THESIS

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

Submitted by

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ABSTRACT

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

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.

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Chapter 1: 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 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, 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 system or 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 such as 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 CO_2 emissions and requires a holistic analytical approach of life cycle assessment (Gursel et al., 2014). Using LCA 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 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 research scholars 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 explore different research efforts which have addressed similar problems and will support the novelty of this study.

Chapter 2: Literature Review

This chapter explores the existing literature addressing this research topic. The concept of LCA, its four stages and LCCA are introduced and explained. Thereafter, the concept of sustainability in precast systems is introduced and existing body of knowledge for different LCA approaches on precast buildings are examined. Also, Past LCA studies on precast concrete in vertical construction have been reviewed and future scope in the application of precast concrete in the construction industry has been further discussed.

2.1 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-LCA

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

2.2 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.

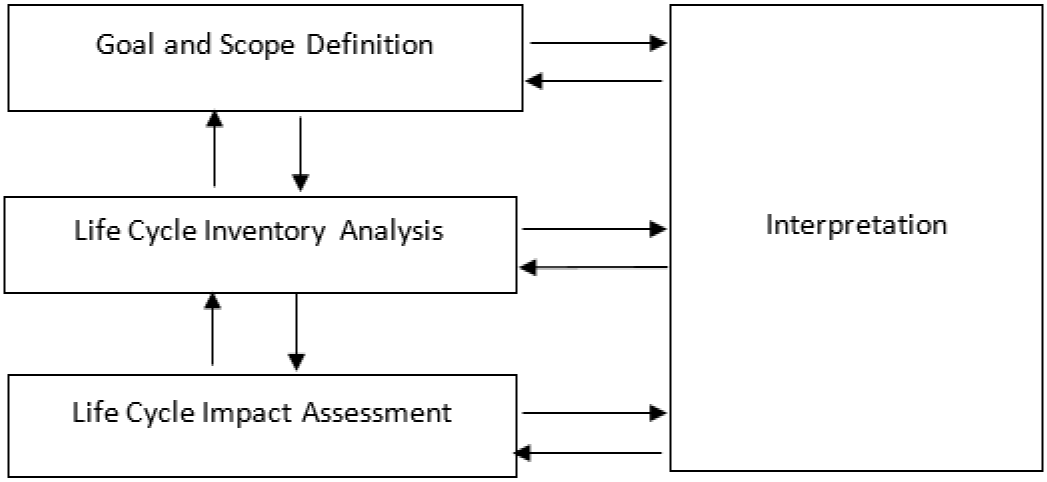


Figure 1: LCA framework based on (ISO, 2006)

2.2.1 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 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). 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 study is 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 and demolition 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 life phase), 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 system identified in scope definition has a significant impact on LCA results because of the total energy consumption during it use phase.

2.2.2 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).

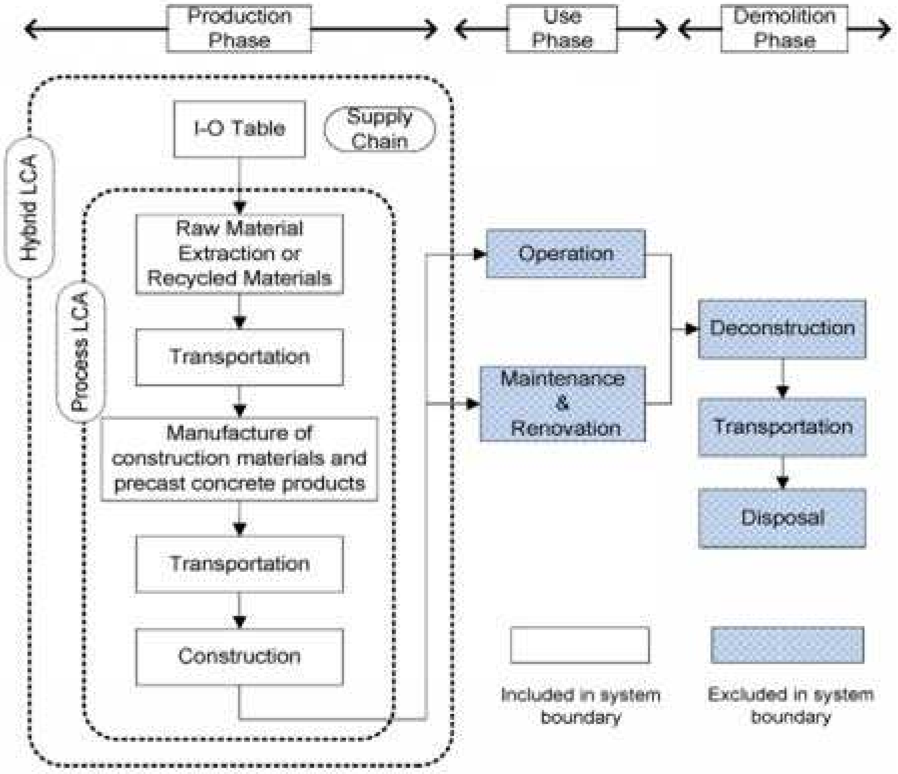


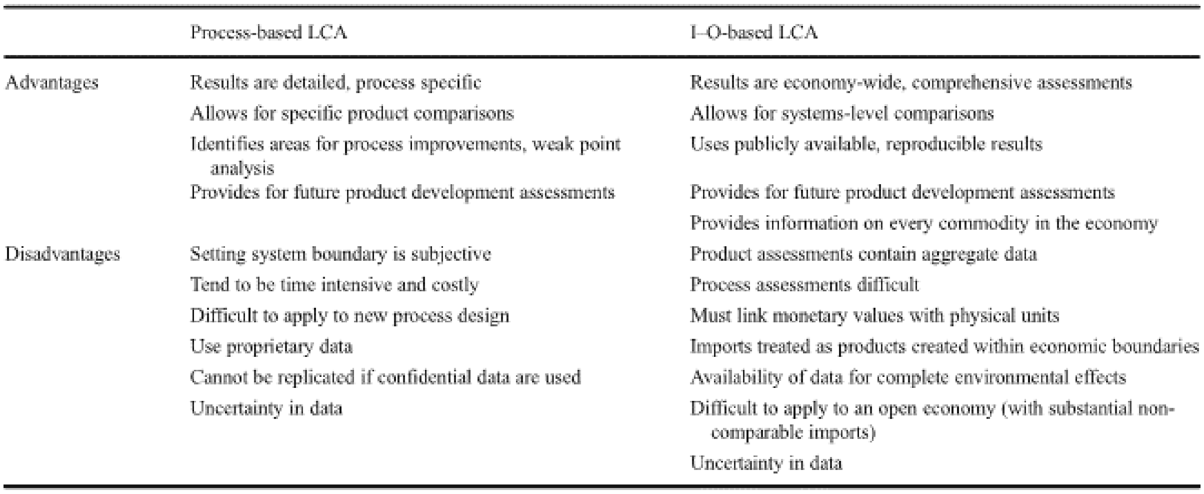
Figure 2: Flow diagram of a system boundary in building construction project (Omar, Doh, Panuwatwanich, & Miller, 2014).

2.2.2.1 Process-based analysis

Process-based analysis is a conventional LCI approach which involves quantifying extensive resource, material and energy uses along with the associated environmental impacts in the form of system inputs and outputs, only within the system boundary, and the remaining successive inputs are considered negligible. The shortcoming of process-based analysis is the omission of contributions outside the system boundary which yields systemic incompleteness and truncation of the product system, that can be in the order of 50-90% depending upon the system studied (Aye, Ngo, Crawford, Gammampila, & Mendis, 2012; Lenzen, 2000). As introduced by (Heijungs, 1994), there are two approaches for process-based analysis, a process flow approach and a matrix approach. The process flow approach only uses the compiled data of the identified system and consider the remaining upstream inputs to have a negligible impact. Whereas, in matrix-based approach, each column of technology matrix is occupied by a vector of inputs and outputs which includes production use to end of life disposal phase. Life cycle inventory is then calculated by inverting the technology matrix and multiplying it by an environmental matrix. Matrix based approach describes infinite upstream process but only those processes are included that are in the scope of system boundary (Suh et al., 2004).

2.2.2.2 Input-output (IO) analysis

According to Lenzen, input-output analysis is a top-down approach that considers infinite sectoral interdependencies of industries in modern economy using national or regional based input-out tables (Lenzen, 2002).The utilization of input-output framework to evaluate environmental impacts has been used since the 1970s and its application is based on the research done by Hendrickson, Horvath, Joshi, and Lave (1998); Isard et al. (1968) and (Proops, 1977). IO analysis describes the economic transactions between the sectors of a national economy in terms of relationships of each sector to the corresponding levels of activities in all other sectors. For instance, the quantity of GHG emissions released in the air due to construction activities has a direct relationship with the number of fuel powered equipment used. It uses sectoral (IO) tables to estimate the material and resource flow in a supply-chain and evaluate its associated environmental impacts. The conventional IO tables show incurred costs (wages, depreciation costs, taxes, profits, payments, transportation costs, labor costs) by each manufacturing/producing sector (Hendrickson et al., 1998; Leontief, 1970). IO analysis treats the whole economy as a system, can account for unlimited potential transactions in the upstream flow of supply-chain, and provide complete analysis of energy requirements associated with each product. However, the data and tables used are incomplete sources of sectoral environmental impacts statistics as they are often published with a lag of a few years. Thus, it may influence the model accuracy when the prices of commodity change drastically. In addition, the failure to address a product and use of outdated IO tables can limit its application for emerging sectors. (Hong, Shen, Mao, Li, & Li, 2016; Suh et al., 2004; Suh & Nakamura, 2007; G. J. Treloar, Love, & Crawford, 2004). A comparison of process-based LCA and IO LCA is shown in Figure 3 in terms of their capabilities (advantages) and disadvantages that were highlighted earlier.



	Process-based LCA	I–O-based LCA
Advantages	Results are detailed, process specific	Results are economy-wide, comprehensive assessments
	Allows for specific product comparisons	Allows for systems-level comparisons
	Identifies areas for process improvements, weak point analysis	Uses publicly available, reproducible results
	Provides for future product development assessments	Provides for future product development assessments
		Provides information on every commodity in the economy
Disadvantages	Setting system boundary is subjective	Product assessments contain aggregate data
	Tend to be time intensive and costly	Process assessments difficult
	Difficult to apply to new process design	Must link monetary values with physical units
	Use proprietary data	Imports treated as products created within economic boundaries
	Cannot be replicated if confidential data are used	Availability of data for complete environmental effects
	Uncertainty in data	Difficult to apply to an open economy (with substantial non-comparable imports)
		Uncertainty in data

Figure 3: Advantages and disadvantages of process-based and I-O analysis (Atmaca, 2016)

2.2.2.3 Hybrid analysis

The hybrid analysis is developed to eliminate many of the shortcomings in process based and input-output techniques by reducing the truncating errors and increasing the specificity in studying environmental impacts. Three different models can be used in this analytical method: (1) Tiered hybrid, (2) Input-output hybrid, and (3) Integrated hybrid (Hong et al., 2016). Tiered hybrid uses process-based data for important lower-order upstream and downstream processes while the remaining higher order processes are accounted for by using input-output analysis approach, and it is entirely compiled by the addition of these datasets. One of the most common mistakes using this method is the double addition of flows integrated in both process-based and input-output analysis which can be a major methodological issue (Crawford, 2008; Crawford & Pullen, 2011; G. J. Treloar et al., 2004). Integrated hybrid framework incorporates physical quantities as well as monetary transaction values.

2.2.3 Life Cycle Impact Assessment (LCIA)

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). ISO standards have described the framework of LCA but there is no fixed method to calculate environmental impacts. The selection of relevant impact assessment method and impact categories depends upon the goal and scope definition. The impact categories or environmental indicators (used interchangeably) might include GHGs emission, eco toxicity, resource uses, eutrophication, acidification, land and water use, oxygen depletion and use of renewable and non-renewable resources. According to the type of environmental indicators considered in research, the environmental mechanism can be chosen by linking the LCI results to impact categories or environmental indicators. Mainly there are two approaches in conducting LCIA, which can also be combined: Problem oriented method (midpoints), and Damage oriented method (endpoints) (Buyle et al., 2013). The problem-oriented method makes use of values at the very beginning or middle of the environmental impact mechanism such as global warming potential, acidification potential and ozone layer depletion. These midpoints are relevant as they are directly linked with physical characteristics but suffer with the problem of incomparability. For instance, the emission of two pounds of carbon dioxide has more environmental impact or two pounds of sulfur dioxide. The damage-oriented method is accounted at the end of mechanism such as human health, natural environment and resources. Most

LCA researchers prefer utilizing already developed modelling platforms rather than building a LCA model from scratch (Goedkoop M, 2010). There are many LCA platforms such as CML 2002, Eco-Indicator 99, Impact 2002+, Recipe, TRACI and LIME.

2.2.4 Interpretation

In this phase, the results from LCIA and LCI are summarized. It is an iterative process of discussing the results using various techniques such as contribution analysis, sensitivity analysis and influence analysis (Morrison Hershfield & the Athena Institute, 2010). According to Khasreen et al. (2009), "the purpose of this phase is to analyze the results, reach conclusions, explain limitations, and provide recommendations based on the findings of the preceding phases of LCA".

2.3 Life Cycle Cost Analysis (LCCA)

The LCC approach was applied by US Department of Defense (White & Ostwald, 1976). Life cycle cost (LCC) of a product or system constitutes the total project cost of that arises from acquisition, operation, maintenance, and ultimate disposal (NIST, 1995). Thus, LCC is the total cost of procurement and ownership (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. LCCA has been considered an important approach in past studies and has been widely implemented for empirical research for buildings (Goh & Sun, 2016). The results of LCCA depends on the number and accuracy of its input parameters. The costs encapsulated in the LCCA phase comprises of construction, agency, user, and environmental costs.

The first step in LCCA is the selection of alternate design options using economic principles and identifying best suitable alternate design options. The second step consist of including activity durations of each alternate identified in the first step. The estimation of direct and indirect costs of each alternate activity is the third step (Hass, Tighe, & Falls, 2005). Finally, the total life-cycle cost associated with each item is calculated after considering the costs represented in land procurement, design, equipment, material, workers, and operational costs. It is also imperative to consider several uncertainty sources while applying LCCA, such as life span of building, future costs, discount rate and inflation rate (NIST, 1995). Several techniques such as sensitivity analysis, fuzzy approach and probability-based approach have been proposed to assess these uncertainties (Arja, Sauce, & Souyri, 2009). There have been several studies about LCCA on buildings (Aye, Bamford, Charters, & Robinson, 2000; Cui, Gao, Xiao, & Wang, 2017; Dwaikat & Ali, 2018; Marszal & Heiselberg, 2011), however not many comparative studies of precast buildings have been conducted.

2.4 Social Life Cycle Assessment (SLCA)

SLCA is a decision-making approach which is directly or indirectly relates to social impacts of products, considering all life-cycle stages. For better application of SLCA, a combined (problem and damage) midpoints and end point indicators should be well defined to study the positive and negative social impacts (Grießhammer et al., 2006). SLCA also follow the same four step approach as in LCA; goal and scope definition, inventory analysis, impact assessment, and interpretation.

2.5 Precast Concrete

The two primary concrete construction methods used in the industry are; Cast-in-place, and Precast concrete. Precast Concrete can be defined as the concrete which is prepared, casted and cured in a controlled environment, other than the place where it is installed (Chen, Okudan, & Riley, 2010). The general transition from conventional methods of cast-in-place to precast has been observed following the formation of Precast Concrete Institute in 1954 (Ramsey et al., 2014). The precast concrete industry maximizes the economic benefits by using products and elements that have been evolved in a controlled environment such as double-tees, hollow-core slabs, square or rectangular columns for column-deck frames, precast concrete piles, raker beams, etc. Precast concrete has its applications in residential, commercial, institutional, and various infrastructure projects (Committee, 2004).

2.5.1 Features and Benefits of Precast Concrete

As per Precast Concrete Institute (PCI) Design Handbook (PCI, 2010), precast concrete offers many benefits to all stakeholders associated with the precast concrete industry. Unlike cast-in-place, which requires additional on-site labor, mixing equipment and various formwork systems for production and installation, precast offers a better and faster way by eliminating several variables such as mixing, placing and curing of concrete onsite. It enables greater control over quality in a controlled environment unlike open weather conditions in cast-in-place. Precast concrete also offers architects flexibility in design considerations which lead to greater aesthetic quality (Tam, Tam, Zeng, & Ng, 2007). Finally, it promotes sustainability by using various alternate construction materials as well as production processes that have lesser environmental and economic impacts (PCI, 2010).

2.5.2 Factors affecting precast concrete application in the United States

Lack of expertise in precast concrete is one of the vital factors that prevents its extensive use. This lack of expertise in various design and production processes can also lead to poor design, improper precast plant operation, and faulty erection practices Other issues that might limit precast application are the repetitive nature of precast elements, defects in design considerations like improper thermal and moisture insulation, cracks and joint failures (Arditi, Ergin, & Günhan, 2000; Polat & Damci, 2007). From structural analysis standpoint, precast concrete structures have shown unstable and volatile behavior during high seismic loads as some precast buildings showed deformations and structural failures in several earthquakes that occurred in 1992 and 1995 in Turkey (Sezen & Whittaker, 2006). However, in the 1994 Northridge earthquake, while most of the precast structures showed very small deformations near the epicenter, other further structures underwent severe failures (Camba & Meli, 1993). This uncertain structural behavior was accounted for by PCI, and changes were proposed in the sixth edition of design handbook. Another challenge in precast systems is the components' allowable size and weight transportation constraints which can limit a designer's vision by forcing them into requisite allowable limits when designing precast concrete structures (Todd, Rapp, & Charlson, 2004). Finally, the use of precast concrete construction methodology effects the number of labor force required at site acutely and this can sometimes instigate resistance from labor unions (Arditi et al., 2000).

2.6 Sustainability Concept in Precast Concrete

Sustainable development establishes a balance of economic, social and environmental impacts. Meanwhile, the construction industry has significant potential to reduce significant environmental impacts as its processes consume huge amount of resources, materials, and energy. According to U.S Green Building Council (USGBC), buildings in the United States consume 10% of global energy use (Council, 2009). Despite the aforementioned benefits of precast concrete (section 2.5.1), there is a need to evaluate the environmental and economic impacts in precast concrete construction. In cradle-to-gate approach, most of the environmental impacts related to precast concrete are due to the processes responsible to 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 benefit of precast concrete in the construction stage where wastage is reduced, further rigorous assessment is needed to validate it (Dong et al., 2015).

2.6.1 LCA of Precast Concrete

Generally, LCA research studies conducted in the construction industry are either for building materials and components (BMCs) or buildings (Hong et al., 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; G. Treloar, Fay, Love, & Iyer-Raniga, 2000).There has been substantial LCA studies to assess the environmental impacts of the construction industry. For instance, 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). Similarly, more than 10 different studies regarding LCA of vertical construction have been published (Anand & Amor, 2017). However, limited research has addressed the LCA of precast concrete buildings (vertical precast construction).

2.6.2 LCA Studies in Precast Building Industry and Future Scope of Research

Past LCA studies on precast systems has made use of cradle-to-gate, cradle-to-site and cradle-to-grave approach to constitute the system boundary for the intended research (Bilec, Ries, Matthews, & Sharrard, 2006; Dong et al., 2015; Holton, Glass, & Price, 2010; Ji, Li, Liu, Shrestha, & Jing, 2016). The choice of method of LCI and the tools used for LCIA vastly determine the nature, extent, and the study outcome (Finnveden et al., 2009). The following section will thoroughly discuss the past literature on precast systems' LCA approach.

2.6.2.1 Functional unit and life span

Different functional units have been used for conducting buildings' LCA (Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014). For instance, meter (m), meter square (m^2), meter cube (m^3) are frequently used for residential buildings. In precast concrete buildings, the quantitative functional unit is mostly used in volumetric scale cubic meter (m^3) (Cabeza et al., 2014; Ramsey et al., 2014; Rashid & Yusoff, 2015). Another approach is to use different functional units for various active and inactive materials and resources which are incorporated in the building LCA (Wu & Apul, 2015). Active materials and resources refers to those resources and materials that are not part of the building but are operated within it to meet the residential needs such as combustion sources (furnaces) and electric sources (electric space heaters) whereas, inactive materials and resources are generally stationery and includes fixed building products, furniture and finishing products. Uncertainty analysis has been used in past studies to calculate the service life span since, several products and materials used in a precast construction project have different lifetime within the same building (Silvestre, Silva, & de Brito, 2015). The life-span of buildings play a vital role in the result of LCA as it determines the total energy consumption in and the operational phase of a building. According to Athena Sustainable Materials Institute, regardless of the construction material type, the average life span of United States residential buildings is 61years. However, a life span of 50 years was considered in majority of past LCA studies on precast concrete buildings (Blengini & Di Carlo, 2010).

2.6.2.2 System boundaries in LCA

For precast concrete structures, several system boundaries have been used such as cradle to gate, cradle to site and cradle to grave (Rashid & Yusoff, 2015; Ye, Lu, Li, & Chang, 2011). Figure 4 shows an example of a cradle-to-gate system boundary for a precast building. Such boundaries specify the extent of research conducted in upstream and downstream processes and the boundaries are set based on the LCA practitioner's scope of work. For example, particulate emissions at construction site during excavation activities, manufacturing of aggregate and admixtures, concrete waste disposal, procurement of water, maintenance of precast plant equipment were excluded in recent LCA studies (Anand & Amor, 2017; Finnveden et al., 2009). Contrarily, material procurement, transportation of precast elements to installation site, cement manufacturing, transportation of labor, and air emissions such as CO_2, SO_2, CO and water and soil emissions were included in many studies (Ingrao, Giudice, Mbohwa, & Clasadonte, 2014; Ji et al., 2016; Ramsey et al., 2014). Past studies did not consider supply-chain flow for electricity, fuel production for cement, and the amount of CO_2 and other gas emissions which depends on the type of fuel used for generating electricity and vary geographically (Anand & Amor, 2017). It is worthy to note that LCA based risk assessment have been suggested for defining system boundaries for buildings (Ayoub, Musharavati, Pokharel, & Gabbar, 2015), which can pertain to precast concrete buildings as well.

2.6.2.3 Inventory analysis

Life cycle inventory (LCI) involves data collection for system inputs and outputs. These datasets can be collected from the building industry, site investigation reports, review of bill of quantities, project reports, environmental product declarations (EPD) and various databases (e.g. Eco invent v.2.2) (Anand & Amor, 2017). The results of the inventory analysis can vary due to the multiple data sources and data collection methods (Lasvaux, Habert, Peuportier, & Chevalier, 2015). Therefore, (Dixit, Fernández-Solís, Lavy, & Culp, 2012) stressed the need to setup a standard methodology for calculation of embodied energy which adheres to ISO . In past studies, the LCA analysts have often faced difficulty in choosing data sources when the required data is unavailable (Peng, 2016) and guidelines have been proposed relating to this issue by (Silvestre, Lasvaux, Hodková, de Brito, & Pinheiro, 2015). Several databases in LCA platforms such as Economic input output- life cycle analysis (EIO-LCA) data have also been used to account for factors such as service sectors, upstream effects, and operation and maintenance of construction equipment (Bilec et al., 2006).

2.6.2.4 Impact Assessment and Interpretation

The past studies on how the environmental impacts were assessed are discussed below.

2.6.2.4.1 Selection of Environmental Impact Category

Mostly, previous LCA studies considered primary energy use and GHG emissions as one of the major environmental indicator (Heinonen, Säynäjoki, Junnonen, Pöyry, & Junnila, 2016). PCI has used the U.S. EPA Tool for the Reduction and Assessment of Chemical and Other

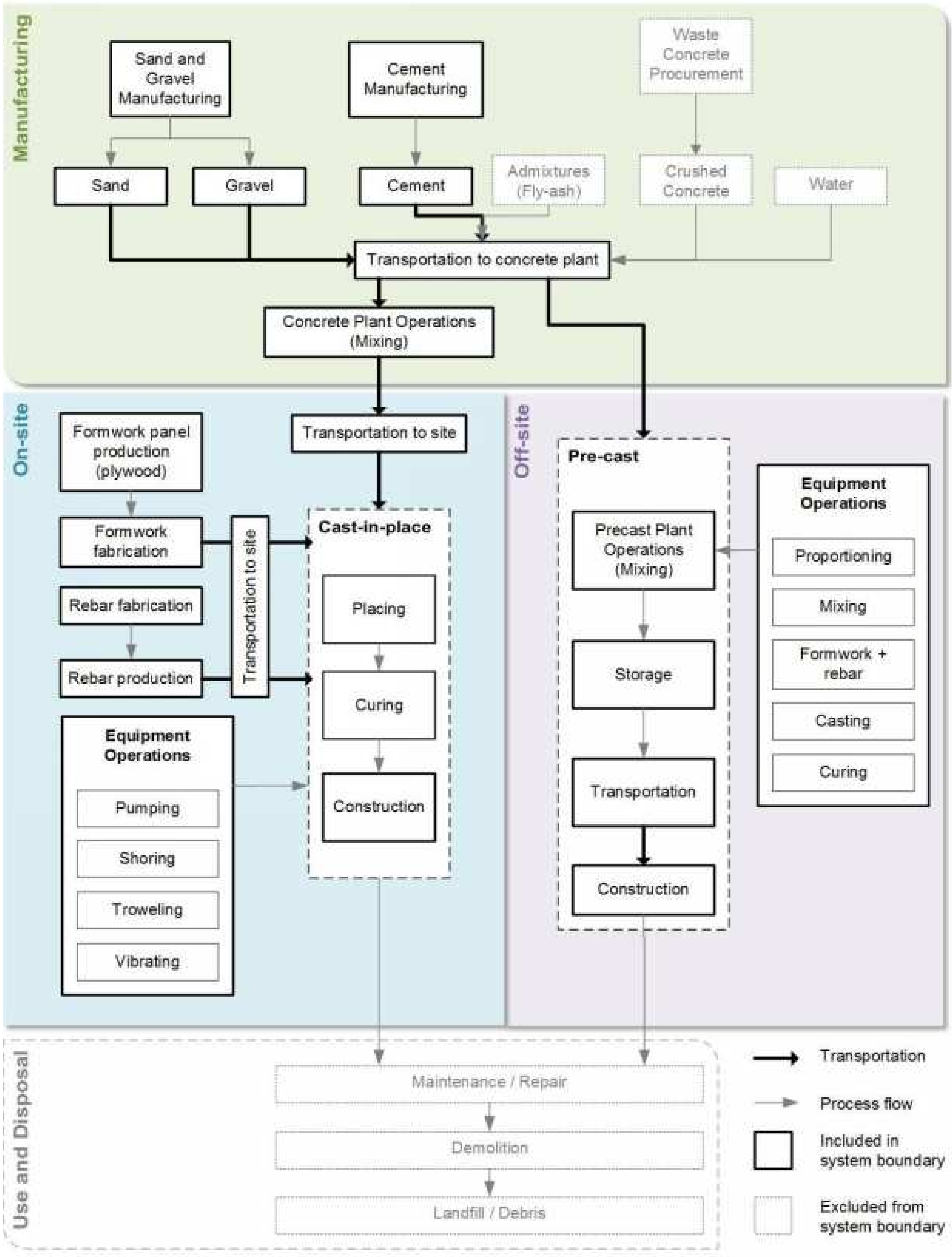
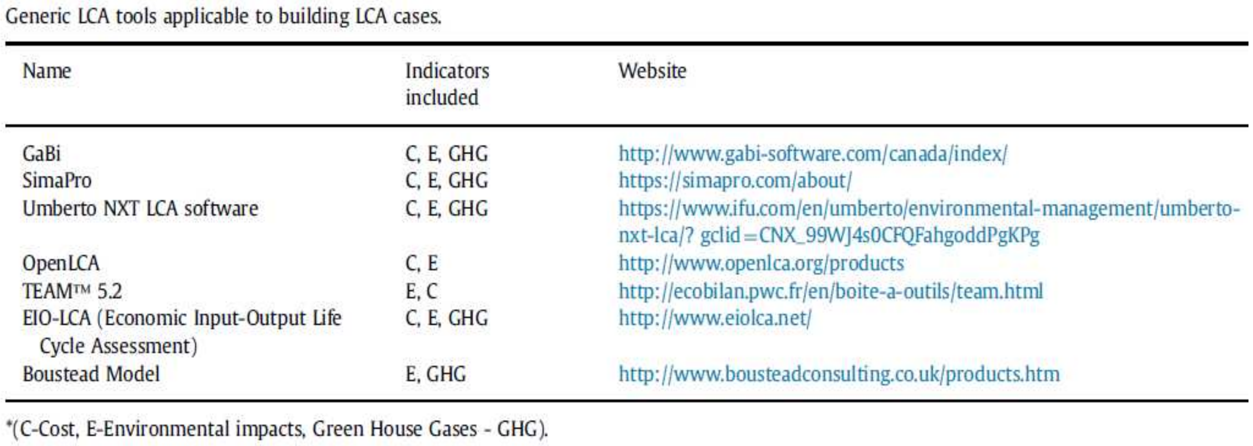


Figure 4: System boundary for precast building project (Ramsey et al., 2014)

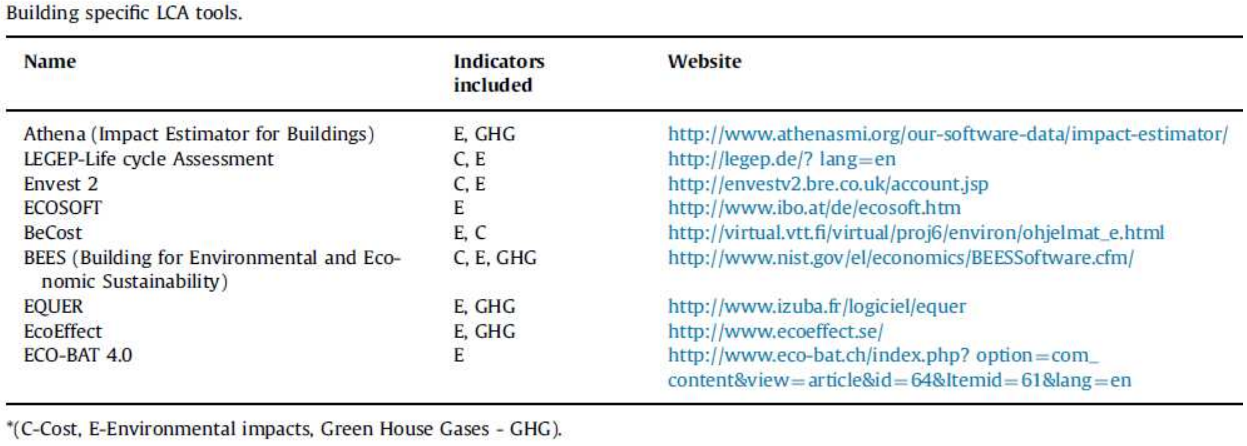
Environmental Impacts (TRACI) impact assessment method to consider global warming potential, acidification, respiratory effects, eutrophication, photochemical smog potential and ozone layer depletion as mid-point indicators (PCI, 2009). Another study on precast have considered water use, abiotic resource depletion, and renewable as well as non-renewable sources for precast commercial buildings (Marceau et al., 2012). Currently, there are various LCIA tools as shown in Figure 5 and Figure 6. Figure 5 shows the generic LCA tools which have been used in the past and Figure 6 focusses on the LCA tools used specifically for buildings' assessment. Environmental indicators like energy (E) and GHG emissions are broadly listed in the above discussed figures. The options of several impact categories for a specific software depends upon the impact assessment methodology available in that software. For instance, Gabi and SimaPro software give several methodological options regarding diverse impact category assessments which can be tailored according to the defined scope and system boundary. Athena and Building for Environmental and Economic Sustainability (BEES) are extensively used for the assessments of buildings. Athena can compare embodied energy, life cycle operation and several environmental impacts which makes it easy to for LCA practitioner to analyze the parameters considered in the study scope. In previous studies, TRACI is used via Open LCA tool to study life cycle assessment of precast concrete structures.


Generic LCA tools applicable to building LCA cases.

Name	Indicators included	Website
GaBi	C, E, GHG	http://www.gabi-software.com/canada/index/
SimaPro	C, E, GHG	https://simapro.com/about/
Umberto NXT LCA software	C, E, GHG	https://www.ifu.com/en/umberto/environmental-management/umberto-nxt-lca/? gclid=CNX_99WJ4s0CFQFahgoddPgKPg
OpenLCA	C, E	http://www.openlca.org/products
TEAM™ 5.2	E, C	http://ecobilan.pwc.fr/en/boite-a-outils/team.html
EIO-LCA (Economic Input-Output Life Cycle Assessment)	C, E, GHG	http://www.eiolca.net/
Boustead Model	E, GHG	http://www.bousteadconsulting.co.uk/products.htm

*(C-Cost, E-Environmental impacts, Green House Gases - GHG).

Figure 5: Generic LCIA tools used for LCA studies (Anand & Amor, 2017)


Building specific LCA tools.

Name	**Indicators included**	**Website**
Athena (Impact Estimator for Buildings)	E, GHG	http://www.athenasmi.org/our-software-data/impact-estimator/
LEGEP-Life cycle Assessment	C, E	http://legep.de/? lang=en
Envest 2	C, E	http://envestv2.bre.co.uk/account.jsp
ECOSOFT	E	http://www.ibo.at/de/ecosoft.htm
BeCost	E, C	http://virtual.vtt.fi/virtual/proj6/environ/ohjelmat_e.html
BEES (Building for Environmental and Economic Sustainability)	C, E, GHG	http://www.nist.gov/el/economics/BEESSoftware.cfm/
EQUER	E, GHG	http://www.izuba.fr/logiciel/equer
EcoEffect	E, GHG	http://www.ecoeffect.se/
ECO-BAT 4.0	E	http://www.eco-bat.ch/index.php? option=com_content&view=article&id=64&Itemid=61&lang=en

*(C-Cost, E-Environmental impacts, Green House Gases - GHG).

Figure 6: Building specific LCA tools (Anand & Amor, 2017)

2.6.2.4.2 Cut-off criteria (excluded impact categories in LCA studies)

Rebound effect in LCA has not been accounted in previous LCA studies in precast concrete industry (Bo P. Weidema, 2008). According to Hertwich (2005), rebound effects acknowledges the fact that any improvements in efficiency results in reduction of cost and increases the chances of demand of that product. Time value of carbon is a crucial factor in life cycle energy assessment which means minimizing GHG emissions to meet the annually set reduction target (Karimpour, Belusko, Xing, & Bruno, 2014). Also, changes due to retrofitting in buildings is less considered for precast concrete buildings however, some studies have been conducted to analyze the prospects of retrofitting in refurbishment of buildings (Nicolae & George-Vlad, 2015; Schwartz, Raslan, & Mumovic, 2015; Tabatabaee, Weil, & Aksamija, 2015).

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. This research will focus on achieving the below discussed research objectives and the next chapter will discuss the methodology to achieve these objectives.

Research Objectives:

1. To evaluate costs and environmental impacts of precast building system 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 which can be used as a framework by research scholars to study the environmental as well as economic impacts and provide a platform for future scope of research.
3. To compare Precast using sandwich panels, cast-in-place and precast without sandwich panel building system in terms of total life cycle impacts and costs.

Chapter 3: 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 envelope to 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).

3.1 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.

3.1.1 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 without sandwich 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.

3.1.1.1 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, as shown 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.

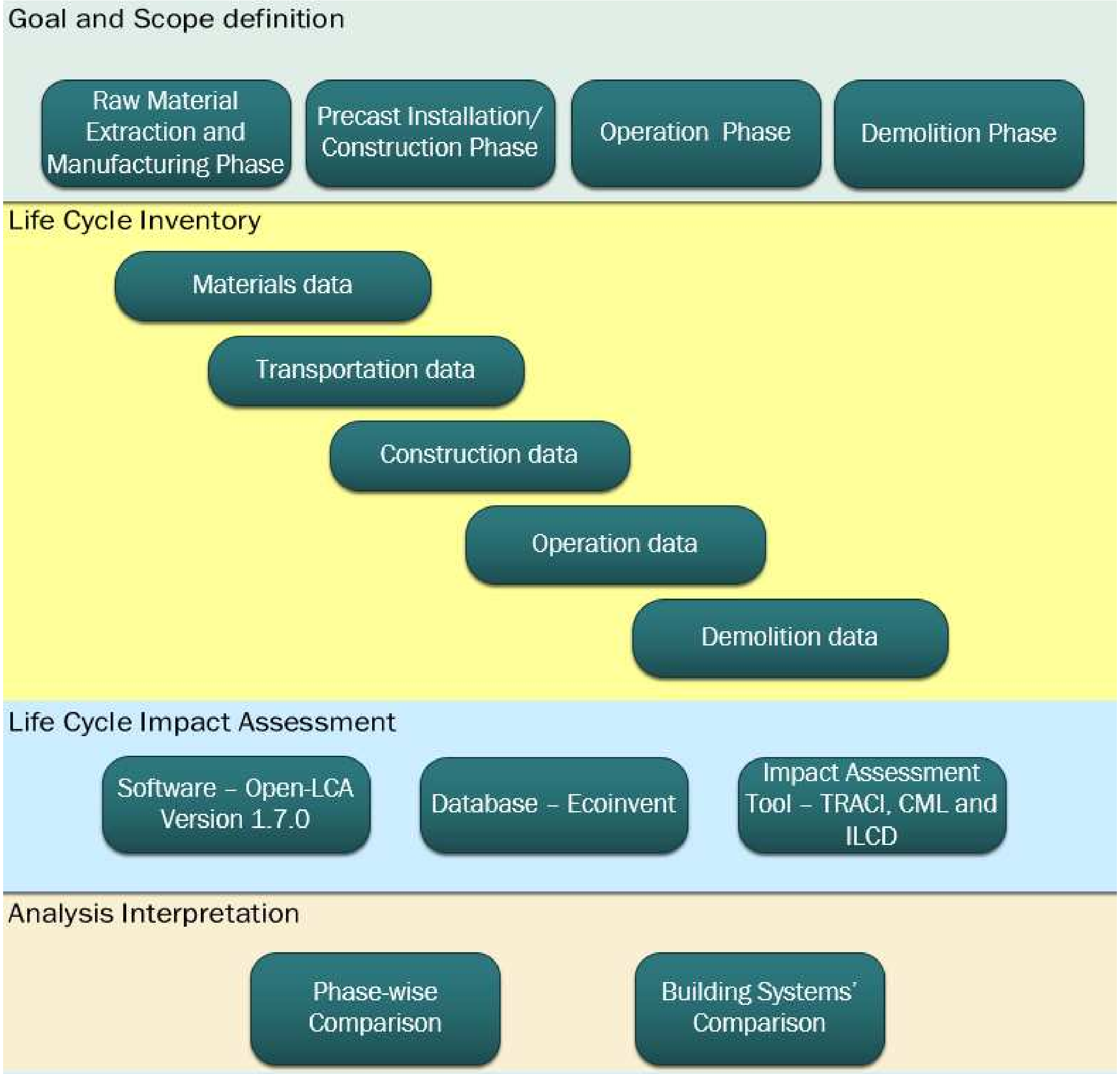


Figure 7: Methodology map

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.

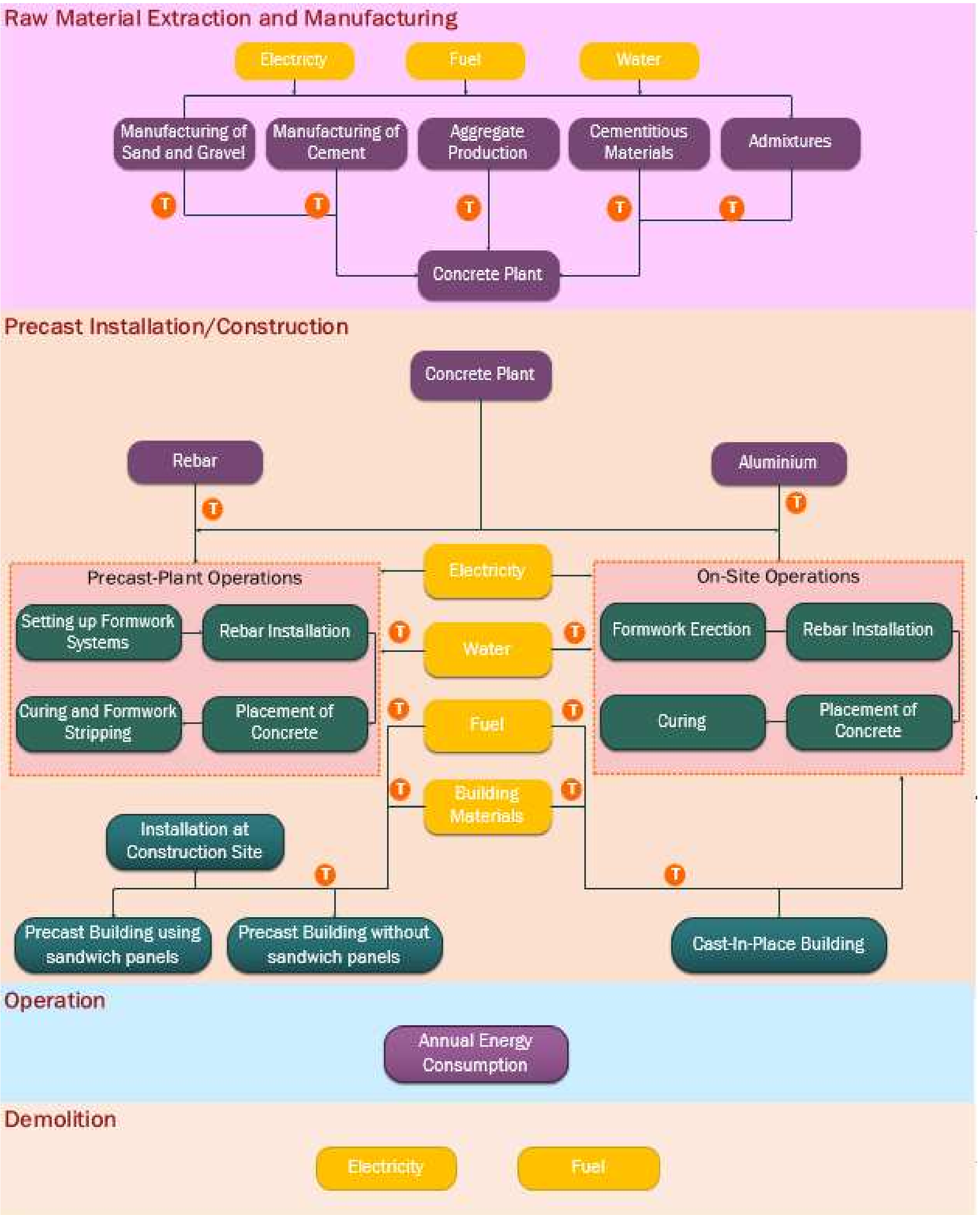


Figure 8: All four phases considered in the research

3.1.1.2 Lifespan

After analyzing the construction phase for both systems, the total annual energy consumption was considered for the operation phase of the building over the life span of 50 years. The lifespan of residential and commercial buildings was assumed to be from 40 to 100 years. Specifically, 50 years has been used by researchers in past LCA studies and the same was adopted for this research as well (Arena & De Rosa, 2003; Kofoworola & Gheewala, 2009; Van Ooteghem & Xu, 2012).

3.1.1.3 Functional unit

This research study set a functional unit of one square feet (1ft^2) of gross floor area (GFA) per year for comparison and future references. The GFA was calculated using the BIM model based upon the total enclosed space meeting the functional requirements of the building. Based on this functional unit, the results determined the environmental impacts and costs per gross square feet of the building.

3.1.2 Life Cycle Inventory (LCI) Analysis

This phase included the data collection and calculations necessary to quantify the costs of processes (LCC) and energy inputs and outputs (LCIA) of a building. Table 1 summarizes the data collection sources for each life cycle phase considered in the system boundary. The data for the building materials was obtained from the bill of quantities (BOQ) and project estimate. The research considered the three main transportation phases in a building life cycle; (1) from resource extraction site to manufacturing plant, (2) from manufacturing plant(s) to construction site and, (3) construction site to disposal facility. The transportation data used for the research was selected from the nearest manufacturer. The construction phase of the building included all the material and energy use for on-site construction activities such as electricity and fuel consumption for construction equipment. This data was collected from general contractor and past literature. Thereafter, the impacts of operation phase were measured in terms of the annual energy consumption. The last phase considered as part of the system boundary was the demolition phase which included on-site demolition activities and transportation of discarded building materials to a landfill. For all phases, OpenLCA software was 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.

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

3.1.3 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).

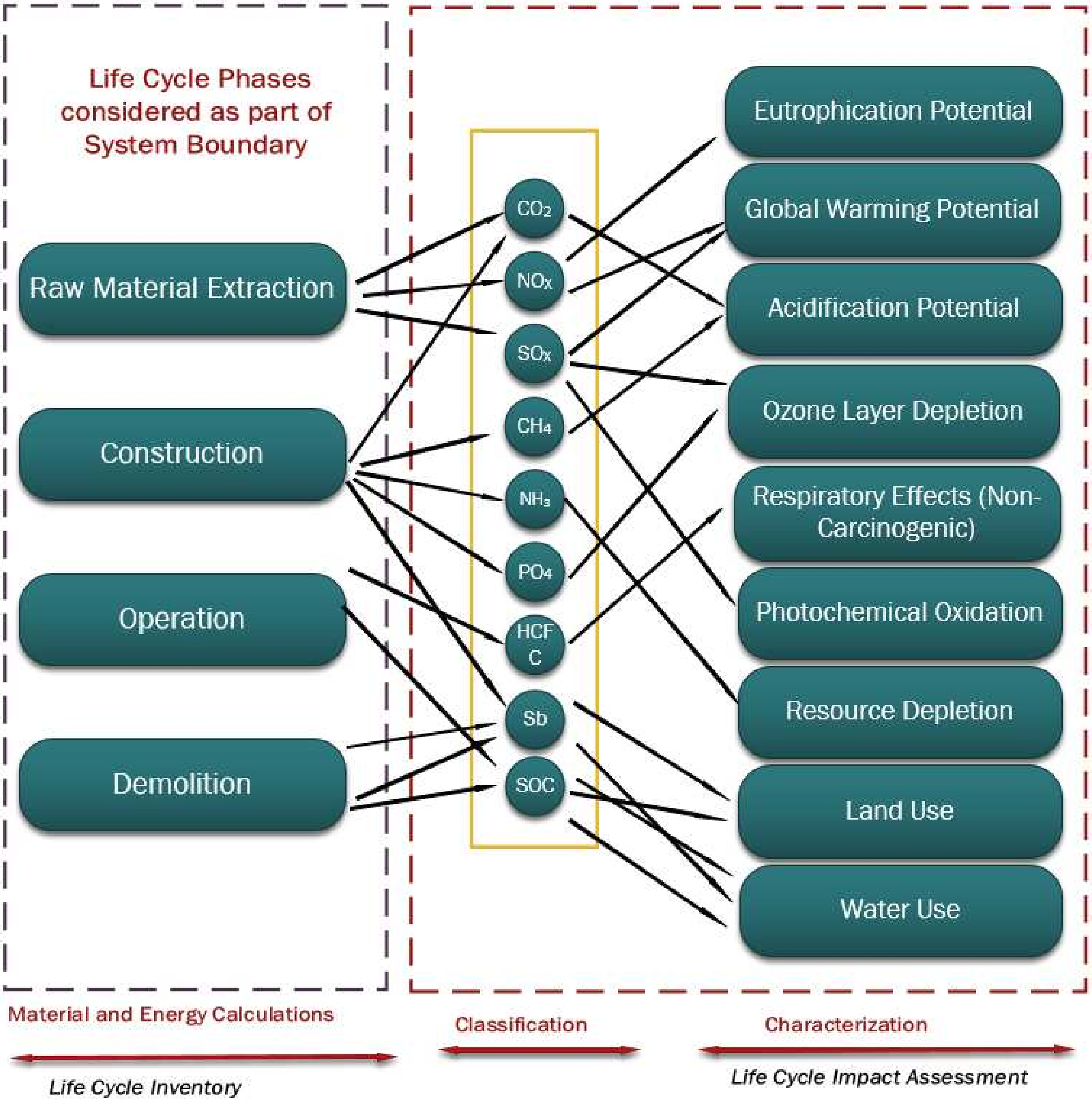


Figure 9: Life Cycle Impact Assessment (LCIA) model

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 was 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 non-carcinogenic respiratory effects, land use and water use effects is done in OpenLCA software (ISO, 2006). These impact categories were specifically assessed since they are the impact categories listed by the United States Environmental Protection Agency (USEPA) as the most impactful ones for assessing the life cycle environmental impacts (Corporation & Curran, 2006). The unit processes considered for each environmental impact indicators are explained below:

3.1.3.1 Environmental impact: Global warming potential (GWP)

Global warming potential was estimated as kilograms of CO_2 equivalent in TRACI. For any quantity and type of greenhouse gas, CO_2-Eq (carbon dioxide Equivalent) can be used as a measure of their global warming potential. During this study, three main contributors were considered for evaluation of global warming impacts resulted from emissions with significant GWP.

- Production of cement clinker: included the whole manufacturing process to produce clinker (raw material provision, grinding and mixing, rotary kiln process); internal processes (transport) and for the infrastructure only the rotary kiln (material consumption) was considered.
- Sinter production of iron: consisted of blending, mixing and sintering operations in the blast furnace to produce pig iron. Water and electricity consumption along with transportation of raw materials were considered however, emissions were abated.

- Hard coal mining operation and preparation: included blasting, mineral extraction, electricity & water consumption and transportation of materials for processing.

3.1.3.2 Environmental impact: Ozone layer depletion

Ozone layer protects from hazardous ultraviolet radiation and its depletion can have adverse effects such as skin cancer to humans and damage to plants. Ozone layer depletion was measured in CFC-11 (Trichlorofluoromethane) equivalent which is degradation of ozone layer due to emissions of trichlorofluoromethane or CFC-11. CFC-11 is far more potent than carbon dioxide and can remain in the atmosphere for significantly longer time. Most of the ozone depletion impact through CFC-11 production came from the petroleum and gas production which included the shore-extraction of petroleum and natural gas (energy use, infrastructure, transport and emissions).

3.1.3.3 Environmental impact: Respiratory effects (non-carcinogenic)

Non-cancerous respiratory effects to humans which is measured in kilograms toluene equivalent (kg toluene- Eq) is comparative human toxicity unit. During the analysis, three major contributors for calculating non-carcinogenic respiratory effects were considered.

- Treatment of brake wear emissions: included the treatment of non-exhaust emissions produced by brake abrasion from road freight transport. The brake wear emissions were to air only and were calculated for 1 kg brake wear. All particulates were accounted for as emissions to air and had particle sizes below 100 um (micrometer).
- Copper Production: consisted of operations such as pre-treatment of the ore, the refining of the material for different construction material and transportation for various technical applications.

- Production of Hot rolling steel: The raw steel production was processed to give greater toughness to it. The processes that were included were scarfing, grinding, heating, descaling, rolling and finishing.

3.1.3.4 Environmental impact: Photochemical oxidation

Photochemical Oxidation has regional as well as local impacts. It increases the frequency of respiratory problems, eye irritation, and decreased visibility when photochemical smog is present in cities. Photochemical oxidation was measured in kilograms nitric oxides equivalent (Kg NOx-Eq) which are mainly nitric oxide (NO) and nitrogen dioxide (NO_2). Four major contributors towards photochemical oxidation were considered.

- Clinker Production: included all operations as previously explained in GWP impact section.
- Heat and power co-generation: included all operations to produce heat and electricity in a co-generation plant where heat is the main product and electricity as a by-product. Key emission factors for NOx (nitrogen oxide), CH4 (methane), and CO (carbon monoxide) were considered.
- Diesel burned in building machines: included inputs such as lubricating oil and fuel consumption, and measured air emissions as output.
- Heat production at 50KW furnace: described the combustion of natural wood chips from forest and included processes were wood requirements, emissions to air, the electricity needed for operations and the disposal of the ashes.

3.1.3.5 Environmental impact: Eutrophication

Eutrophication is defined as a phenomenon when nutrients such as phosphorous and nitrogen enter water bodies, causing oxygen depletion. It was measured in kilograms nitrogen (kg N). The four major contributors towards eutrophication were production of gas, petroleum and cement clinker, diesel burned in building machine, transportation of materials and heat and power co-generation and they are explained above in section 4.1.4.

3.1.3.6 Environmental impact: Resource depletion

Resource depletion was approximately calculated as kilogram of Antimony equivalent (Kg Sb-Eq) which is a measure of the depletion of the nonliving (abiotic) resources. The amount of materials contributing to resource depletion were converted into Kg Sb-Eq. The major contributors towards resource depletion were zinc-lead mine operation, ferronickel production, barite production and tantalum production.

- Zinc-Lead Production: included the raw material extraction processes that included mining operations and transportation.
- Ferronickel production: included the production of 1kg of ferronickel with 25% nickel during processes such as beneficiation of nickel ore, the metallurgy of nickel ore, the mining and metallurgy infrastructure, and the disposal of slag.
- Barite production: Barite was considered as the finished product and it included infrastructure use, energy consumption, and water use and particle emissions as the processes for environmental impacts.

3.1.3.7 Environmental impact: Water use

Water use was measured in cubic meters (m^3) and three contributors were considered to evaluate its environmental impacts. The major contributors are listed below.

- Gravel and Quarry Operation: included mining, infrastructure use, emissions to air, transportation of the multi-output process that yielded co-products as sand and gravel.
- Hot rolling steel production: included the process steps scarfing, grinding heating, descaling, rolling and finishing and did not included the material being rolled.
- Water Supply: included rough estimation for miscellaneous operations such as use of chemicals and emissions for the treatment of water used in industries.

3.1.3.8 Environmental Impact: Acidification Potential

Acidification was measured in kilogram of sulphur dioxides equivalent (Kg SO_2-Eq). Acidification is caused by emissions which increase the acidity (lower pH) of water and soils and contribution to acidification is greatest when the fuels have high level of sulphur. Sulfuric acid was mainly used as a reagent rather than ingredient in operations such as metal processing in factory, mining operations, water-treatment and manufacturing of plasticizers.

3.1.3.9 Environmental impact: Land use

Land Use was measured in loss of soil organic carbon (SOC). SOC is a major indicator if soil health and construction activities lead to increased SOC losses. Onshore drilling operations, gravel and sand quarry operations and wood extraction were considered major contributors to land use and they have been explained in section 4.1.4 and 4.1.8.

3.1.4 Analysis Interpretation

The final step of the research methodology was the application of the framework in case study for three different systems; precast using sandwich panels, cast-in-place and precast without sandwich panels. Two-tiered analysis of environmental impacts and costs of two buildings was performed; (1) Overall comparison and (2) Phase-wise comparison. These comparisons help in understanding the costs and environmental impacts of the two buildings for the complete life cycle of 50 years, impacts for every phase considered (raw material extraction and manufacturing, construction, operation and maintenance and demolition) showing which phase contributes the most. The life cycle environmental impacts of all three building systems, was translated into thresholds per gross square feet per year. Additionally, life cycle environmental impact costs due to GWP, Land use Potential and Water use were also calculated based upon USEPA. The results and discussions of the analysis is explained in detail in Chapter 4: Results and Discussions.

Chapter 4: Results and Discussion

4.1 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.

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 systems was compared with established benchmarks. In addition, environmental impact costs of GWP, land use potential and water use were calculated and compared.

4.1.1 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 life cycle environmental impacts and costs of all four phases.

4.1.1.1 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 planning, design and purchasing of land) (NIST, 1995). Thus, these initial investment costs of raw materials were considered as present value costs as these project costs occur before the operation phase of building. The annualized life cycle costs associated with three building systems were calculated as in ×P

Where, A= annualized costs, d = discount rate and n = life span of building, P = present costs

Equation 1(Park, Kim, & Choi, 2007).

$$A = \frac{d(1+d)^n}{(1+d)^n - 1} \times P$$

Where, A= annualized costs, d = discount rate and n = life span of building, P = present costs
Equation 1. Annualized life cycle costs calculation

4.1.1.1.1 Precast using sandwich panels

The associated costs during raw material extraction and manufacturing phase for precast building systems were mostly due to the raw materials required to produce concrete. The total costs associated with raw material extraction and manufacturing phase, considering the unit processes included in the system boundary was \$662,500. The life cycle costs per year of whole building for this phase was calculated as \$48,004.65. This annualized cost calculated using Equation 1 had a discount rate of 7 % which was the current value recommended in Life Cycle Costing Manual developed by NIST. Table 1 shows the impacts of the various environmental impacts per gross square feet per year for raw material extraction and manufacturing phase. The environmental impacts towards nine indicators had a large variance from the mean value and therefore, the authors decided to represent the impacts in log values. As shown in Table 2, this phase's GWP is 0.32 Kg CO_2-Eq which was majorly attributed to the production of cement clinker, sinter production of iron ore and hard coal. Particularly, the portland cement's related mining, transportation and processing had the highest impacts as a raw material during the extraction phase. The transportation of raw materials from mining and quarrying sites to factories and construction sites contributed towards 1.15 Kg toluene-Eq (transformed log values as shown in Figure 10). Emissions from clinker production and sinter production operations in the blast furnaces contributed towards 8.4E-04 Kg NOx-Eq. Water consumption in processing the materials in the factories contributed towards about 6.40E-04 M^3. Raw material extraction phase also included several mining operations for sand, gravel and aggregates which affected the organic matter content of soil and contributed towards Land Use Potential impact, expressed in terms of 1.118 Kg SOC.

4.1.1.1.2 Cast-in-place

The unit processes included in the system boundary for raw material extraction phase of cast in place building system were similar to precast using sandwich panels. The associated costs during raw material extraction and manufacturing phase were due to the raw materials considered in the system boundary. The total costs associated with raw material extraction and manufacturing phase, considering the unit processes included in the system boundary was \$718,750. The life cycle costs per year of whole building for this phase was calculated as \$52,080. This annualized cost calculated using Equation 1 had a discount rate of 7 % which was the current value recommended in Life Cycle Costing Manual developed by NIST. The higher costs for cast-in-place building systems compared to precast was due to different quantity of raw materials. Table 2 shows the impacts of various environmental impacts (transformed log values as shown in Figure 10) per GSF/year for raw material extraction and manufacturing phase. Both direct and indirect carbon emissions originating from the energy consumption during on-site and off-site activities (such as mining, processing and transportation) as well as upstream and downstream processes were the reason for 0.44 Kg CO_2-Eq of Global Warming Potential. This phase also included several mining operations for sand, gravel and aggregates. These operations affected the organic matter content of soil and contributed towards Land Use Potential, expressed in terms of 1.23 Kg SOC. 1.48 Kg toluene-Eq non-carcinogenic respiratory effects were due to the transportation of raw materials to industries and then to construction sites. As illustrated in Table 2, the marginally greater environmental impacts (transformed log values as shown in Figure 10) and costs for cast-in-place building compared to precast building system were due to the different quantities of raw materials required for cast-in-place building system. In addition, the transportation cost of raw materials to the concrete batching plant and then to construction site was more for cast-in-place building in comparison to precast plant, which incurred additional costs.

4.1.1.1.3 Precast without sandwich panels

This building system was different to precast with sandwich panels in terms of exterior insulation only and thus the system boundary for raw material extraction and manufacturing phase was same for both the building systems. For example, the type and quantity of raw materials required to produce 1 cubic yard of concrete were same and thus, the environmental impacts for both the building systems were same but vary with cast-in-place building system. The total costs associated with raw material extraction and manufacturing phase, considering the unit processes included in the system boundary was $662,500. The life cycle costs per year of whole building for this phase was calculated as $48,004.65. This annualized cost calculated using Equation 1 had a discount rate of 7 % which was the current value recommended in Life Cycle Costing Manual developed by NIST. The total environmental impacts per GSF/year associated with this phase are illustrated in Table 2 and their transformed log values are shown in Figure 10.

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 CO_2-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 NO_x-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 SO_2-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

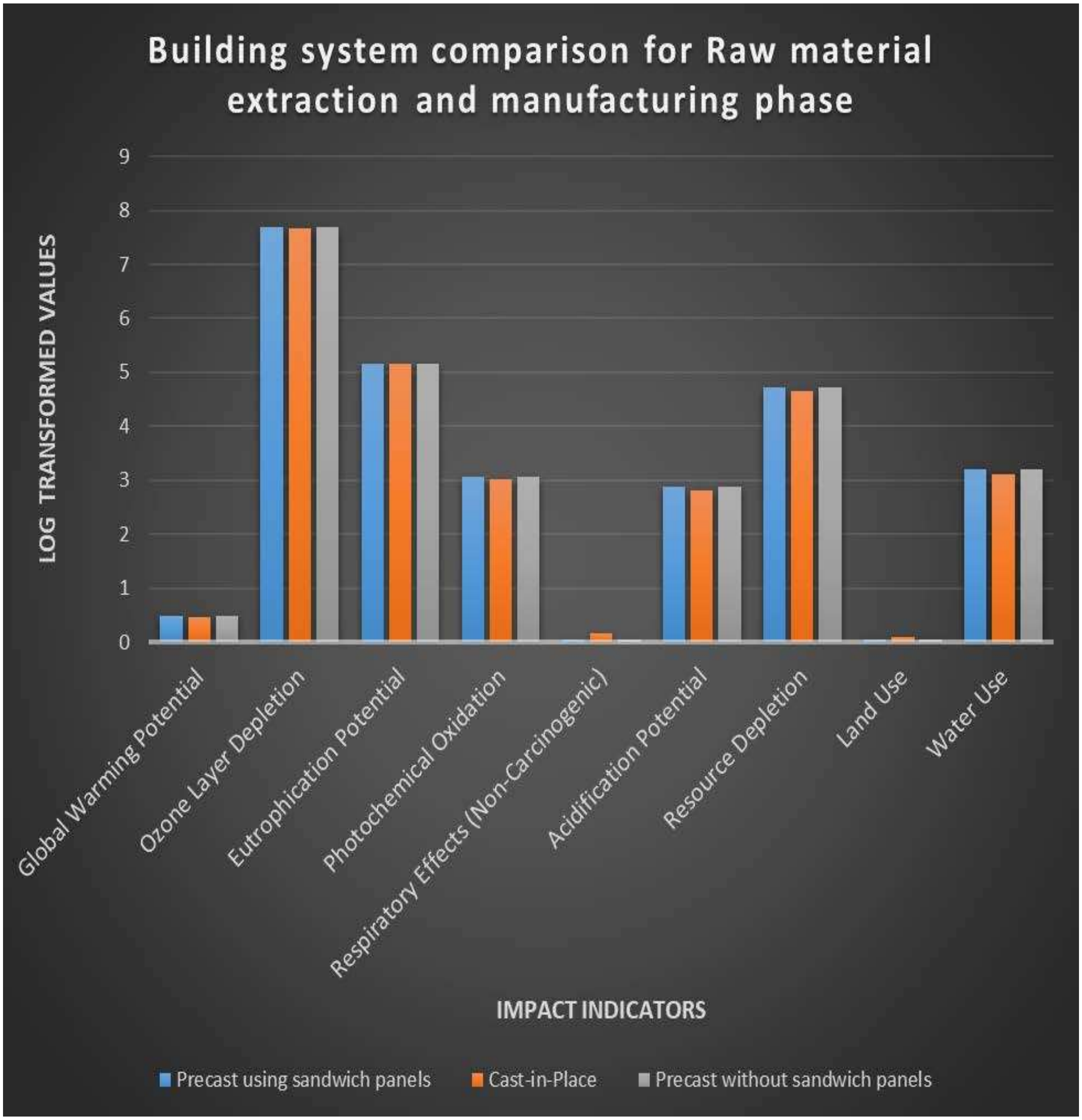


Figure 10: Building system comparison of raw material extraction and manufacturing phase

4.1.1.2. Precast Installation and Construction phase

The installation phase of a precast and precast with sandwich panel building system involved transportation of precast components and installation equipment as the predominant unit processes included in the system boundary. The major resource consumption for installation equipment during precast installation phase were diesel (liters) and electricity (kWh). However, the cast-in-place building system included many on-site construction activities which contributed towards the environmental impacts and its associated costs. Using similar calculation through Equation 1 and OpenLCA outputs, the annualized life cycle costs for installation and construction phase were obtained and the life cycle environmental impacts and costs were calculated respectively.

4.1.1.2.1 Precast using sandwich panels

Table 3 describes the total environmental impacts per GSF/year for all unit processes considered in the system boundary for the three different systems. Similar representation of environmental impacts through log transformed values were done in Figure 11. Precast concrete was produced in a nearby plant situated 22 miles from the project site. The precast units' transportation was the major factor in contributing towards emissions with a Global Warming Potential of 4.39E-03 Kg CO_2-Eq. However, this GWP (transformed log values as shown in Figure 11) was 41% lower than the GWP for the cast-in-place building system and thus have a lower impact towards environment. In addition, construction equipment such as gantry cranes, forklifts, travel lifts, welding and grouting machines used for the installation of precast components contributed towards 0.071 non-carcinogenic respiratory effects which was 29% lower than cast-in-place building system too. The constant fuel consumption in terms of diesel, natural gas and electricity throughout the precast installation phase accounted for the non-carcinogenic respiratory effects, which were quantified as 0.071 Kg Toluene-Eq. The off-site precast plant operations for constructing building components contributed to about more than 60% lower photochemical oxidation potential compared to cast-in-place building system was expressed in Kg NO_x-Eq. The transportation of precast components from precast plant to construction site, use of construction equipment such as gantry cranes to install the building components and welding and grouting machines were the major construction related operations that contributed towards life cycle costs. The total costs associated with precast installation phase, considering the unit processes included in the system boundary was $234,210. The life cycle costs per year of whole building for this phase was calculated as $16,970.82. This annualized cost calculated using Equation 1 had a discount rate of 7 % which was the current value recommended in Life Cycle Costing Manual developed by NIST.

4.1.1.2.2 Cast-in-place

The environmental impacts and associated costs due to the energy consumption of all unit processes were considered for construction phase of cast-in-place building system. Since, construction phase consisted of several on-site activities (erection of formwork, laying reinforcement, pouring and curing concrete), the environmental impacts and associated costs were significant. The total costs associated with construction phase was $382,700. The annualized costs obtained using Equation 1 were $27,730.38. It was 39% higher than precast using sandwich panel building systems due to greater on-site construction activities, therefore stating that precast methodology is less expensive compared to cast-in-place. Table 3 shows the impacts of various environmental impacts per GSF/year for construction phase. Figure 11 represents the transformed log values of environmental impacts for three building systems. The cast-in-place system has considerably greater environmental impacts towards all impact indicators as compared to other two building systems. The on-site construction activities for cast-in-place were major sources of GHG emissions, photochemical oxidation and non-carcinogenic respiratory effects, mainly due to energy consumption (in terms of natural gas, electricity and diesel) in heavy equipment and material transportation. The life cycle of construction phase using cast-in-place was more than precast installation as the latter involves the erection of precast members according to planned sequence followed by connections to provide structural stability. Thus, the associated environmental impacts and costs were found to be significantly more using cast-in-place methodology (transformed log values as shown in Figure 11). For example, both precast and cast-in-place had considerable environmental impacts towards non-carcinogenic respiratory effects but due to greater on-site construction activities as compared to precast installation, 0.10 Kg toluene-Eq of respiratory effects were recorded for cast-in-place which was 29% more than precast using sandwich panels. There was about 62% higher photochemical oxidation for cast-in-place than precast with sandwich panels due to fuel burnt while using heavy construction equipment for on-site operations. In addition, all the upstream and downstream processes of using and transforming the land for constructing the building contributed towards 5.6 Kg SOC land use potential.

4.1.1.2.3 Precast without sandwich panels

Precast without sandwich panels are installed in the same manner as precast sandwich panels. Thus, no additional costs with regards to precast sandwich panels were incurred for the transportation of precast panels without sandwich panels and the annualized life cycle costs for this phase were calculated as $16,970.82 The environmental impacts associated with the installation phase were also similar to the precast using sandwich panels since the methodology of installing the precast components after transportation from precast plant was same. The total life cycle environmental impacts per GSF/year for precast without sandwich panel building system are illustrated in Table 3.

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

S.NO	Environmental Impact Indicators	Units	Precast using sandwich panels	Cast-in-Place	Precast without sandwich panels
1	Global Warming Potential	Kg CO_2-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 NO_x-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 SO_2-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

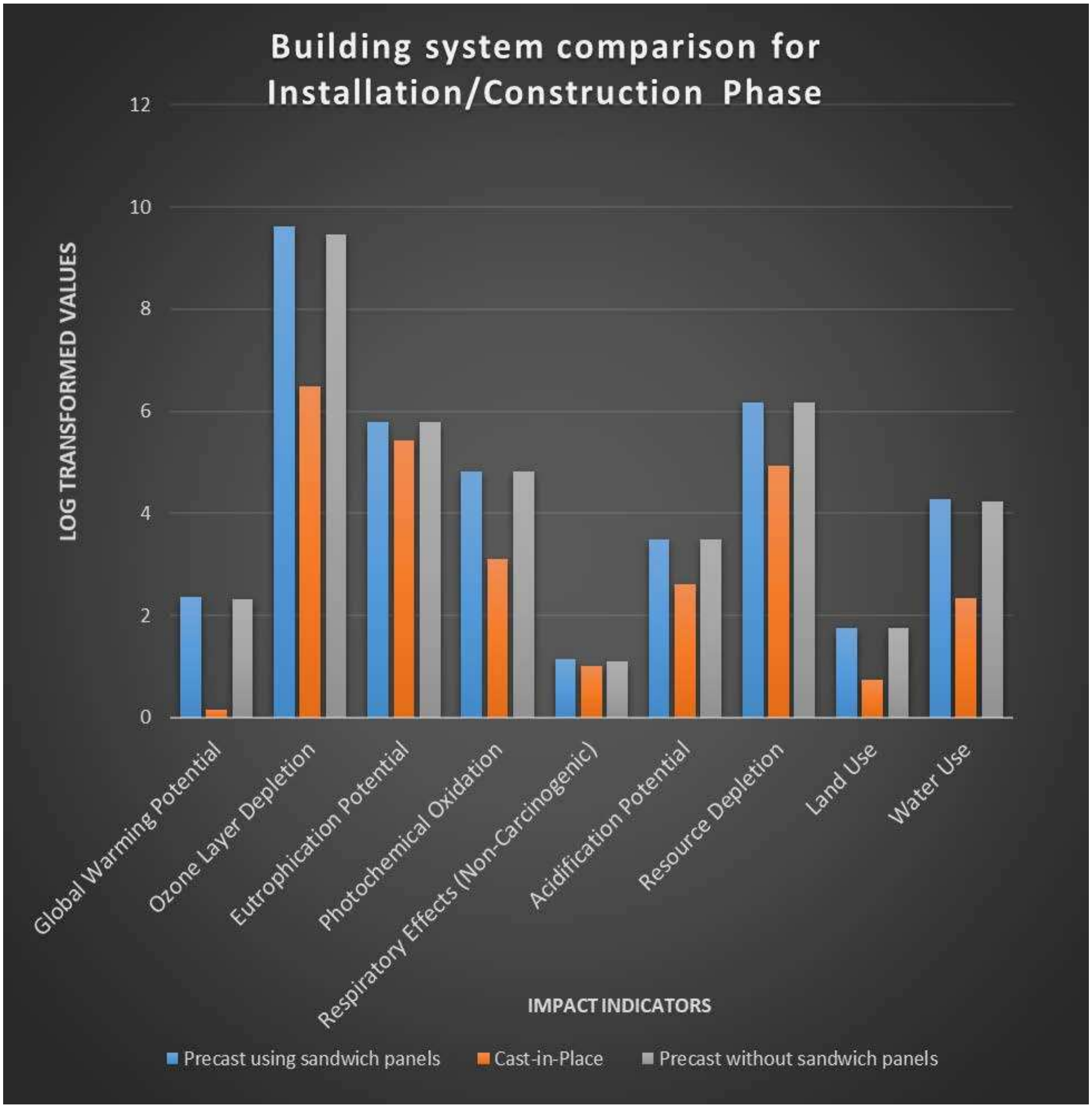


Figure 11: Building system comparison of installation/construction phase

4.1.1.3 Operation phase

The operation phase of all three building systems constituted the major part of their life cycle and thus, had the largest environmental impacts as well as costs associated with it. The annual energy consumption for all three building systems were calculated by creating energy models to calculate the life cycle costs and further explained in detail below.

4.1.1.3.1 Precast with sandwich panels

The annual energy consumption was calculated by performing energy modeling using Insight plugin on Revit which resulted in annual energy consumption of 53.6 kbtu/sqft/year. The energy modeling results were compared with ASHRAE – Standard 90.1.2016 (Laboratory, 2017). According to ASHRAE – Standard 90.1.2016, a medium office building of 53628 square feet has 88.2 kbtu/ft^2/year and thus, the baseline building had considerably lower value in comparison with national average. The purpose of performing energy modeling was to observe the difference in annual energy consumption for the three different building systems and thus the BIM model (as shown in Figure 12). The energy models were also run through industry experts and compared with ASHRAE – Standard 90.1.2016 (Laboratory, 2017). The annual energy consumption for this building system (Precast Sandwiched panels) was found to be under the national average. Based upon average electricity ($0.124/kWh) and natural gas ($7.84 per 1000 cubic feet) (Administration, 2020) rates for commercial buildings, life cycle costs of the precast building system was calculated as $0.90/GSF which resulted in $27,900 in annual energy consumption for the whole building (31,000 GSF). Since, the operation costs are considered as future costs in LCC (NIST, 1995), the annualized present value of LCC for operation phase using 7.0 % discount rate was calculated at $348,750. The transformed log values in Figure 13 illustrates that, the use of energy consumption in terms of natural gas, diesel and electricity were contributing to significant non-carcinogenic respiratory effects, global warming potential, acidification potential, and land use. These impacts were noticeably higher than raw material extracting and manufacturing and installation phase. As illustrated in Table 4, 4.91 Kg SOC of loss of land use potential and 1.82E-04 Kg NO_x-Eq of photochemical oxidation was because operation use constitutes major percentage of the complete life cycle of the building. In addition, environmental impacts contributing towards global warming potential and non-carcinogenic respiratory effects were 0.423 Kg CO_2 Eq and 1.25 Toluene Eq respectively. The total environmental impacts per GSF/year associated with this phase are illustrated in Table 4.

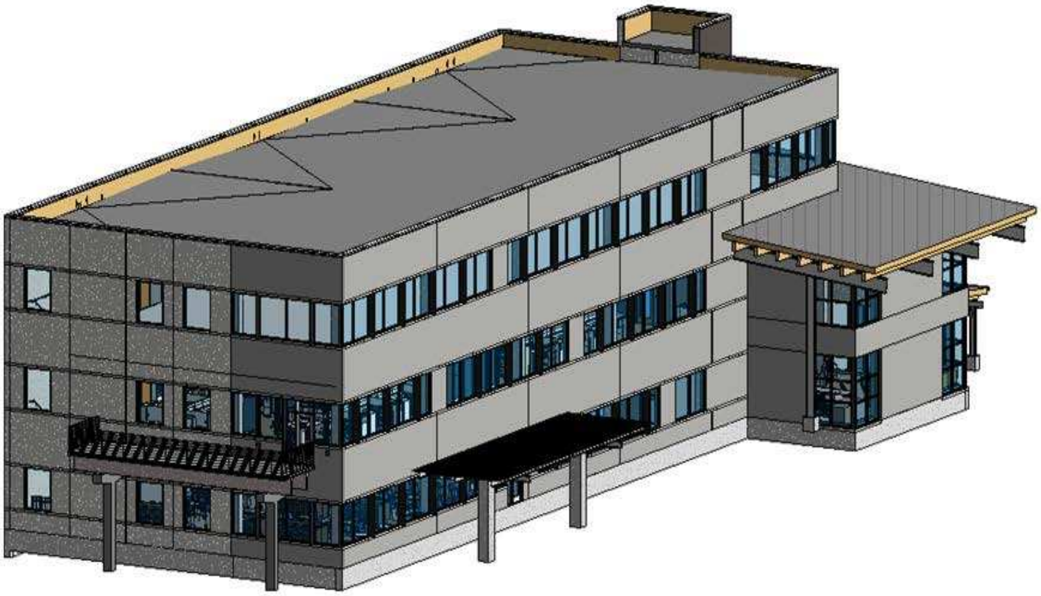


Figure 12: BIM model of precast using sandwich panels

4.1.1.3.2 Cast-in-place

The operation phase constitutes major part of its life cycle and thus, had largest environmental impacts as well as costs associated with it. The annual energy consumption was calculated by performing energy modeling using Insight plugin on Revit and it was 58 kbtu/sqft/year. Though, it was greater than precast using sandwich panels but was still lower than the national average of 88.2kbtu/ft^2/yr. Based upon average electricity ($0.124/kWh) and natural gas ($7.84 per 1000 cubic feet) (Administration, 2020) rates for commercial buildings, life cycle of the cast-in-place building system was calculated as \$1.18/GSF, which resulted in \$36,580 in annual energy consumption for the whole building (31,000 GSF). Since, the operation costs are considered as future costs in LCC (NIST, 1995), the annualized present value of LCC for operation phase using 7.0 % discount rate was calculated as \$457,250. There were considerable environmental impacts towards all nine environmental impact indicators (transformed log values as shown in Figure 13). The use of energy consumption in terms of natural gas, diesel and electricity were contributing towards non-carcinogenic respiratory effects, GWP, and acidification potential and land use. As illustrated in Table 4, 0.139 Kg SOC of loss of land use potential was because operation use constitutes about 70-80% of the complete life cycle of the building. In addition, environmental impacts contributing towards global warming potential (0.47 Kg CO_2 Eq) and non-carcinogenic respiratory effects (0.128 Toluene Eq) were also significant due to longest life cycle of operation use phase. The total environmental impacts per GSF/year associated with this phase are illustrated in Table 4.

4.1.1.3.3 Precast without sandwich panels

The environmental and economic impacts for operation use was similar if not exactly same in comparison with precast without sandwich panels. The annual energy consumption was calculated by performing energy modeling using Insight plugin on Revit and it was found to be 54.5 kbtu/sqft/year. It was greater than precast using sandwich panels since sandwich panels offers better insulation. Life cycle costs per GSF/year of the precast building was calculated as \$0.95 which was lower in comparison with cast-in-place building system. Thus, the annual energy consumption for the whole building of 31,000 GSF was \$29,580. Since, the operation costs are considered as future costs in LCC (NIST, 1995), the annualized present value of LCC for operation phase using 7.0 % discount rate was calculated as \$367,500. The life cycle costs were slightly more in comparison with precast using sandwich panels as using sandwich panels gives better insulation and it has a positive impact over the life cycle of building. All environmental impact indicators were significant contributors towards environmental impacts, and they are represented as transformed log values in Figure 13. The significant impacts towards non-carcinogenic respiratory effects, global warming potential and acidification were due to the energy consumption in terms of natural gas, electricity and diesel.

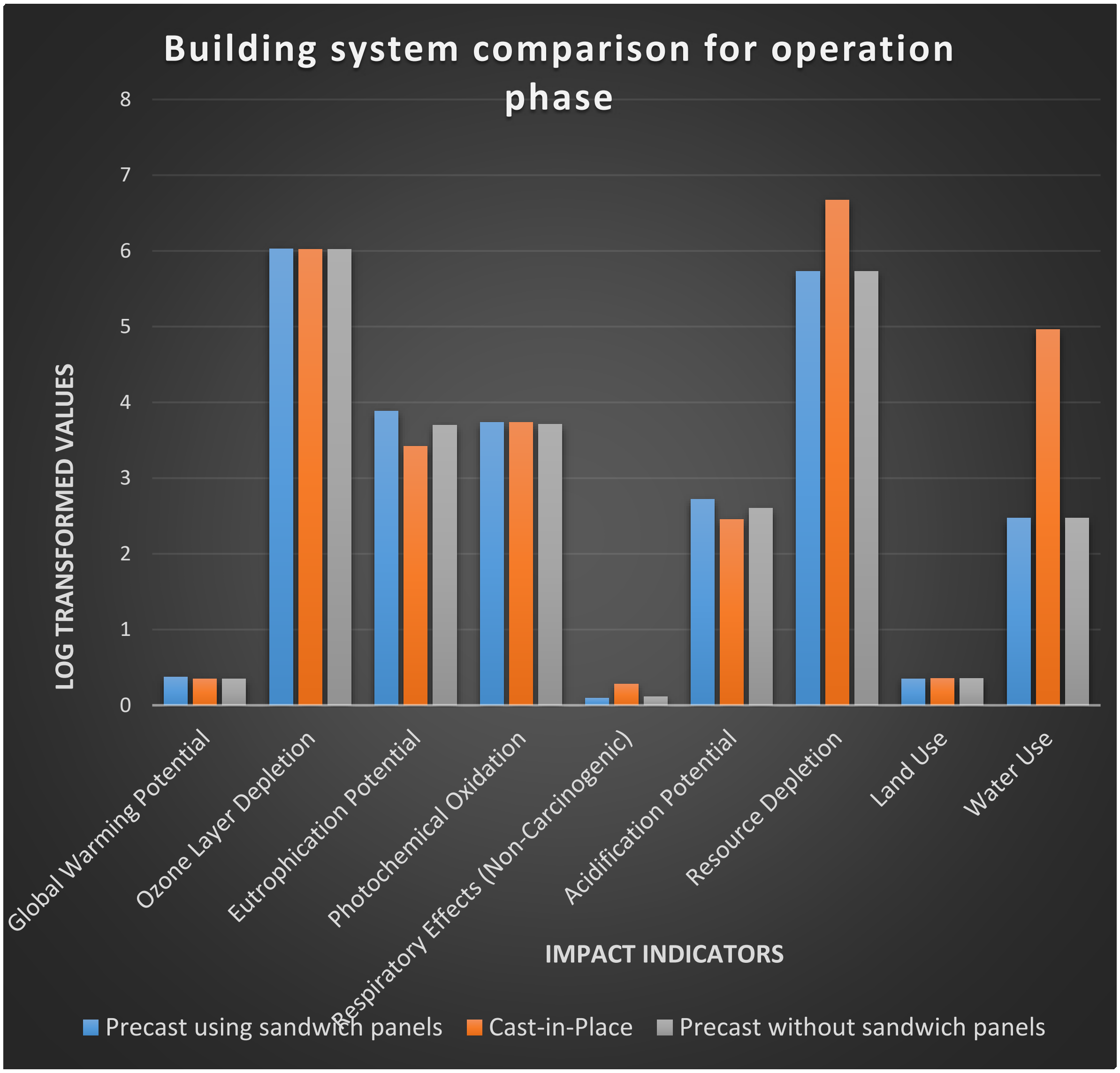


Figure 13: Building system comparison of operation use

Table 4: Environmental Impacts for Three Building Systems During Operation Phase

S.NO	Environmental Impact Indicators	Units	Precast using sandwich panels	Cast-in-Place	Precast without sandwich panels
1	Global Warming Potential	Kg CO_2-Eq	0.423	0.45	4.50E-01
2	Ozone Layer Depletion	Kg CFC-11-Eq	9.42E-07	9.50E-07	9.45E-07
3	Eutrophication Potential	Kg N	1.30E-04	3.77E-04	2.00E-04
4	Photochemical Oxidation	Kg NO_x-Eq	1.82E-04	1.84E-03	1.95E-03
5	Respiratory Effects (Non-Carcinogenic)	Kg toluene-Eq	1.25	1.9	1.30E+00
6	Acidification Potential	Kg SO_2-Eq	0.0019	3.50E-03	2.50E-03
7	Resource Depletion	Kg Sb-Eq	1.86E-06	2.13E-07	1.86E-06
8	Land Use	Kg SOC	2.26	5.6	2.26E+00
9	Water Use	M^3	5.37E-03	4.50E-03	3.36E-03

4.1.1.4 Demolition Phase

The demolition phase constituted the smallest percentage of the complete life cycle of the building. All the unit processes that included demolishing the three building systems and transportation of building components to landfill sites were considered in the system boundary. No further recycling of the debris was considered in the research scope. The annualized life cycle costs were calculated assuming there was no change in general prices – no inflation and deflation when the demolition was performed at the end of 50 years. The total environmental impacts and costs associated with all the three building systems for demolition phase are discussed below.

4.1.1.4.1 Precast using sandwich panels

The total costs associated with demolition phase, considering the unit processes included in the system boundary was \$189,304.60. The life cycle costs per year of whole building for this phase was calculated as \$13,717. This annualized cost calculated using Equation 1 had a discount rate of 7 % which was the current value recommended in Life Cycle Costing Manual developed by NIST. The environmental impacts contributing to land use potential was 0.064 Kg SOC. The major contributor for land use potential was upstream and downstream processes included for preparing those land fill sites. As illustrated in Table 5, environmental impacts towards photochemical oxidation and GWP were 6.5E-04 Kg NO_x-Eq and 0.02 Kg CO_2-Eq per GSF/year respectively. This was prominently due to transportation of precast components to land fill sites and the use of the land for storage of those components for future use. In addition, the use of heavy machinery (such as hydraulic excavators and bulldozers) to demolish the building safely, subsequent transportation to landfill sites and uncontrollable emissions to air were also prominent factors (Anuranjita, 2017). This led to 6.5E-04 Kg NO_x-Eq of photochemical oxidation. The transformed log values are shown in Figure 14, which represents lower environmental impacts compared to cast-in-place building system. This explains that even when precast building system is demolished for new construction, the demolition will still be environmentally friendly as compared to cast-in-place building systems.

4.1.1.4.2 Cast-in-place

The demolition phase constitutes the smallest percentage of the complete life cycle of the building. The total life cycle costs of demolition phase for cast-in-place building system was \$243,020.46. Same discount rate of 7% was used to calculate the annualized life cycle costs and it was \$17,609.23. This phase contributed towards 0.07 Kg SOC. This was majorly due to transportation of precast components to land fill sites and the use of the land for storage of those components. Cast-in-place building system had marginally higher GWP and photochemical oxidation as 0.028 Kg CO_2-Eq and 6.80E-04 Kg NO_x-Eq respectively (transformed log values as shown in Figure 14) compared to precast building systems since, the demolition phase was of cast-in-place system was longer than precast building system. In addition, the demolition phase for cast-in-place system had greater dust and air emissions in form of hydrocarbons, oxides of sulphur and carbon monoxide which led to GWP and photochemical oxidation.

4.1.1.4.3 Precast without sandwich panels

The environmental impacts and costs associated with demolition phase of precast without sandwich panels were same in comparison with precast using sandwich panels. The annualized life cycle costs for demolition phase were calculated as $13,717. The environmental impact contributing towards land use potential was 0.07 Kg SOC because this phase entailed transportation of precast members to landfill sites and subsequent use of land for storage of these components. The other environmental impacts for demolition phase was similar to precast building systems, however, was lower than cast-in-place. The transformed log values of environmental impacts per GSF/year are represented in Figure 14.

Table 5: Total Environmental Impacts During Demolition Phase for all Three Building Systems

S.NO	Environmental Impact Indicators	Units	Precast using sandwich panels	Cast-in-Place	Precast without sandwich panels
1	Global Warming Potential	Kg CO_2-Eq	0.02	0.028	2.20E-02
2	Ozone Layer Depletion	Kg CFC-11-Eq	4.56E-09	4.58E-09	4.60E-10
3	Eutrophication Potential	Kg N	1.39E-05	1.41E-05	1.40E-05
4	Photochemical Oxidation	Kg NO_x-Eq	6.5E-04	6.80E-04	7.20E-04
5	Respiratory Effects (Non-Carcinogenic)	Kg toluene-Eq	3.0E-05	3.20E-04	8.00E-05
6	Acidification Potential	Kg SO_2-Eq	1.4E-03	1.50E-03	1.50E-03
7	Resource Depletion	Kg Sb-Eq	1.87E-07	3.400E-07	1.90E-07
8	Land Use	Kg SOC	0.064	0.07	7.00E-02
9	Water Use	M^3	8.23E-07	8.24E-06	8.23E-07

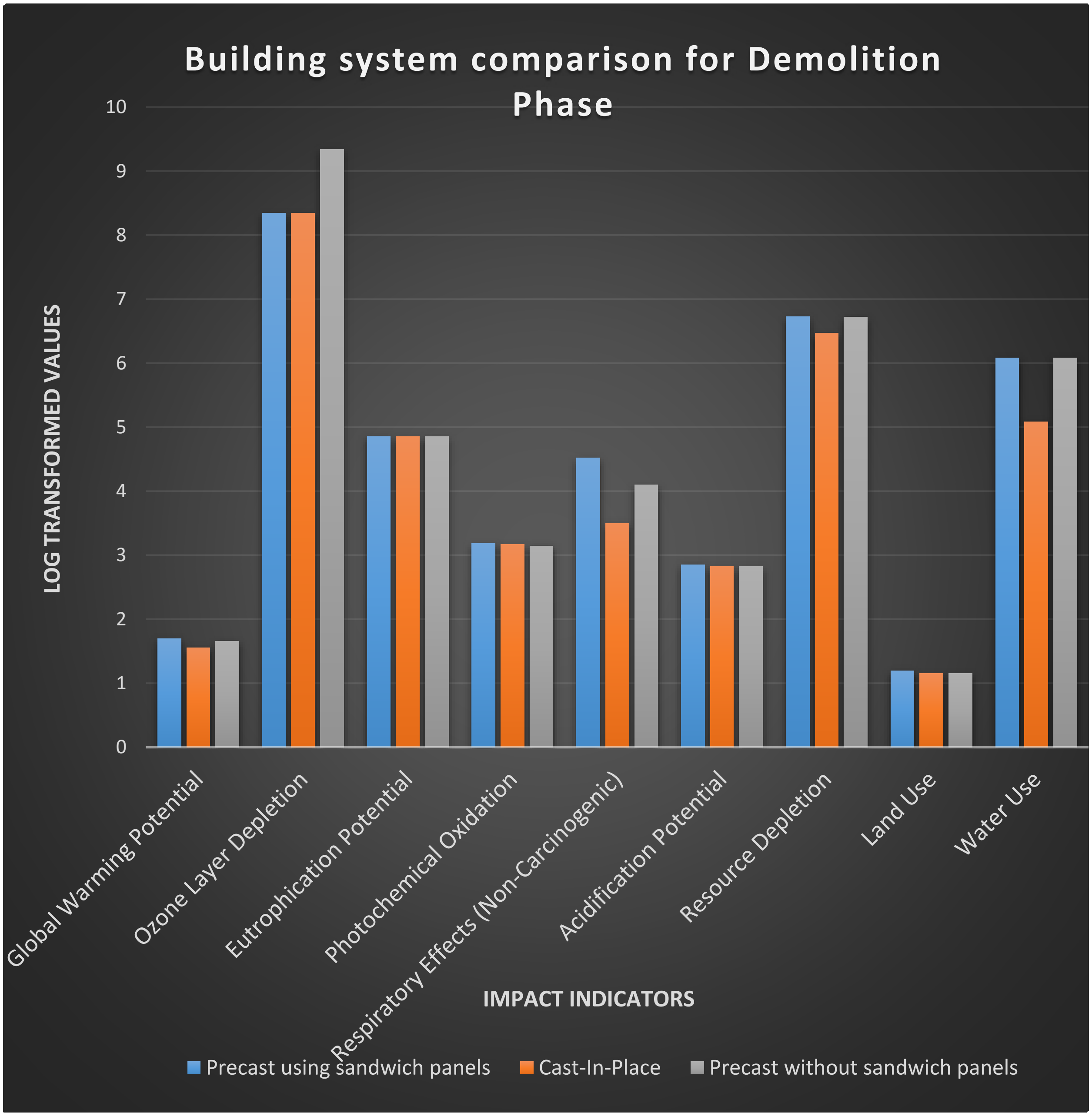


Figure 14: Building system comparison of demolition use

4.1.2 Complete Life Cycle Environmental Impacts and Costs Comparison of Three Building Systems

The total life cycle environmental impacts and costs associated with all three building systems were compared. There was significant difference in environmental impacts and costs between precast using sandwich panels and cast-in-place building system. The total life cycle environmental impacts for the three building systems are illustrated in Table 6. Global warming potential was more than 48 % lower for precast in comparison to cast-in-place building system and it was mostly due to installation/construction phase as precast offers lesser environmental impacts with respect to onsite construction activities. The precast plant used for this research study was 22 miles away from the construction site and the environmental impacts due to the transportation of precast components from precast plant to construction will vary from project to project. About 23% higher water use was observed for the cast-in-place system due to on-site casting and curing operations of cast-in-place components. The construction phase for cast-in-place was longer than the installation phase for the precast system which resulted in 29% higher non-carcinogenic respiratory effects. Moreover, the air emission due to fuel burnt in on-site heavy construction equipment resulted in 35% greater photochemical oxidation. The marginal differences observed for precast using sandwich panels and precast without sandwich panels towards GWP and Acidification Potential were 3% and 6%. However, cast-in-place building system had 27% higher non-carcinogenic respiratory effects and 44% higher GWP. These were majorly due to the higher impacts in operation phase. The LCC for cast-in-place building system was 21% higher than precast using sandwich panel building system. The construction phase and operation phase of precast using sandwich panel building system had 38 % and 24% lower LCC compared to cast-in-place building systems. However, precast without sandwich panels had marginally higher (3%) LCC in comparison with precast with sandwich panels. Thus, the total life cycle environmental impacts and costs for precast using sandwich panel building system was lowest compared to other two building systems.

The authors have compared the environmental impacts according to specific benchmarks. For instance, USEPA has State Inventory Tool which is updated till 2017 to monitor various environmental impacts for all the states across United States of America (USEPA, 2020). However, USEPA does not provide benchmarks for all the environmental impacts indicators considered in this research which could not be translated into thresholds per gross square feet of building for the state of Colorado. This was found to be one of the main reasons where various past studies have failed to cite any standard benchmarks and have compared the results relatively within their research. (Dong et al., 2015; Ji et al.; Marceau et al., 2012). However, this research strived to compare the GHG emissions of three systems with the Climate Mobilization Act passed by New York City Council in April 2019. The Act established limits on greenhouse gas emissions for buildings over 25,000 square feet and aimed at reducing greenhouse gas emissions to 40% by 2025 and 50% by 2030 (Government, 2019). The GHG emissions per occupancy classification is shown in Table 7 and all the three building systems were under the threshold limit of 8.46 Kg CO_2-Eq. The least emissions among the three building systems was for precast using sandwich panels, which had 0.76 Kg CO_2-Eq per year/GSF.

Additionally, the authors also calculated the environmental impact costs of land use potential, GWP and water use. According to United Nations (UN) Sustainable Development Goals (SDGs)(Keesstra et al., 2016) and ecosystem services framework (Wood et al., 2018), these environmental impacts effect the climate change and well-being globally. Thus, authors calculated the environmental impact costs due to land use potential, GWP and water use. The GWP and Land use potential was measured in social cost of carbon (damage done by carbon dioxide emissions in one year) and water use in Kilogallons. As illustrated in Table 6, the life cycle environmental impact towards land use potential for precast building system was 5.35E+06

Kg SOC or 5.347.50 t and with the social cost of carbon of $42/t (Mikhailova, Groshans, Post, Schlautman, & Post, 2019; USEPA, 2017), the total environmental impact costs towards land use potential was calculated as $224,595.0. Similarly, the environmental impact costs for cast-in-place and precast without sandwich panel system was $414,296.40 and $225,540 respectively. The environmental impact costs towards land use potential were 46% higher for cast-in-place building system. Since, the water consumption rate per M^3 is different for all states, in United States, the water consumption rate of $3.74/kgal (Kilogallons) (Water, 2020) for Colorado was taken. This was because since, the building was in the state of Colorado. The environmental impact costs were $6,209 for precast building systems. However, cast-in-place building system and precast without sandwich panel had $8,116 and $6,216 environmental impact cost towards water use. The 24% higher environmental impact cost of cast-in-place building system compared to precast using sandwich panels was due to the on-site construction activities during construction phase. The environmental impact costs towards GWP was also measured in social cost of carbon of $42/t. For precast building system, the environmental impact costs were $49,957 due to GWP. It was 50% higher for cast-in-place building system compared to precast of $99,472.80. However, there was not much difference for precast without sandwich panels as environmental impact costs due to GWP was $51,872. Thus, collectively, precast using sandwich panel building system had lowest environmental impact costs among the three and has a positive impact in meeting the UNSDGs when compared to cast-in-place and precast without sandwich panel building systems.

Table 6: Total Environmental Impacts for Three Building Systems

S. No	Environmental impact indicators	Units	Precast using sandwich panels	Cast-in-Place	Precast without sandwich panels
1	Global Warming Potential	Kg CO_2-Eq	1.19E+06	2.37E+06	1.24E+06
2	Ozone Layer Depletion	Kg CFC-11-Eq	1.49	2.02	1.51
3	Eutrophication Potential	Kg N	2.36E+02	1.19E+03	3.45E+02
4	Photochemical Oxidation	Kg NO_x-Eq	2.61E+03	4.05E+03	2.74E+03
5	Respiratory Effects (Non-Carcinogenic)	Kg toluene-Eq	3.83E+06	1.28E+07	3.92E+06
6	Acidification Potential	Kg SO_2-Eq	7667.54	1.40E+04	8.75E+03
7	Resource Depletion	Kg Sb-Eq	33.03	5.38E+01	3.30E+01
8	Land Use	Kg SOC	5.34E+06	9.86E+06	5.37E+06
9	Water Use	m^3	6284.46415	8.21E+03	6.29E+03

Table 7: GHG Emissions per Climate Mobilization Act (Government, 2019)

Occupancy Classification	2024-2029 Limit (kg CO2 eq/sf/year)	2030-2034 Limit (kg CO2 eq/sf/year)
B-Ambulatory, health, emergency response, another critical application	23.81	11.93
H-High Hazard	11.81	4.03
I & I3-Institutional	10.74	4.2
M-Mercantile	9.87	5.26
A-Assembly	8.46	4.53

R1-Residential (Hotels)	7.58	3.44
B-Business	8.46	4.53
E-Educational	7.58	3.44
I4-Institutional	6.75	4.07
R2-Residential (Multifamily)	5.74	1.67
F-Factory	4.26	1.1
S-Storage	11.38	5.98
U-Utility & Miscellaneous	4.26	1.1
I-Institutional	11.38	5.98

Chapter 5: 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 industry experts, 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 the annual 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 social indicator 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, economic and social) components of sustainable construction.

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Appendix A

Project Estimate Dataset

Item	Quantity	Unit	Total
Engineering	1466	MH	102596
Project Management	151	MH	9740
Structural Forms	1	LS	42,546
Architectural Forms (9 Forms)	1	LS	99,656
Lumber	16446	BF	15,574
Plywood	4756	SF	8,646
Chamfer	4392	LF	2,240
Concrete Stone + 1%	599	CY	74,217
Concrete SLW + 1%	25	CY	5,423
Concrete Architectural + 1%	151	CY	34,277
Concrete Architectural Backup + 1%	423	CY	57,951
Mesh: Deck 12'	8250	SF	1,240
Mesh: Deck 8' and 10'	37,503	SF	9,376
Mesh: Leg	15,680	SF	5,802
Mesh: Wall	62842	SF	34,123
Strand 1/2	50400	LF	17,489
Architectural Liner	1	LS	88,123
Tool Room Supplies	1173	CY	24,623
Lift Inserts	872	EA	12,208

Item	Quantity	Unit	Total
Sand	17423	SF	26,831
Reinforcement	80,084	LB	57,660
Fabricated Plates	81814	LB	111267
Trucking 169 loads @ 4.25mh	718	MH	76278
Erect Materials	1173	CY	5569
Crane Rental	146	HR	43,680
Crane Move in	1	LS	23,000
Grout-Structural	1	LS	5591
Grout Architectural	1	LS	24716

Where,

MH = Man Hours

LS = Lump Sum

BF = Board Feet

LF = Linear Feet

CY = Cubic Yard

SF = Square Feet

EA = Each

LB = Pounds

Mix – Design

Typical Mix With 800 lbs Cementitious and 3/8 Aggregate		
OZ	GRACE ADVA CAST 575	90
OZ	GRACE DARASET 400	20
LBS	CEMENT GRAY TYPE III	600
LBS	CEMENT FLY ASH	200
LBS	SAND	1484
LBS	3/8" PEAGRAVEL	1498

Typical Mix With 700 lbs Cementitious and ¾ Aggregate		
OZ	GRACE ADVA CAST 575	49
OZ	GRACE DARAVAIR 1000	7
OZ	GRACE DARASET 400	49
LBS	CEMENT GRAY TYPE III	700
LBS	3/8" PEAGRAVEL	217
LBS	3/4" HARD ROCK	1452
LBS	SAND	1173

Transportation details of precast components:

Material – Precast Components

Description – From precast plant to Construction Site

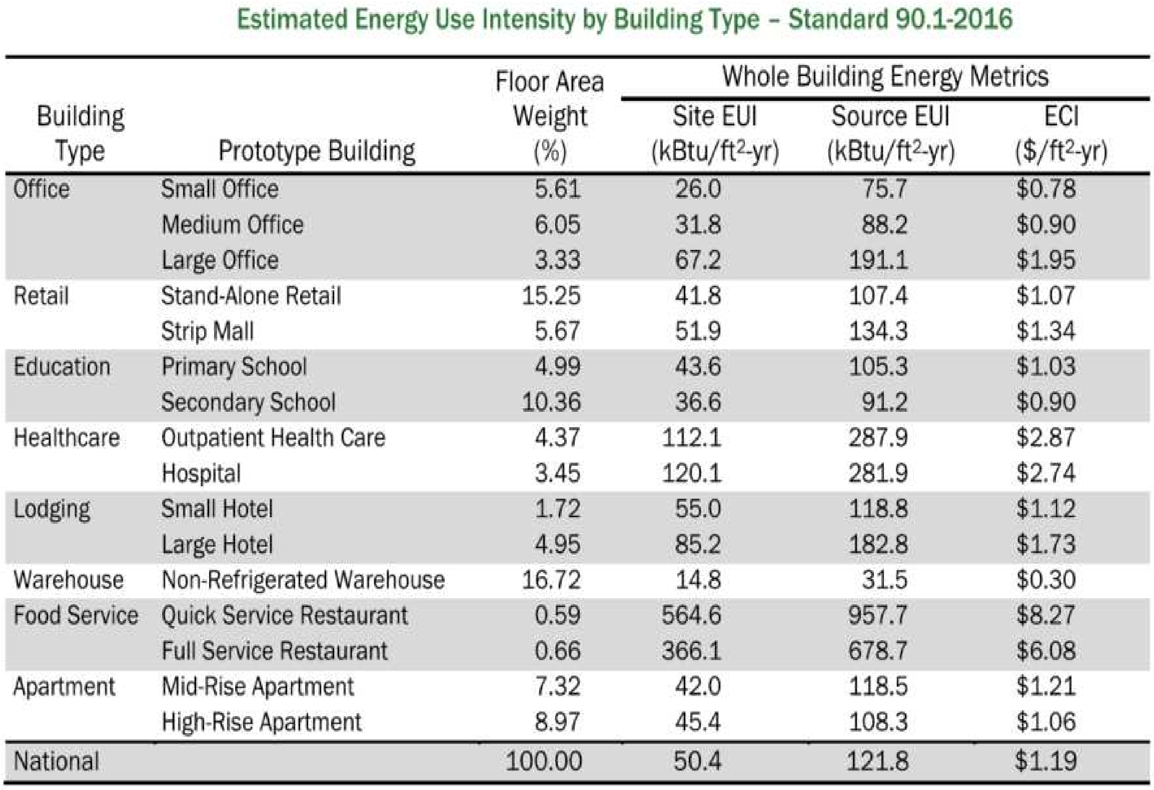
One side Distance – 22 miles

Transport Method – Truck 20-28t

Resource Usage of Equipment for Precast Installation/Construction

S.NO	Resource	Precast	Cast-In-Place
1	Diesel (gal)	4,200	13,280
2	Electricity (kWh)	134,420	210,720
3	Natural gas (per 1000 cubic feet)	273	485
4	Water (m^3)	745	1128

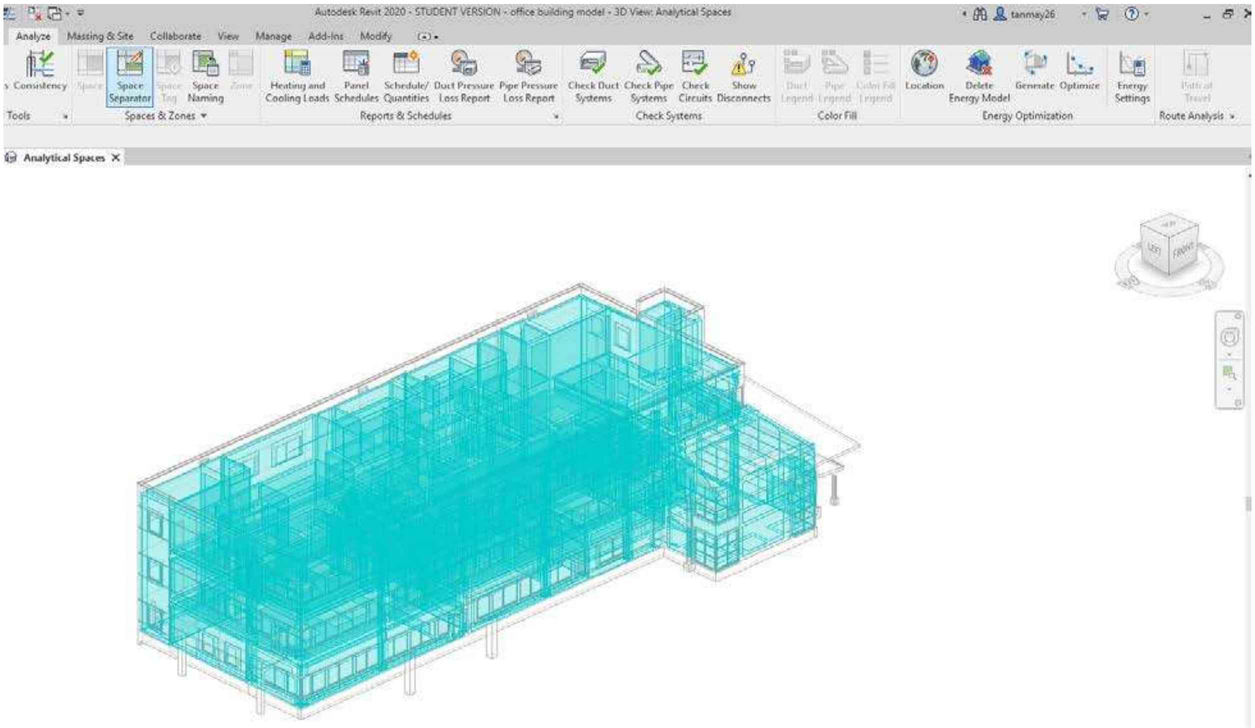
ASHRAE-Standard 90.1.2016



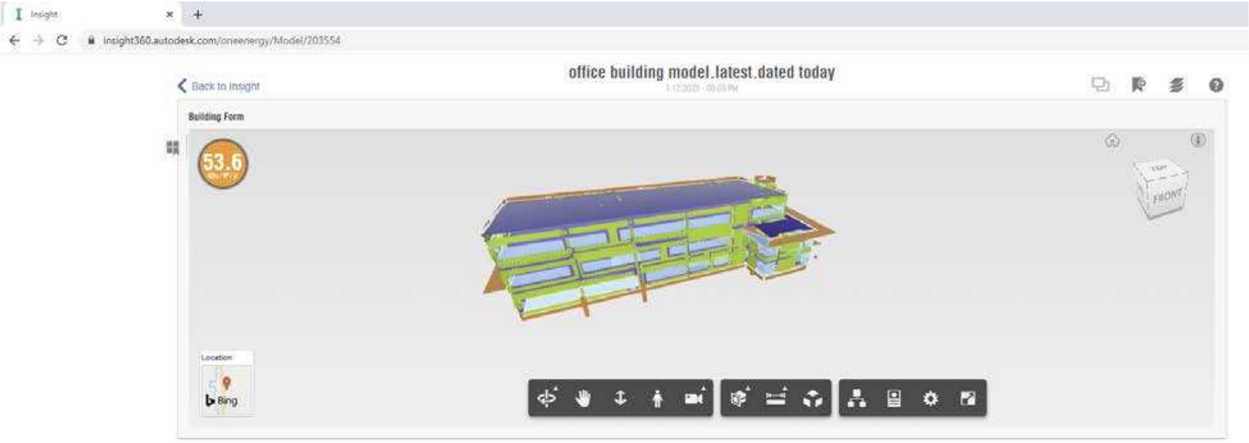
Estimated Energy Use Intensity by Building Type – Standard 90.1-2016

Building Type	Prototype Building	Floor Area Weight (%)	Whole Building Energy Metrics Site EUI (kBtu/ft²-yr)	Source EUI (kBtu/ft²-yr)	ECI ($/ft²-yr)
Office	Small Office	5.61	26.0	75.7	$0.78
	Medium Office	6.05	31.8	88.2	$0.90
	Large Office	3.33	67.2	191.1	$1.95
Retail	Stand-Alone Retail	15.25	41.8	107.4	$1.07
	Strip Mall	5.67	51.9	134.3	$1.34
Education	Primary School	4.99	43.6	105.3	$1.03
	Secondary School	10.36	36.6	91.2	$0.90
Healthcare	Outpatient Health Care	4.37	112.1	287.9	$2.87
	Hospital	3.45	120.1	281.9	$2.74
Lodging	Small Hotel	1.72	55.0	118.8	$1.12
	Large Hotel	4.95	85.2	182.8	$1.73
Warehouse	Non-Refrigerated Warehouse	16.72	14.8	31.5	$0.30
Food Service	Quick Service Restaurant	0.59	564.6	957.7	$8.27
	Full Service Restaurant	0.66	366.1	678.7	$6.08
Apartment	Mid-Rise Apartment	7.32	42.0	118.5	$1.21
	High-Rise Apartment	8.97	45.4	108.3	$1.06
National		100.00	50.4	121.8	$1.19

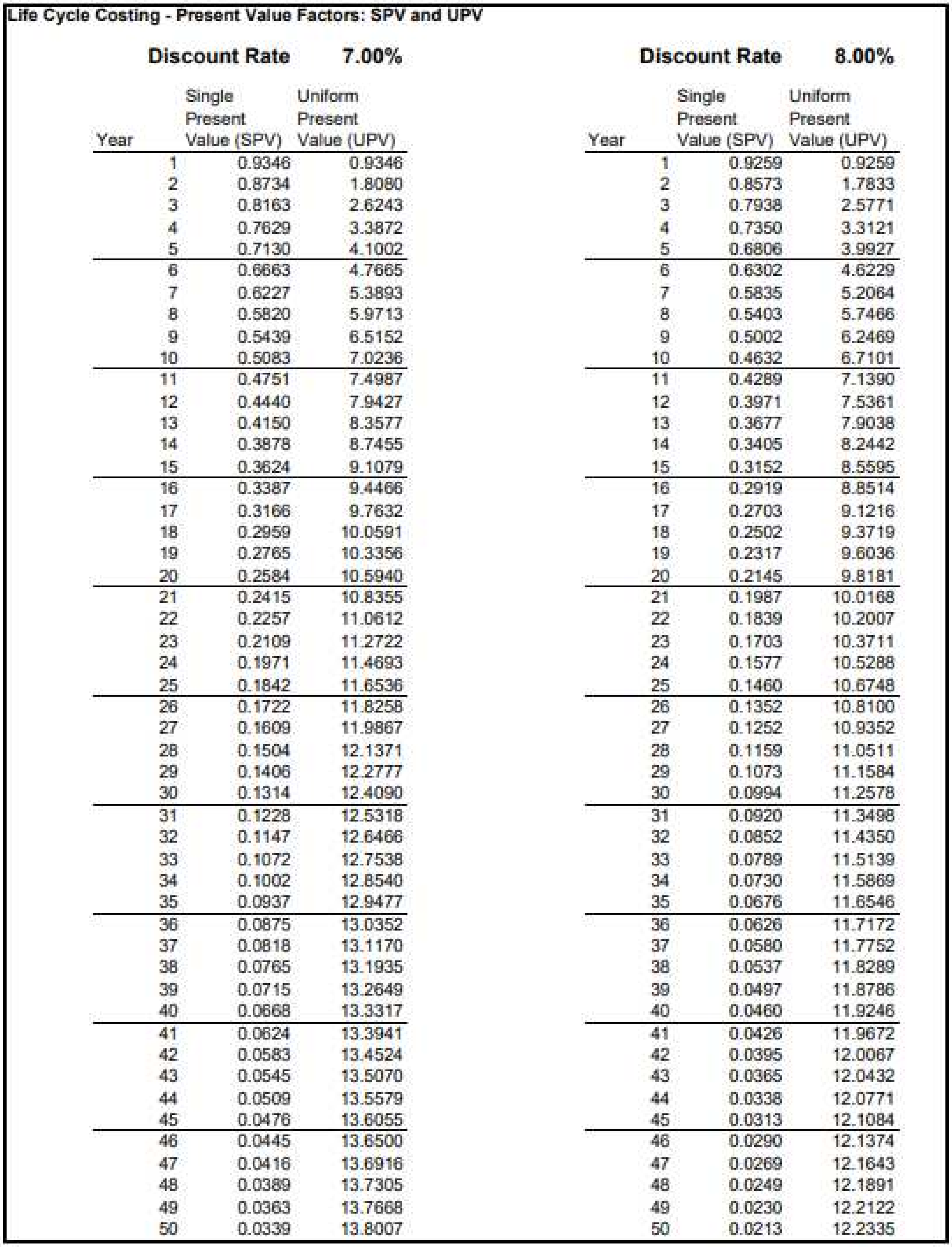
Energy Modeling



Insight Results



Uniform Present Value factor for LCC



Life Cycle Costing - Present Value Factors: SPV and UPV

	Discount Rate	7.00%		Discount Rate	8.00%
Year	Single Present Value (SPV)	Uniform Present Value (UPV)	Year	Single Present Value (SPV)	Uniform Present Value (UPV)
1	0.9346	0.9346	1	0.9259	0.9259
2	0.8734	1.8080	2	0.8573	1.7833
3	0.8163	2.6243	3	0.7938	2.5771
4	0.7629	3.3872	4	0.7350	3.3121
5	0.7130	4.1002	5	0.6806	3.9927
6	0.6663	4.7665	6	0.6302	4.6229
7	0.6227	5.3893	7	0.5835	5.2064
8	0.5820	5.9713	8	0.5403	5.7466
9	0.5439	6.5152	9	0.5002	6.2469
10	0.5083	7.0236	10	0.4632	6.7101
11	0.4751	7.4987	11	0.4289	7.1390
12	0.4440	7.9427	12	0.3971	7.5361
13	0.4150	8.3577	13	0.3677	7.9038
14	0.3878	8.7455	14	0.3405	8.2442
15	0.3624	9.1079	15	0.3152	8.5595
16	0.3387	9.4466	16	0.2919	8.8514
17	0.3166	9.7632	17	0.2703	9.1216
18	0.2959	10.0591	18	0.2502	9.3719
19	0.2765	10.3356	19	0.2317	9.6036
20	0.2584	10.5940	20	0.2145	9.8181
21	0.2415	10.8355	21	0.1987	10.0168
22	0.2257	11.0612	22	0.1839	10.2007
23	0.2109	11.2722	23	0.1703	10.3711
24	0.1971	11.4693	24	0.1577	10.5288
25	0.1842	11.6536	25	0.1460	10.6748
26	0.1722	11.8258	26	0.1352	10.8100
27	0.1609	11.9867	27	0.1252	10.9352
28	0.1504	12.1371	28	0.1159	11.0511
29	0.1406	12.2777	29	0.1073	11.1584
30	0.1314	12.4090	30	0.0994	11.2578
31	0.1228	12.5318	31	0.0920	11.3498
32	0.1147	12.6466	32	0.0852	11.4350
33	0.1072	12.7538	33	0.0789	11.5139
34	0.1002	12.8540	34	0.0730	11.5869
35	0.0937	12.9477	35	0.0676	11.6546
36	0.0875	13.0352	36	0.0626	11.7172
37	0.0818	13.1170	37	0.0580	11.7752
38	0.0765	13.1935	38	0.0537	11.8289
39	0.0715	13.2649	39	0.0497	11.8786
40	0.0668	13.3317	40	0.0460	11.9246
41	0.0624	13.3941	41	0.0426	11.9672
42	0.0583	13.4524	42	0.0395	12.0067
43	0.0545	13.5070	43	0.0365	12.0432
44	0.0509	13.5579	44	0.0338	12.0771
45	0.0476	13.6055	45	0.0313	12.1084
46	0.0445	13.6500	46	0.0290	12.1374
47	0.0416	13.6916	47	0.0269	12.1643
48	0.0389	13.7305	48	0.0249	12.1891
49	0.0363	13.7668	49	0.0230	12.2122
50	0.0339	13.8007	50	0.0213	12.2335

Total Life Cycle Costs for three building systems

S.NO	Building Systems	Total LCC
1	Precast using sandwich panels	$427,442.47
2	Cast-in-Place	$554,669.61
3	Precast without sandwich panels	$446,192.25

GWP comparison with NYC Climate Mobilization Act

Occupancy Classification	2024-2029 Limit (kg CO2 eq/sf/year)	2030-2034 Limit (kg CO2 eq/sf/year)
B-Ambulatory, health, emergency response, another critical application	23.81	11.93
H-High Hazard	11.81	4.03
I & I3-Institutional	10.74	4.2
M-Mercantile	9.87	5.26
A-Assembly	8.46	4.53
R1-Residential (Hotels)	7.58	3.44
B-Business	8.46	4.53
E-Educational	7.58	3.44

I4-Institutional	6.75	4.07
R2-Residential (Multifamily)	5.74	1.67
F-Factory	4.26	1.1
S-Storage	11.38	5.98
U-Utility & Miscellaneous	4.26	1.1
I-Institutional	11.38	5.98

Item	Quantity	Units	Total
Concrete Structure	24,280	SF	568880.40
Plywood 3/4''	12,458	SF	35256.14
Rigid Insulation	22,750	SF	45500.00
6'' Studs	11,450	SF	183200.00
Caulking Miscelleneous	12,000	SF	1800.00
cement	453	T	142164.00
steel	42	T	57660.00

Estimate

Item	Quantity	Units	Total
Concrete Structure	24,280	SF	568880.40
Plywood 3/4''	12,458	SF	35256.14
Rigid Insulation	22,750	SF	45500.00

6" Studs	11,450	SF	183200.00
Caulking Miscelleneous	12,000	SF	1800.00
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