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A Framework for Life Cycle Assessment and Cost Analysis of Precast a Cast-in-Place Buildings in United States

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The concept of construction sustainability has been gaining traction over years now. A large number of tools has been used to assess economic and environmental impacts of the buildings. LCA and LCCA are one of the most widely used tools to evaluate the environmental and economic impacts of the buildings over their complete life cycle. The aim of this research is to develop a framework for assessing the economic and environmental impacts of precast and cast-in-place buildings constructed in United States through Open LCA software. The study will include unit processes and material flows from raw material extraction and manufacturing phase to demolition phase of a building (cradle-to-grave) over the life span of 50 years. The developed framework for LCA and LCCA could be applied to all concrete construction projects across the world and could be used as platform for conducting future LCA and LCCA studies as well. Future research could be conducted through probabilistic approach of calculating the annual cost impacts over the complete life cycle of a building.

Keywords: Life Cycle Assessment (LCA), Life Cycle Cost Assessment (LCCA), Precast, Cast-In-Place, Sustainability

Introduction

The construction industry has a sizeable environmental impact as it consumes plenty of resources, materials and energy during the lifetime of a project, and require a broad spectrum of off-site, on-site and operational activities. These include but not limited to global greenhouse gas (GHG) emissions, high-energy use, air and water pollution, deterioration of ecological systems and improper waste management (Dong, Jaillon, Chu, & Poon, 2015; Shen & Tam, 2002). Besides reduction in energy consumption approaches which could reduce GHG emissions, other aspects such as economic, social and ecological impacts need to be considered to achieve sustainability (Khasreen, Banfill, & Menzies, 2009). Therefore, various tools have been developed to address different aspects and consider the varied sustainability impacts (Buyle, Braet, & Audenaert, 2013) such as Environmental Impact Assessment (Scheuer, Keoleian, & Reppe) (Scheuer et al.), System of Economic and Environmental Accounting (SEEA), Environmental Auditing and Material Flow Analysis (MFA) (Finnveden & Moberg, 2005). Among many, Life Cycle Assessment (Bo P. Weidema, 2008) is the most extensively used tool because it is much more detailed and systematic (Singh, Berghorn, Joshi, & Syal, 2010). LCA (Bo P. Weidema, 2008) is an investigative method used for evaluating the environmental impacts of a system or product over its complete life cycle (Rebitzer et al., 2004). Similarly, Life Cycle Cost Analysis (LCCA) is one of the widely used method to assess the economic impacts of a product/system (Durairaj, Ong, Nee, & Tan, 2002). Concrete is one of the most established construction material with 900 million tons of concrete is used annually by the construction industry which shows that has major economic impacts. Concrete production has significant environmental impacts well which accounts for 5% of carbon dioxide emissions annually (Gursel, Masanet, Horvath, & Stadel, 2014). The traditional concrete construction method, cast-in-place, is one of the major sources of carbon emissions due to on-site construction activities such as mixing, placing and curing (Dong et al., 2015). In the meantime, precast concrete offers an improved economic and environmental performance over cast-in-place concrete but still accounts for some economic and environmental impacts in construction and operation & maintenance phases (Marceau, Bushi, Meil, & Bowick, 2012; Ramsey, Ghosh, Abbaszadegan, & Choi, 2014). The environmental burden related to concrete is not only limited to CO_2 emissions and requires a holistic analytical approach of life cycle assessment (Gursel et al., 2014). Integration of LCA and LCCA in precast concrete assessment can help analyze its environmental impacts, draft different solutions to decrease its effect on the environment, and make it a viable partial replacement to cast in place concrete among other construction materials. Although various phases of life cycle of precast and cast-in-place concrete buildings have been considered in previous studies, the complete life cycle from raw material extraction to the demolition phase (using cradle-to-grave approach) has not been addressed. This study helps in developing a framework for comprehensive sustainability assessment of precast concrete buildings over cast-in-place buildings.

Literature Review

LCA is the only internationally standardized environmental assessment method (Kloepffer, 2008), which is defined by ISO 14040 as the "compilation and evaluation of all inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO, 2006). There are four phases in LCA (ISO): Goal and scope definition (Bo P. Weidema, 2008), Life cycle inventory (LCI), Life cycle impact assessment (LCIA), and Interpretation (ISO). Defining the goal and scope of study gives a comprehensive view of the research context which includes determining the functional units, system boundaries, life span, data requirements, assumptions and limitations, along with establishing the reason for carrying out the study, its application, and the intended audience (Marceau et al., 2012). The purpose of a functional unit is to define the area being studied and form the basis of reference to which all the inputs and outputs of a system is analyzed. The system boundary is the interface between the product system under study and the environment, and it determines which unit processes shall be included within the intended LCA (Morrison Hershfield & the Athena Institute, 2010). LCIA is the next step in life cycle assessment. Based upon the inventory flow data, LCIA phase accounts for the potential associated environmental impacts (ISO, 2006). The selection of relevant impact assessment method and impact categories depends upon the goal and scope definition. Life cycle cost (LCC) of a product or system is a method that constitutes the total cost of acquiring and utilizing it over the entire life span. Thus, LCC is the total cost of procurement and ownership and is one of the widely used methods for assessing life cycle costs of buildings (Elmakis & Lisnianski, 2006). The purpose of LCCA is comparing cost-effectiveness of investing in alternate decisions as it accounts for all the direct cost or benefits to a decision maker during the investment/asset complete economic life. The two primary concrete construction methods used in the industry are; Cast-in-place and Precast concrete (Bo P. Weidema, 2008). In cradle-to-gate approach, most of the environmental impacts related to precast concrete are due to the processes responsible for the production of precast concrete until leaving the precast plant. For instance, the precast concrete plants itself are responsible for contributing 16 % to global warming impact and 27% of primary energy use and transportation of precast components from precast plants accounts for 20% of environmental impacts associated with global warming, acidification and primary energy use (Morrison Hershfield & the Athena Institute, 2010). The materials used to manufacture concrete (cement, aggregates, and admixtures) and support precast plant operations have substantial environmental impacts. For instance, cement manufacturing yields 65% of global CO_2 emissions (Addtek, 2000). LCA aims at evaluating comprehensive environmental impacts for cradle-to-grave approach (Finnveden et al., 2009). Therefore, LCA of precast systems will help provide more information to build a benchmark system on the carbon emissions of buildings using precast concrete. Despite the environmental and economic benefit of precast concrete in the construction stage where wastage is reduced, further rigorous assessment is needed to validate it (Dong et al., 2015).

Generally, LCA and LCCA research studies conducted in the construction industry are either for building materials and components (BMCs) or buildings (Hong, Shen, Mao, Li, & Li, 2016). The former focusses on LCA of environmental impacts and energy use for BMCs (Azari-N & Kim, 2012; Kosareo & Ries, 2007; Lopez-Mesa, Pitarch, Tomas, & Gallego, 2009) while the latter accounts for the environmental impacts of each process in buildings' complete life-cycle (Ding, 2007; Scheuer et al., 2003; Treloar, Fay, Love, & Iyer-Raniga, 2000). The study by Jonsson, Bjorklund, and Tillman (1998) was one of the earliest LCA to study the environmental impacts of building technology. Thereafter, substantial LCA studies on precast concrete have been published such as the environmental impact comparison of cast-in-place and precast concrete floor construction (Lopez-Mesa et al., 2009), LCA of two single-storey residential buildings using precast and cast-in-place concrete construction (Dattilo, Negro, & Colombo, 2012), and LCA of commercial buildings in Canada by Canadian Precast/Prestressed Concrete Institute, (Marceau et al., 2012). However, limited research have addressed the LCCA and LCA of precast concrete buildings (vertical precast construction) over the complete life cycle. Using LCA and LCCA in precast concrete assessment can help analyze its environmental impacts, draft different solutions to decrease its effect on the environment, and make it a viable partial replacement to cast in place concrete among other construction materials. This research will focus on achieving the below discussed research objectives.

Research Objectives

1. To develop a framework for evaluating costs and environmental impacts of precast and cast-in-place building over a complete life cycle using cradle-to-grave approach (from raw material extraction and manufacturing, construction, operation and maintenance to demolition).
2. To derive a comprehensive system boundary using cradle-to-grave approach through Open LCA software which will facilitate research scholars to study the environmental as well as economic impacts of precast and cast-in-place buildings and provide a platform for future scope of research.

Methodology

Past research showed the application of LCA for studying various phases of a building's life cycle, however a comprehensive study using cradle-to-grave approach has not been addressed. Additionally, economic impacts using LCCA of precast buildings in comparison to cast-in-place buildings have not been considered.

The main goal of this research study is to develop a framework to analyze the life cycle cost and environmental impacts of a precast buildings in comparison with cast-in-place systems in United States. The processes in framework would be covered using "cradle-to-grave" approach which includes material extraction, manufacturing, transportation, on-site construction and installation, and the demolition phase. Once, the framework is developed, environmental and economic impacts are studied and analyzed through an integration of Life Cycle Assessment and Life Cycle Cost Analysis (LCCA). The methodology map is derived from the four stages of life cycle assessment framework and modified according to the scope of research as shown in Figure 1.

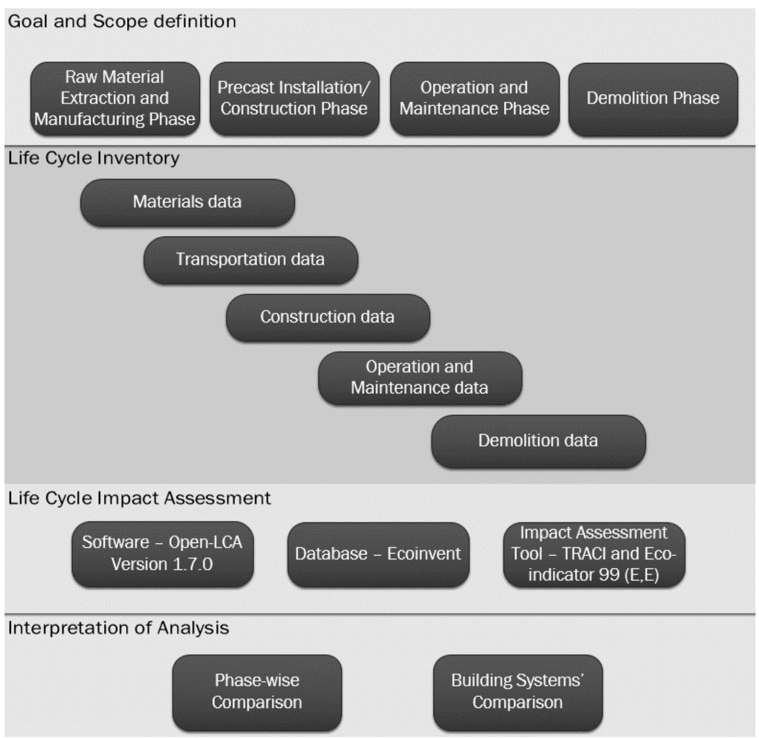

Figure 1: Methodology Map

The costs and environmental impacts analysis which will be carried out on Open LCA software in this ongoing study, begin with raw materials' identification for concrete manufacturing. Unit costs are considered for each every process in the framework for LCA and LCCA. Since, concrete is an integral part of the two systems (Precast and Cast-in-Place), all unit processes associated with concrete manufacturing have been considered. Other unit processes such as mining and wood extraction from forests, are excluded from the system boundary as they are no processes to account for the impacts yet (Finnveden et al., 2009). All the resources consumed during these processes such as fuel consumption, water consumption, electricity, and all associated costs for every unit process have been included in the system boundary as shown in Figure 2.

The costs and environmental impacts of buildings in operation and maintenance phase would be evaluated by means of the energy use. Annual energy consumption would be considered for assessing the energy impacts, dividing the energy use in lighting, electrical equipment and air-conditioning system. The maintenance phase included all of the building life-cycle elements during the 50 years of maintenance such as doors & windows, roof and covering and finishes. For instance, maintenance of building components such as aluminum windows, painting and roof coverings require maintenance and replacement costs as their expected life span is assumed to be 30, 25 and 10 years respectively.

This research study would also take into account the demolition phase as part of the cradle-to-grave approach and evaluates the costs and environmental impacts associated with it. The fuel and electricity consumption of construction equipment required for demolition and subsequent landfill are included in the system boundary. After analyzing the construction phase for both systems, the total annual energy consumption would be considered for the operation phase of the building over the life span of 50 years. The lifespan of residential and commercial buildings is assumed to be from 40 to 100 years. Specifically, 50 years has been used by researchers in past LCA and LCCA studies and the same has been adopted for this research as well (Arena & De Rosa, 2003; Kofoworola & Gheewala, 2009; Van Ooteghem & Xu, 2012).This research study set a functional unit of one square feet ($1ft^2$ / year) of gross floor area (GFA) of building for comparison of two different structural systems; precast and cast-in-place. The GFA would be calculated based upon the total enclosed space meeting the functional requirements of the building. The revit model of the building will be used to change the parameters such as building orientation, building envelope and building type to address different structural systems only. Based on this functional unit, the results would help determine the costs and environmental impacts per ft^2 of the building and will provide a rough estimate which could be used by practitioners to determine the environmental impacts of similar structural systems.

The data collection and calculations necessary to quantify the costs of processes and energy inputs and outputs of a building would be done for each phase of the scope of research. The data for the building materials would be obtained from the bill of quantities (BOQ), project estimate and field-measured data. The research considers the three main transportation phases in a building life cycle; (ISO) from resource extraction site to manufacturing plant, (Bo P. Weidema, 2008) from manufacturing plant(s) to construction site and, (3) construction site to disposal facility. The transportation data used for the research would be selected from the nearest manufacturer. The construction phase of the building includes all the material and energy use for on-site construction activities such as electricity and fuel consumption for construction equipment. This data would be collected from general contractors and sub-contractors. Thereafter, the impacts of operation and maintenance phase would be measured in terms of the annual energy consumption and the use of building is divided into heating, ventilation, and cooling (HVAC) system, and electrical consumption. Electricity consumption and annual water consumption is used to analyze the impacts of the building during maintenance phase and no future extensions, re-constructions or any major changes to building is considered during the 50-year life cycle. The last phase considered as part of the system boundary is the demolition phase which includes on-site demolition activities and transportation of discarded building materials to a landfill. For all phases, Open-LCA software is used to analyze the life cycle inventory data. It is equipped with multiple databases such as Ecoinvent, exiobase, NREL and Ecoinvent database which provide a flexible wide range of materials, construction techniques, locations, manufacturing differences, energy sources and supply assumptions (Kumar, 2019).

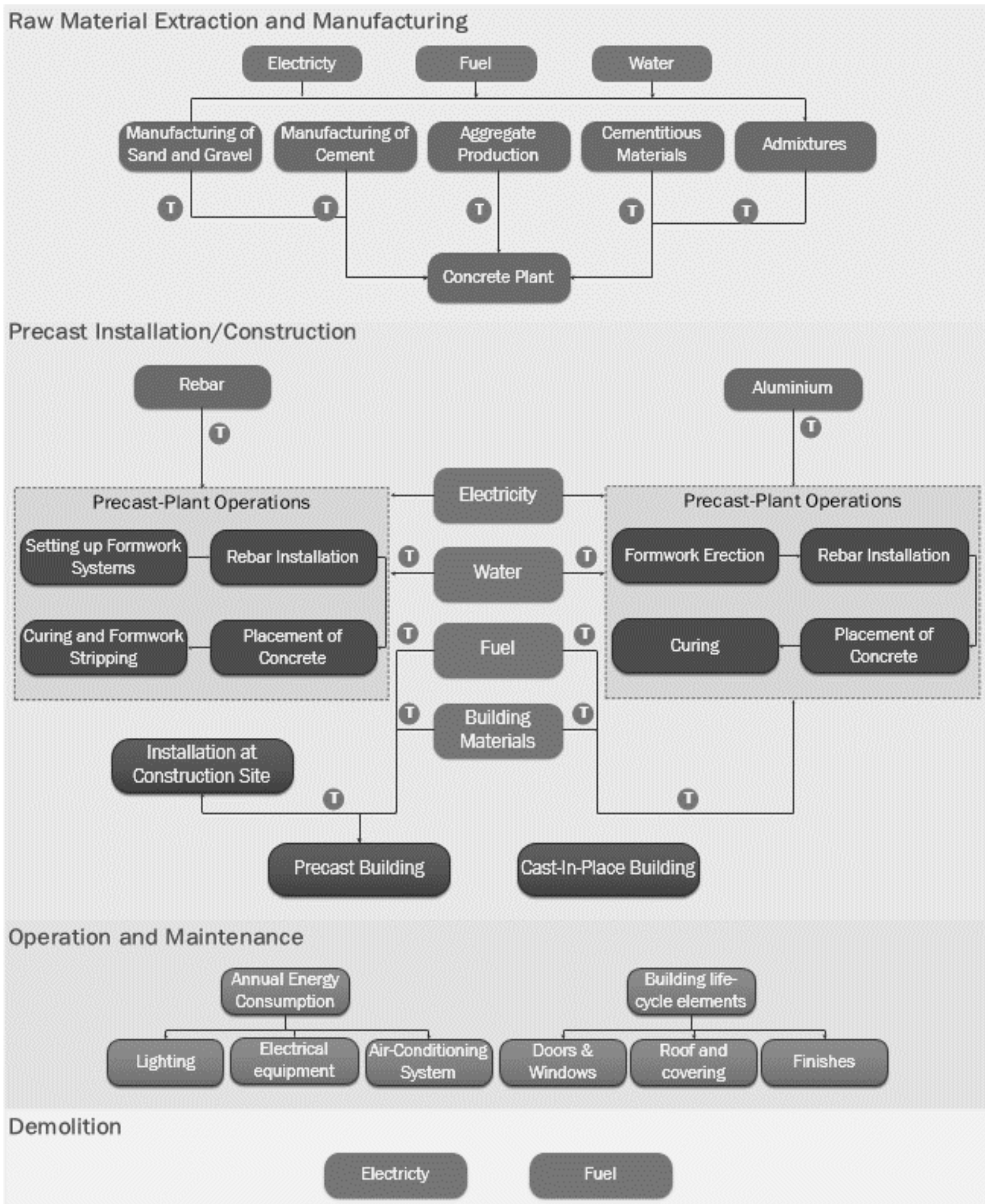

Figure 2: System Boundary

LCIA phase evaluates the significance of the associated life cycle costs and environmental impacts based upon the LCI analysis results. Among several impact assessment methods implemented in the database - Ecoinvent, TRACI 2.0 (Tool for Reduction and Assessment of Chemical and other

Environmental Impacts) and Eco-Indicator 99 would be used to classify and assign the inventory data to the selected environmental and human health impact categories. The classification of environmental impact categories (assigning inventory data to impact categories) into CO_2, NO_x, SO_x, CH_4, NH_3, PO_4, and HCFC is followed by the characterization (modeling of inventory data into impact categories) into eutrophication potential, global warming potential, ozone layer depletion, acidification potential, photochemical oxidation and human health respiratory effects is done in Open-LCA software (ISO, 2006). These impact categories were specifically assessed since they are the impact categories listed by the United States Environmental Protection Agency (EPA) as the most current impactful ones(Corporation & Curran, 2006). The environmental impact absolute values of both precast and cast-in-place building would be compared based upon each system process developed as part of system boundary i.e. raw material extraction and manufacturing, construction, operation and maintenance and demolition phase. The final step of the research methodology would the application of the framework within two case studies; precast building and cast-in-place building.

Discussion

Open LCA software is used to develop the framework for evaluating the economic and environmental impacts between precast and cast-in-place buildings. As, this is an ongoing research, the developed framework will be used to apply on two case studies. The framework developed using cradle-to-grave approach consists of unit processes from raw material extraction phase to the demolition phase of a building. Concrete being the major construction material of precast and cast-in-place buildings, all unit processes associated with concrete manufacturing is considered. Since, the methodology of precast and cast-in-place differs in the installation/construction phase, separate system boundary is developed as shown in figure 2. Three main transportation phases in a building life cycle are considered; resource extraction site to manufacturing plant, manufacturing plant(s) to construction site and construction site to disposal facility. Life cycle inventory data in the framework for precast and cast-in-place buildings would be generated from bill of quantities (BOQ), project estimate and field measured data of most relevant and current buildings' data. TRACI 2.0 and Ecoinvent databases in Open LCA software are used for life cycle impact assessment using the impact indicators suggested United States Environmental Protection Agency (EPA) for buildings. This study will be used to assess the life cycle costs and environmental impacts of two structural systems.

Conclusion

This framework developed using cradle-to-grave approach would provide a detailed comparative assessment of life cycle costs and environmental impacts of precast and cast-in-place buildings which has not been addressed in past studies. The system boundary used to develop the framework on OpenLCA software can be used on various other LCA software such as GaBi, BEES and Athena Impact Estimator for any precast or cast-in-place project across the world. This study would benefit the construction industry in promoting sustainable construction methods which would have reduced costs and environmental impacts over the complete life cycle of a building. Few limitations of the research could be excluding unit processes such as mining and wood extraction from forests from system boundary and no future extensions, re-constructions or any major changes to the building during 50 years of its life span. Deterministic life cycle assessment approach has been used to calculate the life cycle costs. Future research can be conducted using a probabilistic analysis of annual costs associated with the complete life cycle of the building. It is an ongoing research of which developing the framework is part-1 of research. Part-2 entails the application of this framework on precast and cast-in-place buildings explaining the detailed statistical comparison of both products. Overall comparison of precast and cast-in-place building in part-2 would help study the economic and environmental impacts as a whole on two buildings. In addition, the phase-wise comparison of all four phases; raw material extraction and manufacturing, precast installation/construction, operation and maintenance and demolition would assist in evaluating the impacts (economic and environmental) comprehensively showing which phase contributes the most. Such detailed analysis would allow the authors to determine if any improvements can be made in precast concrete construction method to further reduce the environmental as well as economic impacts as compared to cast-in-place construction.

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