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A review of life cycle assessment method for building industry

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ABSTRACT

A recent study suggested that buildings globally consume up to 40% of energy and responsible for half of world greenhouse gas emission. Introducing life cycle assessment (LCA) to the building industry is important because it can measure every environmental impact involved in every process from cradle to grave systematically. Within the last decade, research on LCA has increased covering from construction process to manufacturing of building materials. The methods to assess buildings are diverse as buildings have different functions, materials, sizes and locations. The aim of this article is to review the LCA methods and to distinguish phases and materials that affect significantly to environment. The findings show the methods are based on ISO 14040 series with variance to suit different scopes, aims and limitations. The operational phase is identified to consume the highest energy and concrete responsible for the highest embodied energy. The findings also suggested that building material with lower embodied energy does not necessarily have lower life cycle energy. Therefore, implementation of LCA can determine and mitigate the environmental impacts in the development stage thus promoting sustainability in building industry.

Contents

1. Introduction

The relationship between the building industry and environmental pollution is constantly discussed in close association. Although building industry is crucial for social and economic development, the environmental impacts of the processes are significant. In general, building industry consists of many phases starting from mining, manufacturing, construction, use and

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demolition. Within each phase, a large amount of energy is consumed and at the same time a considerable emission is released. Energy is consumed directly during building construction, use and demolition while indirectly through producing materials (embodied energy) used in the building [1]. Recent studies identified that buildings all over the world responsible for 30–40% of energy use and 40–50% of world greenhouse gas emission [2,3].

Because of the increasing awareness on environmental issues and pressure from various government bodies and environmental activist, many studies have been conducted to reduce building's energy consumption and its environmental impact [4]. Currently, life cycle assessment (LCA) method is one of the measurement instruments that able to assess the environmental impact thoroughly and its implementation to the building industry is relatively recent. LCA has been defined as a systematic analysis to measure industrial processes and products by examining the flow of energy and material consumption, waste released into the environment and evaluate alternatives for environmental improvement [5–8]. LCA is accepted internationally as a tool to improve processes and services environmentally and it can apply to wider field, including in the building industry [9,10].

The implementation of LCA can help designer, engineer and decision maker by providing analytical evaluation environmentally. Without LCA, most decision will likely measure on initial cost rather than the overall environmental benefits [11].

2. Basic concept of life cycle assessment

LCA is a methodology framework to estimate and evaluate the environmental impact throughout the product life cycle from cradle to grave. [12,13]. The first phase of LCA which is defining goals and scopes will determine the purpose of the study, system boundaries and selection of suitable functional units. The second phase, which is life cycle inventory (LCI) is the data collection process of all relevant inputs and outputs of a product life cycle. The third phase, the life cycle impact assessment (LCIA) will use data from LCI and subsequently evaluates potential environmental impacts and estimate resource used in the study. The last phase is the interpretation which identifies significant issues, assess results to reach conclusions, explain the limitations and provide recommendations.

3. LCA concept and methodology in the building industry

Within the last decade, research on LCA has increased considerably covering from manufacturing of building materials and construction processes. Buildings are more difficult to assess as they are massive, diverse materials and their production method is inconsistent because each building has a unique characteristic [14]. Furthermore, quantitative information about environmental impact of producing construction materials or the actual process of construction and demolition are limited [14].

The methodology of LCA research in the building industry however, still in a fragmented state due to a variety of case study buildings with diversity in materials selection, locations, construction process, building design and usage that will produce a different definition of goal and scope and will bind to certain limitations. Sometimes, the goal and scope can change due to unexpected problems encountered during the research [15]. Each research will respond to a predetermined system boundary, functional unit, building lifespan. Basically, there are three approaches in LCA research: 1) Process-based LCA; 2) Economic Input Output LCA (EIO-LCA); and 3) Hybrid LCA (Combination of process based and EIO-LCA). In general, process-based LCA is more complex and time consuming than EIO-LCA but the majority of the LCA research are applying process-based method [16]. Fig. 1 is a proposed LCA framework for the building industry adapted from various published research papers.

3.1. Goal and scope definition

According to ISO 14044 [21], the system boundary determines which processes should be included within the LCA and should be consistent with the goal of the study. Similar to other products, building's LCA system boundary consist of either a cradle-to-grave (Fig. 2), cradle-to-gate (for building product analysis) or gate-to-gate (for construction process analysis). In most cases, cradle-to-grave approach is normally being used which start from the pre-use phase to end-of-life (EOL) phase. Specific spatial and temporal boundary should also be included in the system boundary, acting as a research limitation and also for benchmark for future research.

Functional unit defines the quantification of identified functions of the selected product to ensure comparability [13]. Most researchers used a square meter (1 m^2) of floor area as a functional unit for an LCA of a building. A few research however have included addendums to the 1 m^2 functional unit such as by specifically indicated a certain number of occupants in the building [19] and others only reflected to the heated areas only [17].

The lifespan of a building has a significant impact on the result of the LCA research especially because of the total energy consumption during use phase. In previous research, the lifespan of buildings is varied. For residential buildings, the lifespan is quoted between 40–100 years but mostly 50 years were applied by researchers [3,19,22–24]. The lifespan of commercial buildings is quoted between 40–75 years, but similar to residential buildings, 50 years were commonly used as a standard building lifespan [25–28].

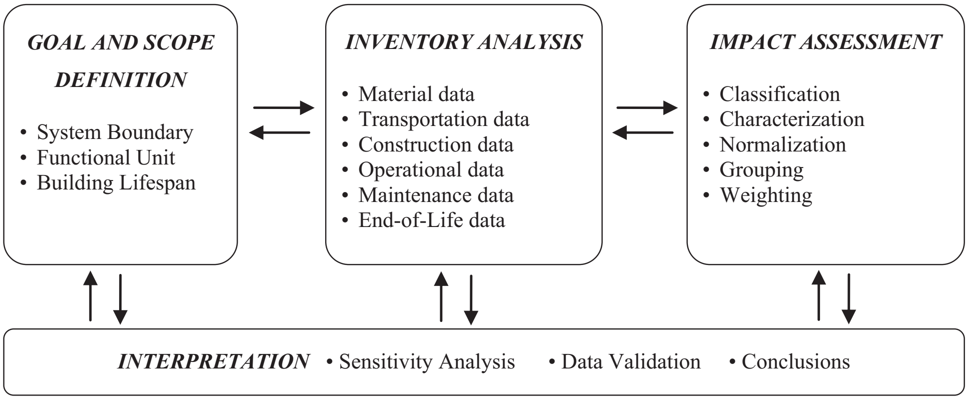

Fig. 1. LCA Framework for the building industry. Adapted from [13], [17]–[20].

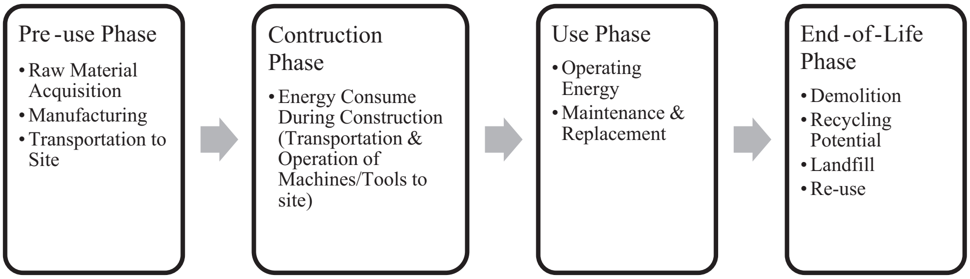

Fig. 2. Cradle-to-grave system boundary used in building's LCA research.

3.2. *Inventory analysis*

The data for building materials are obtained from the bill of quantities or bill of materials [29,30] or from estimated quantities from building drawings and field measured data [17]. Other researchers did not specify which method used but the important finding in this stage is to determine the type and quantity of materials used for the building. Different researcher used different method in determine transportation data. A few researchers used average transportation distances from factories to construction site based on communication with the designer and contractor [17] or selected by the nearest manufacturer and national averages [18]. Ortiz-Rodríguez et al. [19] alternatively use assumptions to determine the distance between manufacturer to building site. Because of the operational phase produces the largest environmental impact, transportation phase has a relatively low share of total emissions of CO_2 [24,30].

Construction phase only contributed low share of total environmental impact [17,18,24]. Some researcher neglected the construction data in the analysis but consider the waste generated during the process [18,24]. If the estimated quantities are based on drawings or bill of quantities are used in the inventory, the allocation of installation waste must be included. Some research estimated that about 5% of material waste on site during construction due to vulnerability of the products, mishandling of materials and unusable residuals due to inaccurate installation [24,31]. Blengini & Di Carlo [17] collected construction data and assumed from field measured data, communication from designer, contractor and literatures. Monahan & Powell [30] managed to collect data on the off-site manufacturing process from manufacturing companies, waste generation, energy and fuels used on-site but no detail records were available which makes detail analysis unattainable. Some data were unavailable due to the confidentiality policy from the manufacturer.

The use phase of a building consists of operating energy and maintenance works of a building. Electricity is the main energy consume during this phase, followed by natural gas. Energy simulation software is being used to estimate annual electricity and natural gas consumption such as DesignBuilder with EnergyPlus, [19], EnergyPlus [18], Edilclima EC501 [17], COMFIE [32,33], CHENATH [5], AccuRate [29], DEROB-LTH [22], ECOTECT [34] and eQUEST [28]. Some software is limited to certain languages, region and needed expert knowledge in CAD and programming. EnergyPlus has been widely reviewed and validated using ASHRAE/BESTEST evaluation protocol [35]. Software like DesignBuilder and OpenStudio use EnergyPlus engine with Graphical User Interface (GUI) for user-friendliness for the non-expert user. Energy consumption is estimated based on heating, ventilation and cooling (HVAC) system, lighting, domestic hot water (DHW), electric appliances and cooking

Maintenance data for inventory are varied according to researcher's assumptions. Ortiz-Rodríguez et al. [19] suggested maintenance activities included are painting, reroofing, PVC siding, windows, replacing kitchen and bathroom cabinet. Replacing of electric appliances and light bulb, impact from house-cleaning and wastewater was not included. Blengini & Di Carlo [17] stated that little reliable data on lifespan of building materials are available resulting to assumptions based on literature. Ochsendorf et al. [18] recommended roof and window replacements and interior and exterior repainting. Iyer-Raniga & Wong [29] used data based on a report entitled “Study of Life Expectancy of Housing Components” produce by US based National Association of Home Builders (NAHB) as its basis for maintenance pattern. Sensitivity analysis was performed later to test the applicability of data to local context.

EOL phase was rarely being incorporated into earlier research of LCA for buildings but recent research identifies that it is significant because of the ability of recycling potential of building materials thus decrease in life cycle impact [17]. Materials such as aluminium and steel are often treated as recycle materials while non-metallic materials will be transported to landfill as waste excluding concrete which assumed to reuse as aggregate [18]. Energy consumed by machineries were evaluated during demolition and average transportation data to landfill or recycling centre will be included in EOL.

Various LCA tools have been developed and according to Ortiz et al. [10], it can be classified into three levels; Level 1 is used for generic product comparison which includes GaBi, SimaPro and OpenLCA; Level 2 is a streamline tool to assess whole building design such as LISA, Eco-Quantum, ATHENA and eTool; Level 3 is for whole building assessment framework such as BREEAM and LEED. Databases for environmental assessment sometimes included in the LCA tools and others are available commercially such as Ecoinvent. Several databases are available for free for example USLCID, BEES and Spin. Due to the wide range of materials, construction techniques, locations, manufacturing differences, energy sources, supply assumptions etc., no single database available can be considered complete [10,15]

3.3. *Impact assessment*

The impact assessment is the next step in the LCA. In this phase, the results from the inventory will be evaluated the potential environmental impacts [13]. Similar to the inventory phase, the selection of the method and the impact categories will be bound by the Goal and Scope definition [36]. Most LCA practitioners prefer to select the existing assessment methodologies that have been published rather than develop it from scratch [36]. Blengini & Di Carlo [17] suggested that the selection of indicators is always subjective but must be consistent with ISO recommendations for impact assessment method. There are two (2) methods in conducting impact assessment which is problem oriented (midpoints) and damage-oriented methods (endpoint). Midpoints are considered to be a point in the cause-effect chain of a particular impact category after the LCI prior to the end point [38]. Different researcher used different impact categories but most commonly used were global warming potential, acidification, ozone depletion and eutrophication [10,15]. Ortiz et al. [10] suggested that the mid-points can be assessed using CML 2002 baseline method, EDIP 97 and EDIP 2003 and IMPACT 2002+ whilst the end points can be assessed using Eco-indicator 99 and IMPACT 2002+.

3.4. Interpretation

The final step in LCA is the interpretation of results where values from the impact assessment will be analysed for robustness and sensitivity to inputs [18] and conclusions are drawn with reference to the goals and objectives of the LCA [39]. Data validation also will be conducted by comparing to other published research [18] and by conducting sensitivity analysis to evaluate reliability of nonlocal databases [29]. Blengini & Di Carlo [17] suggested that in order to minimise uncertainty in input data, a 10,000 cycles of Monte Carlo simulation to get deterministic value.

4. Environmental impact of building

4.1. Impact of different building phases

Building phases can be separated according to process involve during its life cycle (Figure 3). Most researchers found the use phase of buildings contributed to the largest environmental impact because of its extensive duration. The emissions produce during the use phase is related to fossil fuel combustion for electrical generation and for space heating [14].

Kofoworola & Gheewala [27] identified that the use phase of a 60,000 m2 office building in Thailand for 50 years accounted for 81% of total energy consumption. Mithraratne & Vale [40] conducted a comparison of three construction type of residential building in New Zealand namely light construction, concrete construction and insulated construction and its use phase contributed 74%, 71% and 57% respectively for a 100 years building life cycle. A comparative research was conducted on low energy house and standard house in Italy. The research suggested that the use phase in standard house contributed more than 80% total energy use compared to lower than 50% in low energy house [17].

A research on a new university building in Michigan, USA by Scheuer et al. [14] identified that building operation represent 94.4% of total energy consumption. Ding [41] conducted a life cycle energy analysis of 20 secondary schools in Australia for 60 years lifespan and suggested that operational energy in building use phase represent 62% compared with 38% in pre-use phase. Ooteghem & Xu [28] conducted LCA research to five single storey retail building in Canada for 50 years lifespan and identified that space heating consume the highest energy during building use phase (42%), followed by lighting (37%), ventilation fans (7%), space cooling (6%) and miscellaneous equipments (6%). There are also other studies that produce similar results in which heating is the biggest energy consumer [3,17,29,40,42]. Nevertheless, buildings in a different location will produce a different energy use pattern. A building in tropical region for example, will not reflect to the result from a colder region as space heating is unnecessary.

4.2. Impact of material selection

The selection of building materials is closely related to the total embodied energy during production, influence towards total energy consumption in the use phase and its potential for recycling or reuse. Recycling potential of building materials can reduce its embodied energy. An energy efficient apartment building in Sweden was analysed for a lifespan of 50 years [22] and the recycling potential can reclaim up to 15% of the total energy used.

Asif et al. [2] identified that concrete contributed 61% of initial embodied energy, followed by timber (13%) and ceramic tiles (14%) for a residential building in Scotland. The study also suggests that the concrete has smaller initial embodied energy itself but the amount of concrete used in the building is very large thus responsible for the highest total embodied energy, as reported in other studies [17,43]. However this research was conducted only for pre-use phase, not the life cycle of the building. Some study suggested that building material with low initial embodied energy does not necessarily have low life cycle energy [7,34].

Three identical design residential buildings were analysed using LCA with different core materials namely light construction (timber frame), concrete construction and light construction with superinsulated construction [40]. Concrete and superinsulated buildings produce higher initial embodied energy compared with light construction by 8% and 14% respectively. Both concrete and superinsulated buildings however have lower life cycle energy by 5% and 31% respectively than light construction. Insulated materials also were used to reduce thermal transmission in a low energy house in Italy [42], a green home in Australia [5] and a residential building in Netherland [44] producing similar results. Recent research also suggested that residential buildings using Insulated Concrete Form (ICF) in the USA are more efficient during its life cycle compared with a light frame timber house with a similar design [18].

Buildings in tropical climate have different findings. Clay based products have been identified as a better alternative to cement based products. Utama and Gheewala [34] concluded that the selected residential building (a single landed house) in Indonesia with clay bricks and clay roof tiles have better life cycle energy than cement based bricks and roof tiles because of lower thermal transfer thus preserving cooling effect of air-conditioning. Another research claim that high-rise residential apartment with external clay brick walls, gypsum plasterboard walls internally and air gap in between have lower life cycle energy compare with single clay brick wall up to 59% [7].

López-Mesa et al. [45] conducted an LCA research for two seven story residential buildings with similar concrete based products but with different construction methods. Two systems were analysed namely in situ cast concrete floors and precast concrete floors. The advantage of precast concrete floor system is the ability to have a longer span between beams thus lessen columns and footings which also reduce total concrete used in the building. The environmental impact of precast concrete floors was calculated at 12.2% lower than in situ concrete floors.

5. Discussion

Research in LCA in the building industry has increased steadily since the early 1990 s. Although the methods applied are diverse, most research used International Organization of Standardization (ISO) 14040 series as a basic guideline. From previous research, it was suggested the building use phase consume highest energy compared with other phases in the building life cycle. Space heating was identified as the highest energy consumer in a colder climate, but buildings in a tropical region might have a different energy use pattern.

It also suggested that building material with low initial embodied energy does not necessarily have low life cycle energy. Concrete which is being used extensively in buildings all around the world, has the largest initial embodied energy because of its large quantity used. However, in the life cycle energy perspective, concrete is slightly better than timber building. The introduction of precast concrete and insulation materials helps to reduce total energy consumed by the building. Other research suggested that clay is a better building material than cement based materials for tropical country.

6. Conclusion

The building industry is unique due to its vast materials selection, various construction methods and its extensive lifespan. The introduction of new materials and new construction method will constantly occurs thus widen the gap of the adequacy of current available databases thus more research are needed. The diverse LCA research method with specific goals, scopes and limitiations will limit accurate comparisons between research findings for future references. Therefore, there is a need to standardised LCA methodology for building in order to create a robust database. The findings from LCA research will enable policy makers, designers, engineers and building users to make more sensible judgements in promoting sustainable development in the future.

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