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COMPARATIVE LIFE CYCLE ASSESMENT (LCA) AND LIFE CYCLE COST ANALYSIS (LCCA) OF PRECAST AND CAST-IN-PLACE BUILDINGS

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ABSTRACT

Precast construction is one of the growing construction methods for buildings across United States. Many tools have been used to assess environmental and economic 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 for their complete life cycle. The research aims to understand the life cycle environment impacts and costs over the complete life cycle for precast and cast-in-place building system. Cradle-to-grave approach was used to develop a framework for assessing the these impacts for precast and cast-in-place building systems constructed in United States through Open LCA software and NIST handbook for LCCA. The environmental impacts and costs associated with the four phases (raw material extraction and manufacturing, installation/construction, operation and demolition) of a precast building in United States were calculated and compared to cast-in-place building system. The research findings implicated that precast using sandwich panel building system had 21% lower life cycle costs (LCC) compared to cast-in-place building system. The construction phase and operation phase also had 38 % and 24% lower LCC compared to cast-in-place building systems. Additionally, lower life cycle environmental impacts towards nine environmental impact indicators were recorded for precast building systems. This study concluded that precast methodology has lower life cycle environmental and economic impacts than cast-in-place and is more sustainable construction method. 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. The research can also be used by practitioners to understand the phase-wise and total life cycle environmental and economic impacts of precast and further investigate to reduce these impacts.

KEYWORD: Life Cycle, (LCCA), Precast, Cast-In-Place, Buildings, Comparative, Analysis, (LCA)

INTRODUCTION

The concept of construction sustainability has been gaining traction ever since several reports were published regarding the improvement of social, economic and environmental sustainability bottom lines in the construction industry (Bennett & Crudgington, 2003; Du Plessis,2002; Environment & Development, 1987). The construction industry has a sizeable environmental impact as it consumes plenty of resources, materials and energy during the lifetimeof 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 waterpollution, deterioration of ecological systems, improper waste management etc. (Dong, Jaillon, Chu, & Poon, 2015; Shen & Tam, 2002).

With the increasing awareness of environmental issues, sustainable construction using a comprehensive environmental impact assessment has been promoted (Damtoft, Lukasik, Herfort, Sorrentino, & Gartner, 2008; Enshassi, Kochendoerfer, & Rizq, 2015; Flower & Sanjayan, 2007;Freedman & Jaggi, 2005) which in part, led to the "Kyoto Protocol". The Kyoto protocol is an international agreement between several countries to reduce the GHG emissions (Freedman & Jaggi, 2005). 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, LCA is the most extensively used tool because it is much more detailed and systematic (Singh, Berghorn, Joshi, & Syal, 2010).

LCA is an investigative method used for evaluating the environmental impacts of a systemor product over its complete life cycle (Rebitzer et al., 2004). The construction industry involves a complex process of design, material selection, construction methodology, operation and maintenance. Therefore, LCA practitioners should consider the different environmental impacts of each phase under the scope of study.

Concrete is one of the most established construction materials with 900 million tons of concrete is used annually by the construction industry. However, concrete production has a significant environmental impact 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 suchas mixing, placing and curing (Dong et al., 2015). In the meantime, precast concrete offers an improved environmental performance over cast-in-place concrete but still accounts for some 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 CO2 emissions and requires a holistic analytical approachof life cycle assessment (Gursel et al., 2014). Using LCA in precast concrete assessment can helpanalyze 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 using a comprehensive LCA approach to assess the impacts of precast concrete buildings from cradle-to-grave. As discussed above, the use of precast construction also accounts for environmental impacts and the comparative assessment between cast-in-place and precast construction will prove to be a vantage point for the industry and researchscholars to come up with better solutions which can contribute towards more sustainable construction methods.

This research also studies the impacts over a complete life cycle of precast concrete buildings using a Life Cycle Cost Assessment (LCCA) approach. To address the identified research problem, the following research questions were developed:

1. How was the system boundary developed for evaluating life cycle environmental impacts and costs?
2. Which building system has the highest total life cycle environmental impacts?

3. What are the total life cycle costs of the considered building systems?

4. What are the total life cycle environmental impacts during each phase of the considered building systems?

In answering these questions, the study helps in providing better sustainability assessment of precast concrete building systems over cast-in-place. Although various phases of life cycle of precast 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 in previous research studies. Additionally, life cycle costs of precast in comparison with cast-in-place is also the scope of research conducted. The following literature review will exploredifferent research efforts which have addressed similar problems and will support the novelty of this study.

LITERATURE REVIEW

Life Cycle Sustainability Assessment (LCSA)

Life cycle sustainability assessment is defined as a method which combines three different life cycle techniques: (1) Life cycle assessment, (2) Life cycle cost assessment (LCCA) and (3) Social life cycle assessment (S-LCA) (Dong & Ng, 2016). In essence, those three techniques assess the environmental, economic, and social sustainability respectively. Several scholars expressed LCSA as a formula (Finkbeiner, Schau, Lehmann, and Traverso (2010); Kloepffer (2008):

$$LCSA = LCA + LCCA + S\text{-}LCA$$

The LCSA is further discussed with respect to environmental, economical (LCCA) and social (S-LCA) considerations.

Life Cycle Assessment

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). LCA is extensively used to analyze the environmental impacts by resources and materials used from raw materials accession phase to end-of-life phases, and thus it is considered a “cradle to grave” approach (Finnveden et al., 2009; Joshi, 1999). As shown in Figure 1, there are four phases in LCA: (1) Goal and scope definition, (2) Life cycle inventory (LCI), (3) Life cycle impact assessment (LCIA), and (4) Interpretation.

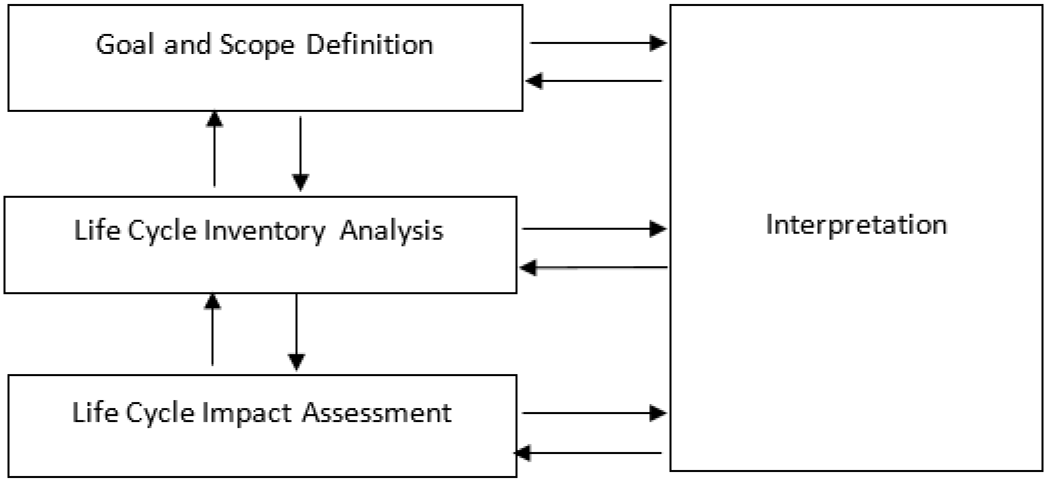

Figure 1: LCA framework based on (ISO, 2006)

Goal and Scope Definition

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 outputsof 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). As per ISO 14040 and ISO 14041, system boundaries are determined by the iterative process of choosing an initial system boundary and then making changes according to the desired scope of study. The system is modelled in a way where inputs and outputs at the boundaries are elementary flows i.e. the material and energy flows entering and leaving the system being studied (Suh et al., 2004).

The unit process excluded from the system boundary and unaccounted in the scope of studyis called cutoff and it depends upon the LCA practitioner. As shown in Figure 2, extraction of raw materials, transportation, manufacturing and subsequent on-site construction phase constitute a system boundary and the arrows in-between illustrates the iterative LCA procedure which establishes a causation between any information exchanges between the phases while, the use anddemolition phases has been excluded from the system. Figure 2 uses a cradle-to-site approach LCA for the study of carbon emissions. LCA system boundary approach is dependent on the phases considered during the analysis which can be categorized as cradle-to-grave (pre-use to end of lifephase), cradle-to-gate (raw material extraction to manufacturing) or cradle-to-site (raw material extraction to construction phase) (Rashid & Yusoff, 2015). The life span of any product or systemidentified in scope definition has a significant impact on LCA results because of the total energy consumption during it use phase.

Life Cycle Inventory (LCI) Analysis

Life cycle inventory (LCI) analysis is the data collection process aimed at quantifying the inputs and outputs of the system considered. LCI is an iterative process based upon new data requirements where the data collection methods are changed to meet goals of the intended study. Sometimes, due to limitation of existent data inventory, the system boundary is also redefined which results in a revised study scope. LCI compilation is achieved through a process based analysis, input-output analysis, or a hybrid analysis approach (Finnveden et al., 2009) (Atmaca, 2016).

RESEARCH METHODOLOGY

To achieve the aforementioned objectives, this research employed a quantitative research method to study and compare the environmental and economic impacts of precast and cast-in- place construction methods. This research study used Life Cycle Assessment and Life Cycle Cost Analysis (LCCA) approaches. The scope of the research study was to cover the unit processes from "cradle-to-grave", which included raw material extraction, manufacturing, transportation, on-site construction and installation, and the demolition phase. Environmental and economic impacts were studied and analyzed through an integration of Life Cycle Assessment and Life Cycle Cost Analysis (LCCA). The scope of research was to compare life cycle environmental impacts and costs associated with building constructed with precast using sandwich panels, cast-in-place and precast without sandwich panels. A precast building located in the state of Colorado was selected for the research and was designated as baseline building.

The 31,000 square feet building constructed had precast sandwich panels as the exterior envelope. Three BIM models were created of the building by interchanging the exterior envelopeto precast using sandwich panels, cast-in-place and precast without sandwich panels. Thus, the three buildings – (1) precast using sandwich panels, (2) cast-in-place and (3) precast without sandwich panels acted as individual building systems for the purpose of this research. The procedure of changing the building systems for comparative life cycle assessment has been observed in past studies as well (Dong et al., 2015; Ji et al., 2016).

Life Cycle Framework

The methodology map for this research, as illustrated in Figure 7, was derived from the four stages of life cycle assessment framework (ISO, 2006); (1) goal and scope definition; (2) life cycle inventory analysis; (3) life cycle impact assessment, and (4) analysis interpretation. The individual four phases (raw material extraction and manufacturing, precast installation/construction, operation and demolition) are a part of cradle-to-grave approach used in this research. Scope definition of the four phases was followed by the data collection of each phase. Life cycle environmental impacts and costs were evaluated through OpenLCA software and NIST Life Cycle Costing Handbook and the analysis of different building systems were performed. The following sections discuss the whole methodology map in detail.

Goal and Scope Definition

The main goal of this research study was to analyze the life cycle cost and environmental impacts of buildings constructed with precast sandwich panels, cast-in-place and precast withoutsandwich panels. To further define the study scope, the research established the system boundaries, the functional unit, and the lifespan which was considered during this study.

System Boundary

The building life cycle was evaluated with a cradle-to-grave approach as shown in Figure 7, where the system boundary starts from the raw material extraction phase (Cradle Start) and end up with the demolition phase (Grave). The environmental impacts and costs analysis begin with raw materials' identification for concrete manufacturing. Since, concrete was an integral part of the three systems (precast sandwich panels, cast-in-place and precast without sandwich panels), all unit processes associated with concrete manufacturing were considered. Therefore, asshown in figure 8, the manufacturing and/or mining of sand, gravel, cement, cementitious materials and admixtures were unit processes (inputs) for the manufacturing of concrete. Other unit processes such as mining and wood extraction from forests, were excluded from the system boundary. All the resources consumed during these processes such as fuel consumption, water

Consumption, electricity, and all associated costs for every unit process were included in the system boundary.

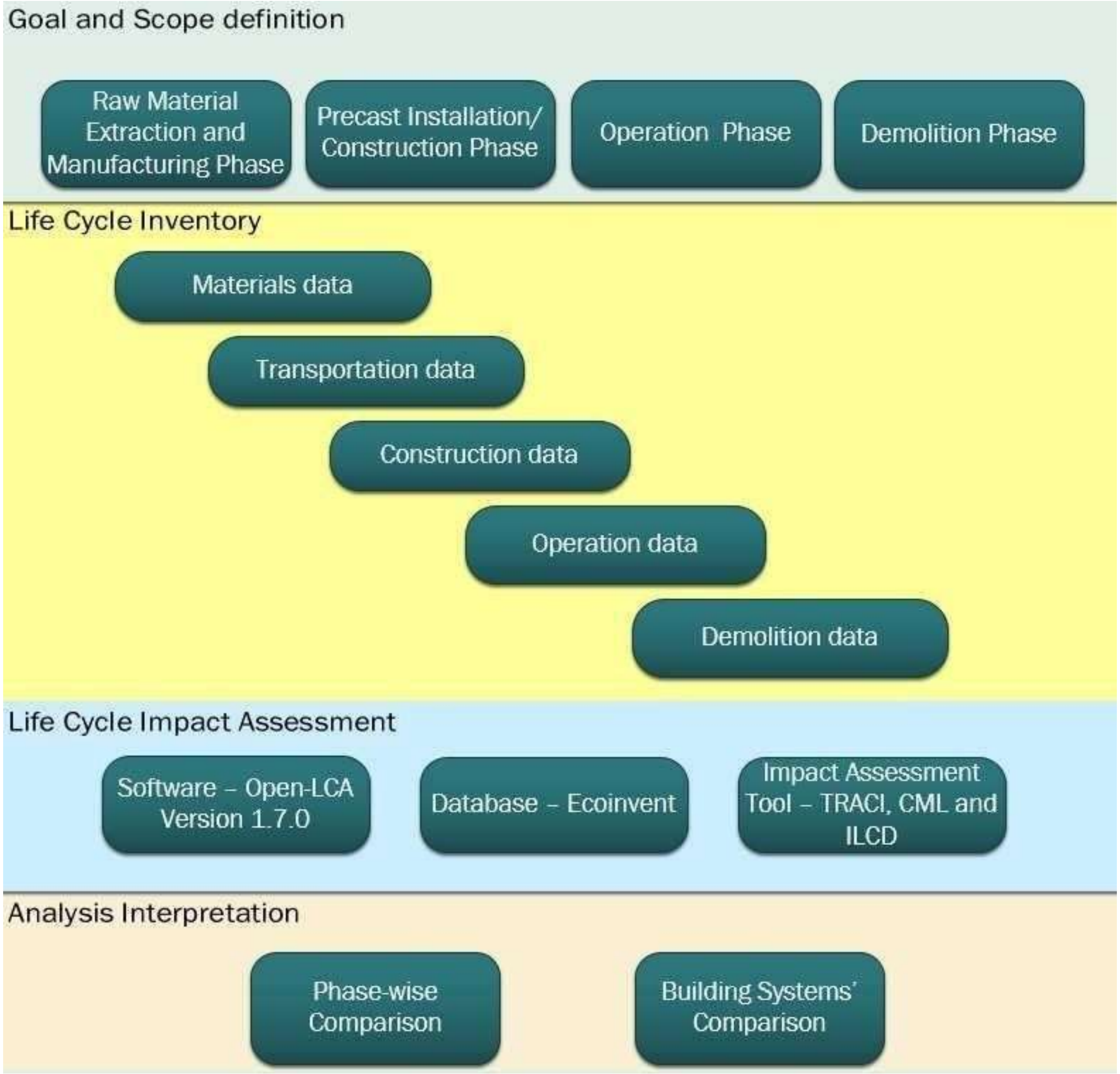

Figure 7: Methodology map

Precast and cast-in-place building systems have a unique and a different set of unit processes due to their different construction methodology as shown in Figure 8. However, building systems such as precast sandwich panels and precast without sandwich panels had same precast plant operations. For precast plant operations, concrete mix-design was followed by setting of formwork systems according to the size of required structural members such as beams,columns, stairs, rake beams and walls. The installation of rebar as per specifications and thereafter placement of concrete and curing for 28 days were considered. The casted panels were stored and transported to the construction site for installation. Differently, the on-site construction of cast-in-place concrete building system included a concrete batching plant (ready-mix concrete manufacturing) and transportation of the concrete to the area of concrete casting in concrete mixers. Erection of formwork and installation of rebar were other on-site activities before the concrete was poured and casted. The transportation of steel for rebar, water for curing and casting operations, and the formwork systems were also included in the system boundary to evaluate the costs and environmental impacts along with the electricity and fuel consumption of on-site construction equipment.

The building environmental impacts and costs in the operation phase was evaluated by means of annual energy consumption as shown in Figure 8. After constructing a BIM Model for the building, energy modeling was performed for all three building systems using Insight plugin to calculate the building annual energy consumption per square feet. The purpose of analyzing the energy modeling was to observe the difference in annual energy consumption for the different building systems. For external validation, the same BIM model for different building systems was run my industry experts as well.

As shown in Figure 8, this research study also considered the demolition phase as part of the cradle-to-grave approach and evaluates the environmental impacts and costs associated with it. The fuel and electricity consumption of construction equipment required for demolition and subsequent landfill were included in the system boundary.

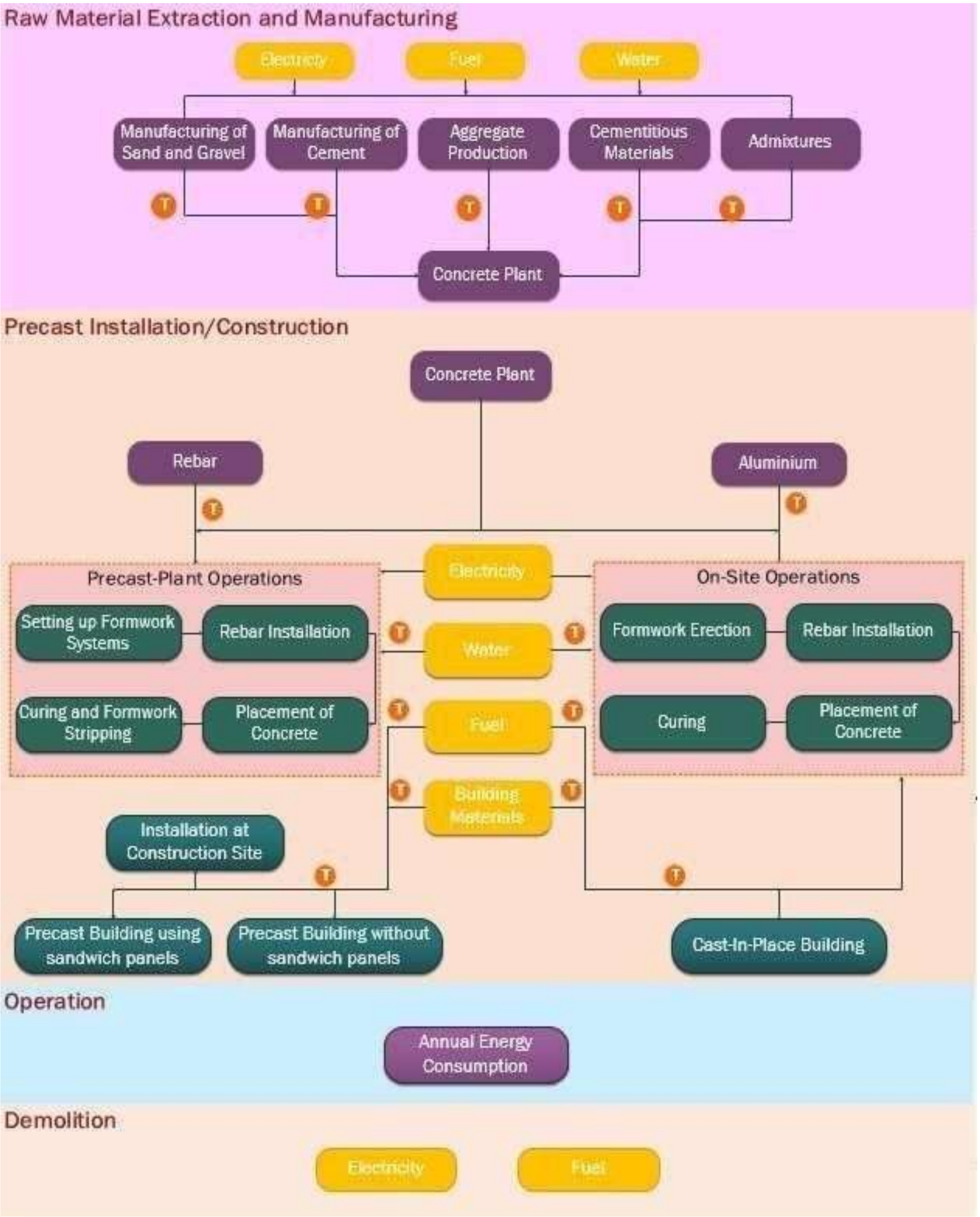

Figure 8: All four phases considered in the research

Table 1: Data Collection Sources for Each Life Cycle Phase

Life- Cycle Phases	Data Sources
Raw materials' extraction and manufacturing	Bill of Quantities (BOQ), Ecoinvent database, Project Estimate
Construction	General Contractor, Estimate, Ecoinvent database and Past Literature
Operation	Utility Department, Ecoinvent, Energy modeling
Demolition	General Contractor, Ecoinvent database, RS Means and Past Literature

Life Cycle Impact Assessment (LCIA)

LCIA phase evaluated the environmental impacts and associated life cycle costs 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), CML, ILCD (International Reference Life Cycle Data System) were used to classify and assign the inventory data to the selected environmental and human health impact categories. Figure 9 represents a LCIA model, which shows the selection of environmental impact categories (far right) guided by the scope of the study and environmental impacts (middle column) of life cycle phases considered as part of system boundary (far left column).

RESULTS AND DISCUSSION

Case Study Systems Application

As discussed in the methodology section, three BIM models for three different building systems were constructed; precast using sandwich panels, cast-in-place and, precast without sandwich panels. The precast sandwich panels consisted of two concrete wythe with insulation between them. The first precast concrete layer was 3.5 inches with rigid insulation of 3 inches followed by another concrete layer of 6 inches. The cast-in-place system had exterior walls converted to cast-in-place concrete walls in the BIM model. The concrete panel had a thickness of 9 inches followed by 2 inches of rigid insulation. Precast without sandwich panels was the third building system where exterior precast panel had a thickness of 9 inches followed by 2 inches of layer rigid insulation. Along with phase-wise comparison of all the systems, the three building systems as a whole for complete life cycle were also analyzed and compared among themselves. The life cycle environmental impacts contributing towards global warming potential of three building systems was compared with established benchmarks. In addition, environmental impact costs of GWP, land use potential and water use were calculated and compared.

Phase-Wise Comparison of Building Systems

Using the defined system boundary along with the unit processes of each phase as explained in the Methodology (section 3.1), the three building systems were analyzed for lifecycle environmental impacts and costs of all four phases.

Raw material extraction and manufacturing phase

Raw material extraction phase was the first phase considered for the life cycle analysis that included all the upstream and downstream processes to produce concrete (such as extraction of raw materials, preparation of raw materials, pyro processing, clinker production and transportation). These operations had major environmental impacts in terms of global warming potential, non-carcinogenic respiratory effects and land use. Though raw material extraction has a lower life cycle in comparison with construction and operation phase, the environmental impacts and associated costs were significant. The major inputs during this phase were extraction of raw materials (gravels, sand, admixtures, silica and limestone), energy consumption in the form of fuel (diesel and natural gas) and their upstream and downstream processes. These inputs were majorly responsible for the environmental impacts and costs for the life cycle of raw material extraction phase. As per the National Institute of Standards and Methodology (NIST) Handbook 135 for Life-Cycle Costing Manual, the life cycle costs associated with raw material extraction and manufacturing phase were considered as investor costs (excluding costs related to

The system boundary framework was applied to case study's building using the three different systems as discussed above to evaluate the life cycle environmental impacts and costs. Individual comparative assessment of all four phases (raw material extraction, construction/installation, operation and demolition) were performed and the results were compiled to investigate which environmental impact indicator has the greatest impact among cast-in-place, precast, and precast with sandwich panels systems. For comparing the environmental impacts, environmental impacts indicators showing significant contributions for each phase were discussed in detail. In addition, life cycle costs of all phases were also compared across the three systems due to different upstream and downstream unit processes, especially between precast and cast-in-place. Two - tiered results were drawn based upon the comparison between precast using sandwich panels, cast-in-place and precast without sandwich panels. Along with phase-wise comparison of all the systems, the three building systems as a whole for complete life cycle were also analyzed and compared among themselves. The life cycle environmental impacts contributing towards global warming potential of three building systemswas compared with established benchmarks. In addition, environmental impact costs of GWP, land use potential and water use were calculated and compared.

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Table 2: Environmental Impacts for Three Building Systems During Raw Material Extraction and Manufacturing Phase

S.NO	Environmental Impact Indicators	Units	Precast using sandwich panels	Cast-in-Place	Precast without sandwich panels
1	Global Warming Potential	Kg CO2-Eq	0.32	0.35	0.32
2	Ozone Layer Depletion	Kg CFC-11-Eq	2.0E-08	2.10E-08	2.0E-08
3	Eutrophication Potential	Kg N	6.79E-06	6.90E-06	6.9E-06
4	Photochemical Oxidation	Kg NOx-Eq	8.40E-04	9.50E-04	8.40E-04
5	Respiratory Effects (Non-Carcinogenic)	Kg toluene-Eq	1.15	1.48E+00	1.15
6	Acidification Potential	Kg SO2-Eq	1.33E-03	1.53E-03	1.33E-03

7	Resource Depletion	Kg Sb-Eq	1.86E-05	2.22E-05	1.86E-05
8	Land Use	Kg SOC	1.118	1.23E+00	1.118
9	Water Use	M^3	6.40E-04	7.80E-04	6.40E-04

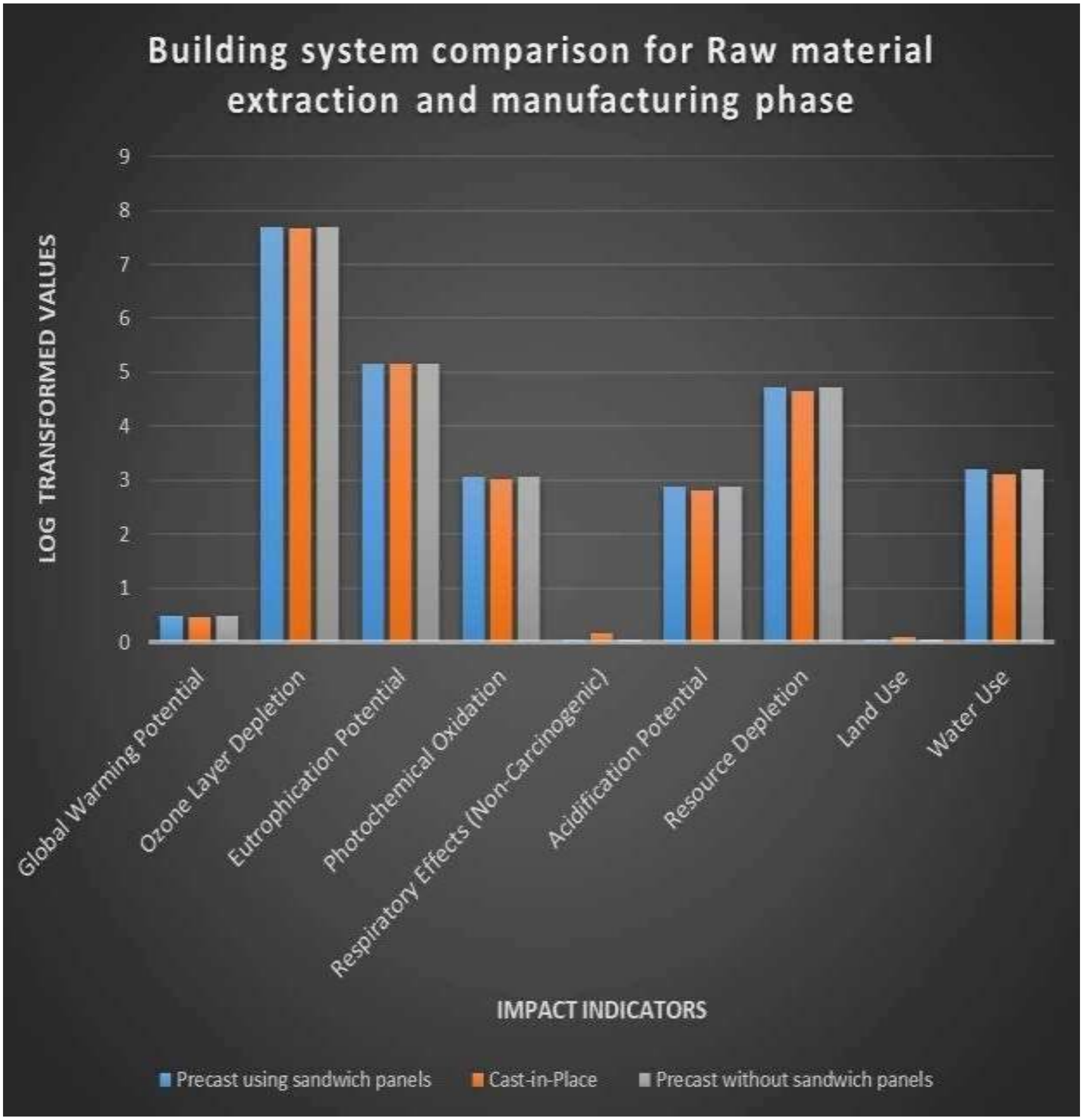

Figure 10: Building system comparison of raw material extraction and manufacturing phase

Table 3: Environmental Impacts for Three Building Systems During Installation/ConstructionPhase

S.NO	Environmental Impact Indicators	Units	Precast using sandwich panels	Cast-in-Place	Precast without sandwich panels
1	Global Warming Potential	Kg CO2-Eq	4.39E-03	0.70	4.81E-03
2	Ozone Layer Depletion	Kg CFC-11-Eq	2.40E-10	3.26E-07	3.40E-10
3	Eutrophication Potential	Kg N	1.66E-06	3.70E-06	1.66E-06
4	Photochemical Oxidation	Kg NOx-Eq	1.50E-04	8.0E-04	1.50E-05
5	Respiratory Effects (Non-Carcinogenic)	Kg toluene-Eq	0.071	0.10	7.80E-02
6	Acidification Potential	Kg SO2-Eq	3.17E-04	2.5E-03	3.17E-04
7	Resource Depletion	Kg Sb-Eq	6.79E-07	1.20E-05	6.79E-07
8	Land Use	Kg SOC	0.018	5.6	1.80E-02
9	Water Use	M^3	5.37E-05	4.50E-03	5.78E-05

CONCLUSION

Precast construction is one of the growing methodologies in the construction industry of United States and has been a modular alternative to conventional cast-in-place construction. The research commenced with a comprehensive literature review of LCA, LCCA and past studies on studying the environmental and economic impacts of buildings. The literature review further continued in understanding the gaps in past studies conducted on LCA and LCCA of precast buildings. This study investigated the life cycle environmental impacts and costs between the three building systems using cradle-to-grave approach. The study developed a framework with a comprehensive system boundary, using cradle-to-grave approach, that included raw material extraction and manufacturing, construction/installation, operation, and demolition phases to assess the life cycle environmental impacts and costs of each phase. This research has substantial contribution by introducing a novel framework for integrated comparative assessment of three building systems. While this research study is conducted in United States, the dynamic framework developed can be potentially applied on other precast and cast-in-place building projects across the globe. The findings in this study illustrated that adoption of precast construction can lead to better environmental performance as total life cycle environmental impacts were considerably lower for precast system in comparison to cast in place. For instance, life cycle environmental impacts contributing towards GWP was 48% lower for precast compared to cast-in-place. The precast building system also proved to be more economically efficient compared to cast-in-place building system as the total life cycle costs were 21% lower. The operation phase was the highest contributor towards environmental impacts and costs for all three building systems. However, precast sandwich panel system had lower environmental impacts and 24% lower costs compared to other two building systems due to the better insulation of sandwich panels which helps in reducing the operational costs during the building longest phase of its life cycle. Further consideration of research findings suggested that improving the sustainability of construction industry by using precast construction can substantially contribute to a more sustainable buildings by reducing the life cycle environmental impacts and costs. For instance, life cycle environmental impact costs due to GWP, land use potential and water use was also lowest for precast using sandwich panel system and thus contribute towards achieving United Nations Sustainable Development goals (UNSDGs). The two-tiered analysis will provide a vantage point to industry experts and research scholars to determine if any improvements can be made in precast concrete construction method to further reduce the environmental as well as economic impacts compared to cast-in-place construction by understanding the whole process of cast-in- place and precast methodology. The framework developed in this research study is also beneficial to research scholars to analyze and quantify the total and phase-wise life cycle environmental impacts and costs for precast and cast-in-place building systems and thus, investigate on how the environmental impacts and costs can be further reduced.

The results of this research study and the assessment framework can be used by industryexperts, sustainability consultants, general contractors and clients to understand the lower environmental and economic impacts of precast construction for the complete life cycle of the building or compare the different building system alternatives during the planning phase. This will encourage various industry stakeholders to adopt precast construction method over conventional cast-in-place and promote sustainability in construction industry. The comparison between precast with and without sandwich panels also prove that upfront costs of using sandwich panels is justifiable due to cost savings and lower environmental impacts over the building life cycle. The energy modeling technique adopted in this research study to calculate theannual energy consumption is a great example to compare the energy efficiency among several building systems. This method can be applied by clients to monitor the energy efficiency during the operation phase of their projects. In addition, LCA and LCC approaches used in the current research study can be used to calculate the life cycle environmental impacts and costs upfront and make necessary design changes to make the projects more sustainable. The application of LCA and LCC on building projects proposes a significant guidance to the decision makers and as per LEED 4.1 for New construction, it can help achieve up to 5 LEED points, which is a well- known and widely used building rating system in United States. Therefore, based upon above conclusions, research findings provide strong implications to industry practitioners to recommend and implement precast construction using sandwich panels for vertical construction in order to reduce the life cycle environmental impacts and costs of concrete systems.

Although the findings of this research study could be very helpful to decision makers as it addressed the different phases of the three building systems, it still has several limitations that can be addressed in further studies. This research study did not consider the maintenance or rehabilitation environmental impacts due to the volatile nature of such phases and how different owners can treat maintenance and rehabilitation policies and procedures differently. Another limitation of the study is that it did not cover a cradle-to-cradle approach where no recycling of building components after demolition was considered in the research scope. Due to the versatile nature of precast, it offers designers to develop sustainable solutions by designing for reuse and recycle which can further reduce the environmental impacts and can be considered in future research studies. Finally, deterministic life cycle assessment approach has been used to calculate the environmental and cost impacts and probabilistic analysis of annual costs associated with the complete life cycle of the building can be a future research opportunity. Due to complexity of construction and data constraints, labor costs and price escalation was not considered in the scope and we propose that further research by research scholars can be carried out to include them in LCC studies. As sustainability is not just limited to environment and economy, the socialindicator should also be taken into consideration for a more holistic life cycle analysis. There are no studies that consider all dimensions of sustainability impacts of precast buildings and the current conducted study provides a robust platform to further analyze the life cycle social impacts by conducting Social-LCA and embrace the triple bottom line (environmental, economicand social) components of sustainable construction.

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