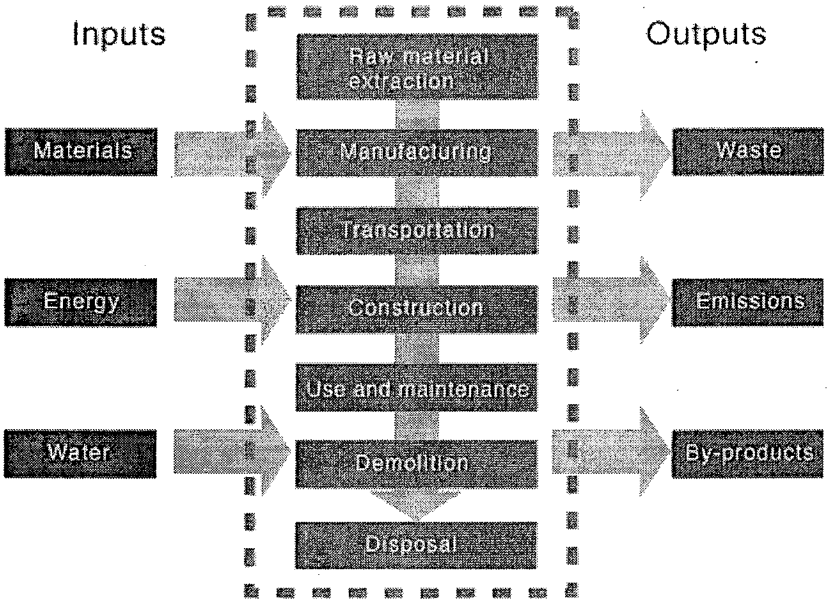

Figure 10 Relative analysis between the input process and output process of target product

3. Life cycle impact assessment

This is the impact assessment observed from the inventory analysis. This state of LCA is purposed by assessing the significance of potential environmental impacts based on the LCI flow results. Classical life cycle impact assessment (LCIA) is composed of the following mandatory elements:

1. Selection of the impact categories, the category indicators, and the characterization models,
2. Classification stage(the inventory parameters are sorted and assigned to specific impact categories),
3. Impact measurement (the categorized LCI flows are characterized, using one of many possible LCIA methodologies, into common equivalence units that are then summed to provide an overall impact category).

The results of the impact categories from the study, which are usually compared with the total impacts in the region of interest such as the selection of global warming boundary and the ozone layer depletion, are shown in

Figure 11. Grouping consists of sorting and possibly ranking the impact categories. The different environmental impacts are weighted relative to each other so that they can then be summed to get a single number for the total environmental impact as shown in

Figure 12.

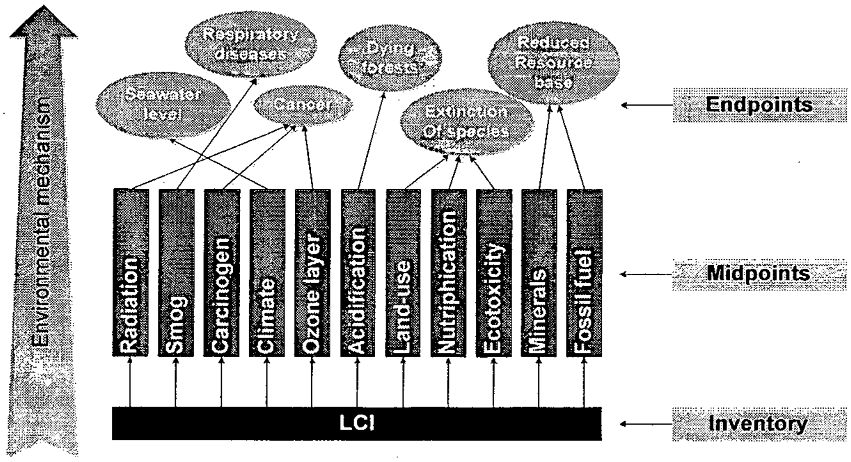

Figure 11 Environmental impacts for life-cycle assessment

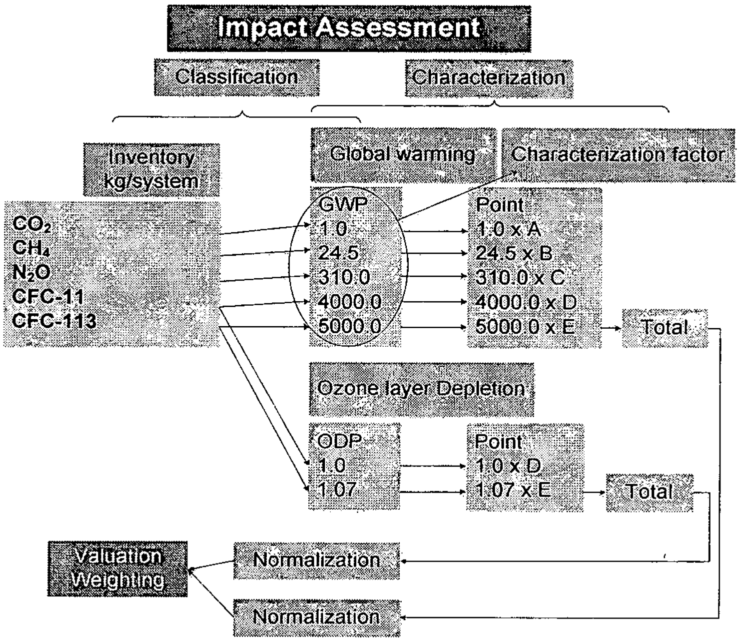

Figure 12 The procedure of life-cycle impact assessment

4. Interpretation

Life cycle interpretation is a systematic technique to identify, quantify, verify, and evaluate information from the results of the life cycle inventory or the life cycle impact assessment. The results from the inventory analysis and impact assessment are concluded during the interpretation phase. The result of the interpretation state is a set of summations and recommendations for the study. According to ISO 14040:2006, the interpretation should include:

1. Identification of the significant issues based on the results of LCI and LCIA states of an LCA,
2. Assessment of the correctness, completeness, sensitivity and consistency,
3. Conclusions, limitations and recommendations.

A major purpose of performing life cycle interpretation is to determine the level of confidence in the final results, and to communicate the results in a fair, complete, and accurate manner and related to the goals of the study. This is completed by identifying the data elements that contribute significantly to each impact category, evaluating the sensitivity of these significant data elements, assessing the completeness and consistency of the study, and drawing conclusions and recommendations based on a clear understanding of how the LCA was conducted and the results were developed.

Data analysis

The life cycle usually considered consists of a number of stages including: materials extraction, processing and manufacturing, product use, and product disposal. If the most environmentally harmful of these stages can be determined, then the impact on the environment can be effectively reduced by focusing on making changes for that particular phase as shown in Figure 13.

Variants

Cradle-to-grave

Cradle-to-grave is the full life cycle assessment from the resource extraction to the use state and disposal state as shown in Figure 13. All inputs and outputs are considered for all states of the life cycle.

Cradle-to-cradle

Cradle-to-cradle is an assessment of a specific kind of cradle-to-grave, where the end-of-life disposal step for the product is a recycling process. It is a technique, which was used to reduce the environmental impact of products by employing the sustainable production, operation and disposal practices and aims, to incorporate social responsibility into product development [79].

Cradle-to-gate

Cradle-to-gate is a partial product life cycle assessment from resource extraction to the factory gate (i.e., before it is transported to the consumer) as shown in Figure 13. The use state and disposal state of the product are neglected in this case.

Gate-to-gate

Gate-to-gate is a partial LCA looking at only one value-added process in the entire production chain as shown in Figure 13. Gate-to-gate modules may also later be linked in their appropriate production chain to form a complete cradle-to-gate evaluation [80].

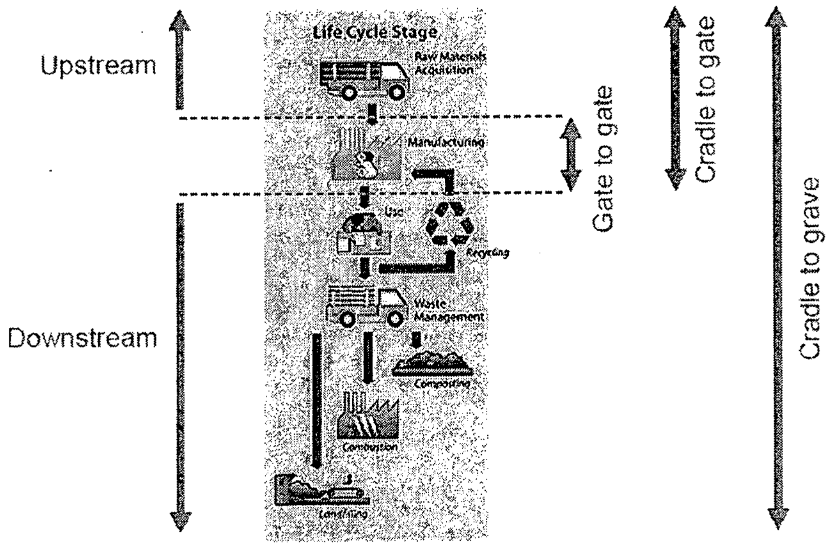

Figure 13 Pattern of Life-cycle assessment