Life Cycle Assessment of Wall Systems

by

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ABSTRACT

Natural resource depletion and environmental degradation are the stark realities of the times we live in. As awareness about these issues increases globally, industries and businesses are becoming interested in understanding and minimizing the ecological footprints of their activities. Evaluating the environmental impacts of products and processes has become a key issue, and the first step towards addressing and eventually curbing climate change. Additionally, companies are finding it beneficial and are interested in going beyond compliance using pollution prevention strategies and environmental management systems to improve their environmental performance. Life-cycle Assessment (LCA) is an evaluative method to assess the environmental impacts associated with a products' life-cycle from cradle-to-grave (i.e. from raw material extraction through to material processing, manufacturing, distribution, use, repair and maintenance, and finally, disposal or recycling).

This study focuses on evaluating building envelopes on the basis of their life-cycle analysis. In order to facilitate this analysis, a small-scale office building, the University Services Building (USB), with a built-up area of 148,101 ft^2 situated on ASU campus in Tempe, Arizona was studied. The building's exterior envelope is the highlight of this study. The current exterior envelope is made of tilt-up concrete construction, a type of construction in which the concrete elements are constructed horizontally and tilted up, after they are cured, using cranes and are braced until other structural elements are secured. This building envelope is compared to five other building envelope systems (i.e. concrete block, insulated concrete form, cast-in-place concrete, steel studs and curtain wall constructions) evaluating them on the basis of least environmental impact. The research methodology involved developing energy models, simulating them and generating changes in energy consumption due to the above mentioned envelope types. Energy consumption data, along with various other details, such as building floor area, areas of walls, columns, beams etc. and their material types were imported into Life-Cycle Assessment software called ATHENA impact estimator for buildings. Using this four-stepped LCA methodology, the results showed that the Steel Stud envelope performed the best and less environmental impact compared to other envelope types. This research methodology can be applied to other building typologies.

To my family
…. who have been with me
all the time

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TABLE OF CONTENTS

PAGE

PAGE

PAGE

LIST OF TABLES

LIST OF FIGURES

DEFINITION OF TERMS

ACI	American Concrete Institute
ACP	Acidification Potential
AEC	Architecture Engineer and Construction
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning
ASTM	American Society for Testing and Materials
ATHENA	Institute which developed and Environmental Impact Estimator Tool
BEES	Building for Environmental and Economic Sustainability
BREEAM	Building Research Establishment Environmental Assessment Method
C	Construction Life Cycle Phase
C2ES	Center for Climate and Energy Solutions
Cal green	California Green Building Standards Code
CB	Concrete Block
CEN	European Committee for Standardization
CFC	Chlorofluorocarbon
CIP	Cast in Place Concrete
CW	Curtain Wall
EDIP	Environmental Development of Industrial Products
EIA	Environmental Information Administration
EIA	Energy Information Administration
EIO	Economic Input Output
ENVEST	Environmental Estimator
EOL	End-of-Life Life Cycle Phase

EP	Eutrophication Potential
EPA	Environmental Protection Agency
EPD	Environmental Protection Declaration
ET	Ecological Toxicity
FDM	Facilities Development & Management
FFD	Fossil Fuel Depletion
GaBi	Product Sustainability Performance Tool developed by PE International
HH	Human Health Criteria
ICF	Insulated Concrete Form
IMPACT 2002	Life Cycle Impact Assessment Method
ISO	International Organization for Standardization
ISO 14044	International Organization of Standardization - Environmental
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
M	Manufacturing Life Cycle Phase
Ma	Maintenance Life Cycle Phase
ODP	Ozone Depletion Potential
OE	Operating Energy Life Cycle Phase
PCA	Portland cement Association
REPA	Resource and Environmental Profile Analysis

SETAC	Society of Environmental Toxicology and Chemistry
SFP	Smog Formation Potential
SS	Steel Stud
TRACI	Tools for the Reduction and Assessment of Chemical and other
UNEP	United National Environmental Programme
US LCI	United States Life cycle Inventory Database
WU	Water Use

BACKGROUND

Global Issues and their impacts

Planet earth has showed patterns of change in climate and in physical formations from Pangaea to Mount St. Helens. The planet is currently changing, but the rate at which it is changing is an interesting thing. Climate disturbs all inhabitants of the earth, and a rapid change should be of concern to us. Humans, as beings of cognition and reason, have the opportunity and the responsibility to understand what is happening and why. If human actions are having a negative effect on other human beings and species, then we should be aware of it and know what we can do about it. (Millerd J. A., 2008)

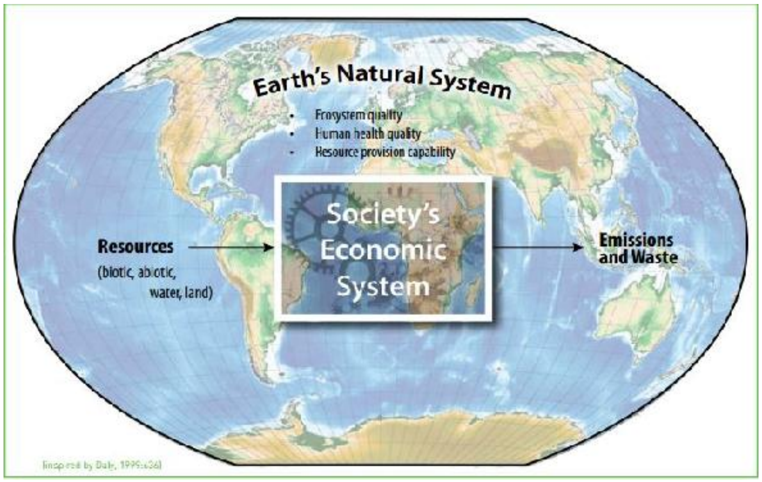


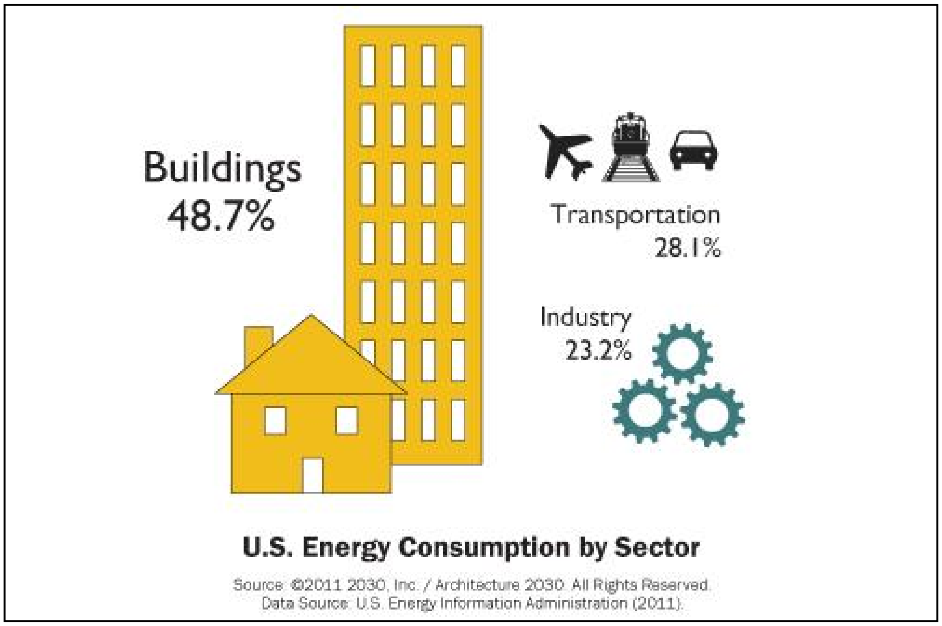
Figure 1: The relationship between the Economic and Natural System (Source: UNEP Resource Panel)

All economic activities needs resources such as energy, materials, and land, invariably generates material residuals, which enters the environment as waste or polluting emissions. The Earth, is a finite planet and has a restricted capability to supply resources and to absorb pollution (Knesse, 1969).

The Millennium Ecosystem Assessment (MA) of 2005 is the most authoritative analysis with regard to the status of global ecosystems contributed by 1300 scientists from all parts of the world. It identified factors that threaten ecosystems and contributions of ecosystems to human well-being. In the past 50 years, humans have changed ecosystems more rapidly and extensively than in any equivalent time period in human history, to meet the rapidly growing demand for food, fresh water, timber, fibre and fuel. This has resulted in a substantial and largely irreversible loss in the diversity of life on Earth. It has also examined that the supply of ecosystem services to humans: the provision of food, fibres, genetic resources, biochemicals and fresh water; the regulation of air quality, climate, water, natural hazards, pollination, pests and disease; the support derived from primary production, nutrient cycling, soil formation and water cycling; and cultural services such as spiritual and aesthetic values, and recreation. (Mark Huijbregts, 2010)

Practice of the Building Industry

The construction and engineering industry is debatably the world's largest. It is fast-paced, often governed by strict deadlines, where completing a project successfully requires cooperation and teamwork among owners, architects, engineers, contractors, subcontractors, and many others. The resource consumption and energy use are not only the major factors in the changing state of the planet and atmosphere, but also that the earth is unable to support the current consumption patterns for the population that is expected. If we want our planet to be infinite, and want to experience all the joys and luxuries that the nature provides, then we must find areas in the economy where using the resources could reduce throughout. (K&L Gates, 2013)



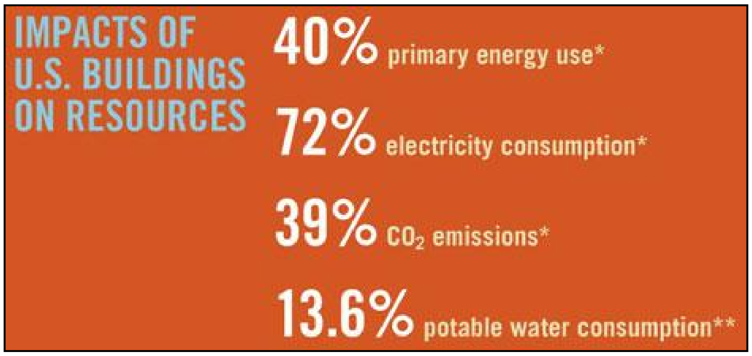
U.S. Energy Consumption by Sector

Source: ©2011 2030, Inc. / Architecture 2030. All Rights Reserved.
Data Source: U.S. Energy Information Administration (2011).

Figure 2: U.S. Energy Consumption by Sector (Source: Architecture 2030)

In the United States, buildings consume 48.7 percent of the country’s energy production, compared to the other industries and transportation, and demands 76 percent of the energy produced by the coal plants (United States Green Building Council, 2013). Also buildings produce 30 percent of the country’s greenhouse gas emissions including carbon dioxide, carbon monoxide, nitrous oxide and CFC’s among many others. The energy requirements of a building’s HVAC and lighting could be reduced by improved building design and appliance choice.

The *U.S. Energy Information Administration (EIA)* now reports that, in coming years, the energy consumption of the building Sector is expected to grow faster than that of industry and transportation. Between 2010 and 2030, the total Building Sector energy consumption will increase by 5.85 Quadrillion Btu (QBtu), Industry will grow by 4.01 QBtu and Transportation by 3.15 QBtu. These projections implies that 1 QBtu is equal to the delivered energy of thirty-seven 1000-MW nuclear power plants, or 235 coal-fired power plants at 200-MW each. (Mazria, 2011)



IMPACTS OF U.S. BUILDINGS ON RESOURCES

40% primary energy use*

72% electricity consumption*

39% CO_2 emissions*

13.6% potable water consumption**

Figure 3:U.S. Impacts of Buildings on Resources

Added to this buildings consume a huge amount of materials; as they account for 40 percent of raw materials used globally and produce 30 percent of total waste output. The *Environmental Protection Agency (EPA)* estimates that 136 million tons of building-related construction and demolition debris was generated in the U.S. in a single year, compared to 209.7 million tons of municipal waste that same year. At the same time, the U.S. was stripping the land, harvesting non-renewable resources and overharvesting renewable resources.

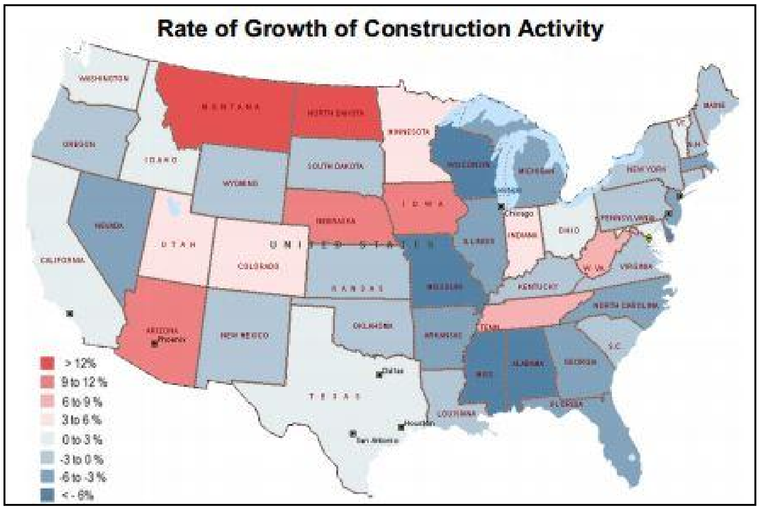


Figure 4: Rate of Growth of Construction Activity (Source: Construction Industry Market Report 2012)

Current building practices are very inefficient in both energy use and material consumption. A building when constructed in a right manner can reduce stress, uses 35 percent less energy, 85 percent less water outside, 20 percent less water inside, and makes 50 percent less contribution to landfills (United States Green Building Council, 2013). The building industry represents an excellent opportunity for the management of the impact that human activity is having on the environment. Within the U.S. and globally, the debt crises, political transitions and regional conflicts have created a level of uncertainty not seen for several years. This has led to creating an environment where there is little prospect of stable growth in the demand for construction. In most parts of the country the construction activity seems to pick up, with the majority of states showing some growth over the past years. In most cases however, the rate of growth is hovering very close to zero, with construction activity close to negligible. (Morris, 2012)

The Building Industry in Phoenix

According to the *US Census Bureau*, over the last years, three of the top ten fastest growing cities in the United States, are located in the Phoenix metropolitan area. The growth of places like Gilbert, Chandler and Peoria has helped to make the Phoenix Valley the fastest growing metropolitan area in the United States with a 34.3% population growth between years 1999-2000. This enormous growth which undoubtedly demands construction responses, resulted in building materials being used in staggering quantities, which are used once most often and then discarded to landfill. Phoenix's sprawl is not conducive to high-rise buildings, but this is changing as more businesses desire a central location. Over the years, the construction industry has seen progress, with lot of construction activity in the first quarter of 2013. (CoStar, 2013)

Buildings on ASU campus

Originally named the *Tempe Normal School*, was founded on March 12, 1885. It was instituted on February 8, 1886 under the supervision of *Principal Hiram Bradford Farmer*. Initially, the Normal School enrolled high school students with no other secondary education facilities. Of the 18 buildings constructed while Matthews was president, six are still currently in use. Arizona State University began to expand over the years its academic curriculum by establishing several new colleges and beginning to award Doctor of Philosophy and other doctoral degrees. Then grew through the creation of the Polytechnic campus and extended education sites under the leadership of Dr. Lattie F. Coor, from 1990 to June 2002. (Wikipedia, Arizona State University, 2013)

Figure 5: ASU Tempe Campus Development over the years (University, 1928)

Further, Michael Crow (Present President) initiated the idea of transforming ASU into *"One University in Many Places"* by merging ASU's several campuses into a single institution, sharing students, faculty, staff and accreditation. The Tempe campus is located in downtown Tempe, Arizona, about eight miles (13 km) east of downtown Phoenix. The campus is urban, and is approximately 642 acres (2.6 km^2) in size. Along with the research facilities, the university faculty was expanded, ASU at the Tempe campus has embarked on a dramatic research infrastructure expansion to create more than one million square feet of new research space, moving the university closer to its goal of tripling research capacity during the next five years. In addition, ASU's Downtown Phoenix campus was vastly expanded with several of the University's colleges and schools relocated to the downtown campus. Since fiscal year 2002 ASU's research expenditures have tripled and more than 1.5 million sq. ft. of new research space has been added to the university's research facilities.

The economic downturn that began in 2008 took a particularly hard toll on Arizona, resulting in large cuts to ASU's budget. From then on, ASU underwent several rounds of reorganizations, combining of academic departments, consolidation of colleges and schools, and reducing university staff and administrators. However, with an economic recovery underway in 2011, ASU continued its campaign to expand the West and Polytechnic Campuses, and establishing a set of low-cost, teaching-focused extension campuses in Lake Havasu City and Payson, Arizona. (Wikipedia, Arizona State University, 2013)

LIFE CYCLE ASSESSMENT

What is LCA?

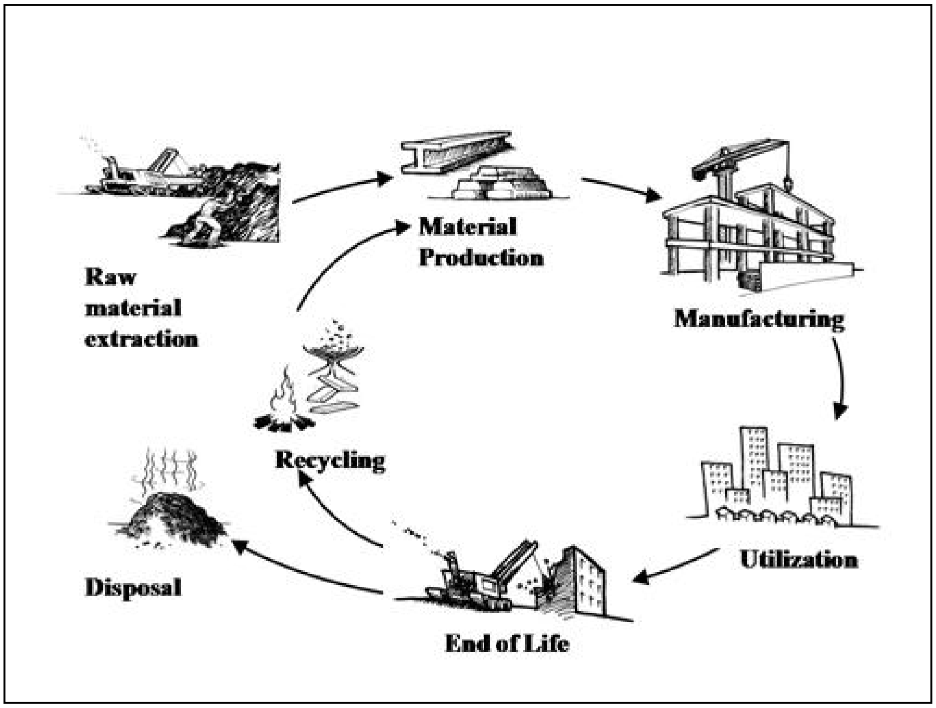


Figure 6: Life Cycle Stages (Source: Fraunhofer Institute of Physics)

Although many definitions exist, LCA essentially comprises a systematic evaluation of environmental impacts arising from the provision of a product or service. The original *International Organization for Standardization (ISO) ISO 14040* defines LCA as:

"… a technique for assessing the environmental aspects and potential impacts associated with a product, by

- compiling an inventory of relevant inputs and outputs of a product system;
- evaluating the potential environmental impacts associated with those inputs and outputs;

- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.

It is also known as the *'Cradle to gate'* analysis which begins with the gathering of raw materials from the earth to create a product and ends at the point when all materials are returned to the earth. LCA evaluates all stages of a product's life from the perspective that they are interdependent, meaning that one operation leads to the next and enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection. ISO-compliant life cycle assessment is the most reliable method to verify environmental impacts and support claims providing designers, regulators and engineers with valuable information for exploring decisions in each life stage of materials, buildings, services and infrastructure. (Henrikke Baumann, 2004)

Who does LCA and Why?

Life Cycle Assessment (LCA) is the most reliable method of verifying the environmental impacts. In the recent years, it has extended its roots into the building construction sector. The environmental hot spots in products and materials are highlighted in an LCA study and establishes the benchmark against which improvements can be measured. Companies uses this method to demonstrate the transparency and corporate credibility to stakeholders and customers, facilitating in new product research and development, where environmental footprint is important to the future marketing or cost structure of a product. (ATHENA, 2013)

The strength of LCA is that it studies the whole product system. This enables us to avoid the sub-optimization that may be the result only if a few processes are focused on. The results are related to the function of the product, which allows comparisons between alternatives. It is an engineering tool in the sense that technical systems and potential changes in them are studied. At the same time, it is a multi-disciplinary tool in the sense that impacts on the natural environment and even people`s relations to such impacts are modelled. The benefit of doing an LCA study is simple reliable, transparent data for both manufacturers and consumers, enabling better decisions. (Henrikke Baumann, 2004)

Origin of LCA

1960’s - LCA has its roots in the 1960s, when scientists were apprehensive about the rapid depletion of the fossil fuels and resulting climatological changes sparked interest on industrial processes. They developed it as an approach of understanding the impacts of energy consumption. A few years later, global-modeling studies predicted that the effects of the world’s changing population on the demand for finite raw materials and energy resource supplies. In 1969, the *Midwest Research Institute* (and later, Franklin Associates) initiated a study of the *Coca-Cola Company* to determine which type of beverage container had the lowest impact on the environment and made the fewest demands for raw materials and energy.

1970’s - The *U.S. Environmental Protection Agency (EPA)* refined the above methodology, creating an approach known as *Resource and Environmental Profile Analysis (REPA)*. Approximately 15 REPAs were performed between 1970 and 1975, driven by the oil crisis of 1973. (Svoboda, 2005)

Early 1980’s- Environmental concern shifted to issues of hazardous waste management which resulted in incorporating life cycle logic into the emerging method of risk assessment, used with increasing frequency in the public policy community to develop environmental protection standards.

1990’s- LCA was used for external purposes, such as marketing. Its application in the present decade then broadened into building materials, construction, chemicals, automobiles, and electronics. This was primarily because of the formalization of LCA standards in the ISO 14000 series (1997 through 2002) and launch of the Life Cycle Initiative, a combined effort by *United Nations Environment Programme (UNEP)* and the *Society of Environmental Toxicology and Chemistry (SETAC)*, in 2002.

2000 and beyond- In addition to the ISO 14040 standards, there have been some developments specifically targeting the construction sector. In 2003, SETAC published a state-of the-art report on *Life-Cycle Assessment in Building and Construction, an outcome of the Life Cycle Initiative*. This study highlighted the differences between the general approach of LCA and LCAs of buildings. Such standardization continued, with two leading organizations the *International Organization for Standardization (ISO)* and the *European Committee for Standardization (CEN)*. The ISO Technical committee (TC) 59 ‘*Building Construction*’ and its subcommittee (SC) 17 ‘*Sustainability in Building construction*’, described a framework for investigating sustainability of buildings, implementation of the *Environmental Product Declaration (EPD)* and published four standards. The CEN Technical Committee (TC) 350 '*Sustainability of construction works'* developed standards for assessing all of the three aspects of sustainability *(economical, ecological, social)* for both new and existing construction works and also for the environmental product declaration of construction products. (Svoboda, 2005)

Scope and Limitations of LCA study

It takes a lot of effort to do an LCA study, exploring large industrial systems, collecting and analyzing a lot of environmental information. In practice, this can seem an overwhelming task. As the whole life cycle is studied, it is not site specific. Thus, environmental impact cannot be modelled at a very detailed level. An LCA study doesn't include economic, social aspects other than when used as a basis of weighting, and risk management. The accuracy of an LCA study depends on the quality and the availability of the relevant data, and if the data is not accurate enough, the accuracy of the study is limited. These facts affect the precision of the final results. (Henrikke Baumann, 2004)

LCA in the building industry

Building construction and operation have extensive direct and indirect impacts on the environment. Building owners, designers, contractors face a unique challenge to meet the demands for new and renovated facilities that will be accessible, secure, healthy, and productive while minimizing their impact on the environment. Elective green-building scorecards and branding schemes such as *Energy-Star* and *Leadership in Energy and*

Environmental Design (LEED) are being followed by a large segment of the decision makers procuring new buildings.

Life cycle assessment (LCA) is the latest addition to the life cycle toolbox for buildings which looks at the upstream and downstream burdens throughout the entire building life cycle with a focus on embodied environmental impacts. Embodied impacts become more critical when operating consumption, such as energy and water, is reduced through the optimization of design and building management. Retrofitting an existing building can be more cost effective than building a new facility and designing major renovations and retrofits for existing buildings to include sustainability initiatives reduces operation costs and environmental impacts, and can increase building resiliency.

There are three basic options for bringing LCA into building design decisions: at the product level, the assembly level, or the whole building level (Architects, 2010).

Material Level

Process-based LCA is defined at the material level. In the United States, the LCI (Life cycle impacts) database managed by the *National Renewable Energy Laboratory (NREL)* is the primary source for information about the environmental impact of materials is. Participants in the US LCI Database Project are actively involved in analyzing widely used building materials and formatting their analysis for inclusion in the LCI database. Prior to the development of this database, LCA software for the United States used LCA data from foreign data sources. The early versions of *Building for Environmental and Economic Sustainability (BEES)* used US data for energy production and European data for materials, along with proprietary material-supplier data for the manufacturing life cycle. The current version of BEES uses these proprietary data, the US LCI database, and supplemental analysis from Simapro with the Eco Invent database.

Both cement and concrete are building materials, but cement is a constituent of concrete. Due to the extraction of precursor minerals from the earth and the energy necessary to create the Portland cement clinker the environmental footprint of Portland cement is significant. An LCA of a given concrete will depend on the percentage of cement that is included in the concrete and whether fly-ash is used as a substitute for cement. In addition, the location of cement production relative to the building site will have a significant impact on the LCA outcomes. For example, in the BEES LCA tool, it allows for the user to select a concrete with 100 percent Portland cement, and also other concretes with fly-ash, limestone, and slag as substitutes for a portion of the cement. This information is calculated by process chemists, chemical engineers, and associated specialists and submitted for inclusion in various LCI databases. There is some direct use of material-level LCI data by building professionals. But to calculate the positive impacts of using fly-ash as a substitute for part of the Portland cement in concrete, this calculation could be made easy by directly accessing the data from the LCI database.

Product Level

At the product level, an LCA is calculated as a collection of materials, which are assembled into a final (or intermediate) product. A quantity takeoff of the product is completed, and the emissions from each component of the products are summed. For instance, the product LCA of a heat pump would include the production of the pre-cursor materials—steel, copper, aluminum, plastics, refrigerants— and emissions from galvanizing processes, painting, metal fabrication, welding, etc. Completion of the heat pump LCA might be made easier if the LCA of a particular component, say an electric motor, is already available. In order to complete a product LCA, thorough knowledge of the source and quantities of materials and the manufacturing processes of the finished product is required. General-purpose LCA software, such as *Gabi, Boustead, or SimaPro,* is usually employed to complete a product LCA. A large quantity of product-level LCA data is emerging that is useful to architects. This is helpful especially in the areas where products can clearly be compared on a one-to-one basis or as per the LCA terminology, wherein the functional unit for a product can be clearly described. Office furniture and carpets manufacturers are adopting the LCA method widely and providing the results of these LCAs to architects to demonstrate the “green-ness” of their products.

Building Level

Building LCA, or whole-building LCA, can be thought of as a product LCA where the product is the building. The architect being LCA expert in this case, understands how the building is constructed, how building materials and products flow to the jobsite, and how the building is going to be operated over time.

Industry Level

At the building industry level, the best tool for completing an LCA would be the *Economic Input-Output (EIO)* based LCA method. For example, to characterize the environmental impact of the residential housing industry, surveys of homebuilders, housing start data, income of wood-products suppliers, property tax rolls, and construction employment data could be collected and analyzed each year to predict the amount of green-field land, non-renewable materials, and energy are directed into residential construction on a national or regional basis. In this way, an LCA of an entire segment of the Architecture Engineer and Construction (AEC) industry could be created, but with little of the specificity found in process-based LCAs. The EIO LCA method quantifies the impacts of cement and steel production, suburban sprawl and urban densification, and changes in land use, etc. But it is also clear that LCA at this industry-wide scale is not actionable for a practicing architect. Instead, it is at a very small scale as material, product, and building that the LCA becomes useful to the architect.

Standards in LCA

The leading standards for Life Cycle Assessment (LCA) are *"International Standard Organization" ISO 14040 and ISO 14044*. These international standards focus mainly on the process of performing an LCA. Requirements and guidelines are given for:

- Defining the goal and scope of the LCA
- Life cycle inventory analysis (LCI) phase
- Life cycle impact assessment (LCIA) phase
- Interpretation phase
- Reporting and critical review of the LCA

There are many practical guidelines available on how to conduct an LCA study such as the *SETAC Code of Practice and guidelines* for environmental LCA from the Netherlands, the Nordic countries, Denmark and the US. These guidelines made important contributions to the development of the standard as were written before the standards were issued. The Dutch guidelines have been updated to an operational guide to the ISO standards, with more detailed recommendations than the standards and mostly includes data for impact assessment. But some of them explicitly support LCA for a specific purpose. For example, the *Danish EDIP method* was designed for product development purposes whereas the *Nordic Guidelines* are guidelines on how to perform LCA‘s with “key issues’’ identification. (Henrikke Baumann, 2004)

The *Leadership in Energy and Environmental Design (LEED)* rating system has experimented with LCA in a past pilot credit. Currently, there are two LCA-based pilot credits which are in place and two new MR LCA-based credits that are proposed for LEED v.4. (United States Green Building Council, 2013).

- *LEED Pilot Credit 63: MR (Materials and Resources)* -Whole Building Life Cycle Assessment, earned by using LCA to show a reduction in environmental impacts for a final design compared to a reference building.
- *MRc1*: Building life-cycle impact reduction, a 3-point option for whole-building LCA very similar to pilot credit 63 (LEED v.4).
- *LEED Pilot Credit 61: Material Disclosure and Assessment*, earned by including enough products with LCA-based information either an LCA report or an environmental product declaration (EPD). This paperwork is got from product suppliers, who will develop it after completing LCA studies for their products.
- *MRc2*: Building product disclosure and optimization – environmental product declarations, gives 2 points and is similar to pilot credit 61. For products with LCA-based information: either an LCA report or an environmental product declaration (EPD), one

point is earned. Another point could be earned if enough products are certified by a USGBC-approved program as having LCA performance better than industry average.

LCA and Green Globes™

Green Globes, the first national building rating system in North America to integrate LCA as a credit. Green Globes awards points for educational experience of using LCA and does not credit any particular performance level. In 2010, ANSI/GBI 01-2010: *Green Building Protocol for Commercial Buildings* was officially approved; which is derived from Green Globes and LCA is included in this standard as an alternative compliance path to prescriptive material requirements.

LCA and ICC 700

The *International Code Council (ICC)* 700 National Green Building Standard, a residential green standard was initiated by the *National Association of Home Builders*. The current version of the standard gives points for reducing environmental footprint on the basis of life cycle assessment.

LCA and the IGCC

The 2012 *International Green Construction Code* from the *International Code Council*, belonging to section 303, offers whole-building LCA as an alternative compliance path to the prescriptive material requirements in section 505. Final design must show improvement over a reference building.

LCA and ASHRAE 189.1

The ANSI/ASHRAE/USGBC/IES Standard 189.1-2011, a whole-building LCA is available as an alternative performance compliance path to prescriptive material requirements. Final design must show improvement over a reference building.

Cal green

The *2010 California Green Building Standards Code* offers LCA under non-residential voluntary measures, at either the whole-building level or for building assemblies. To avoid prescriptive material requirements, whole-building LCA can be used (ATHENA, 2013).

BUILDING ENVELOPE

What is a Building Envelope?

The building envelope or wall is defined as an interface between the interior of the building and the outdoor environment, including the walls, the roof, and the foundation serving as a thermal barrier and plays a very vital role in determining the amount of energy necessary to maintain a comfortable indoor environment in relation to the outside environment. This fundamental need for shelter was a concept that is as old as the recorded history of mankind. However, as our needs have changed and our technologies advancing , the demand to both understand, and integrate, a wide range of increasingly complex materials, components, and systems into the building enclosure has grown in equal proportion and this task is placed on the designers. The envelope, or "enclosure" or wall of a building or structure serves a variety of basic functions. It can also be used to carry or distribute some services within the building. The enclosure will also have several aesthetic attributes, which can be summarized as finishes. (Guide, n.d.)

Burnett and Straube have defined four general building enclosure function categories. They are:

- Support
- Control
- Finish (aesthetics)
- Distribution of Services (where required)

Support

The envelope or the exterior wall must be capable of withstanding all internal and external forces applied to them. The majority of these forces are structural loading. They include both static and dynamic loading, but not limited to, dead load, live loads, wind loads, earthquake loads and possible blast loads. These loads have to be properly supported, resisted, and transferred.

Control

The envelope must be able to control mass, energy, and particulate flows both within and across the system which include, but are not limited to, heat, air, moisture, smoke, odor, fire, blast, birds, and insects.

Finish

The finish function includes both the exterior and interior aesthetics of the finished surface, the visual, textural, and other aspects the designer wishes to convey with the visible elements of the system.

Distribution

This function relates to the distribution of services through a building, both within a single element, and also through multiple elements.

Energy Performance of Building Envelopes

Residential and commercial buildings account for nearly 39 percent of total U.S. energy consumption and 38 percent of U.S. carbon dioxide (CO_2) emissions. Parameters like space heating, cooling, and ventilation account for the largest amount of end-use energy consumption in both commercial and residential buildings. The commercial sector are responsible for 34 percent for energy used on site and 31 percent of primary energy use, whereas in the residential sector, space heating and cooling are responsible for 52 percent of energy used on site, and 39 percent of primary energy use. The exterior wall or the envelope acts as a thermal barrier, and plays an important role in regulating interior temperatures and helps determine the amount of energy required to maintain thermal comfort. It minimizes the heat transfer through the building envelope which is crucial for reducing the need for space heating and cooling. In the case of cold climates, the building envelope can reduce the amount of energy required for heating; and in hot climates, the building envelope can reduce the amount of energy required for cooling. (Center for Climate and Energy Solutions, Working together for Environment andd the Economy, n.d.)

A climate-responsive wall system or building envelope uses a combination of shading, high performance windows, and the thoughtful placement of windows which in turn enhances the comfort and energy performance of the building. Additional design features such as selecting "cool" white roof materials and insulation options greatly impact the energy demand and occupant comfort of the building. The ultimate performance and comfort of the building will identify the interaction of the envelope choices with other building systems.

There are some key elements of modern building envelopes like integration of design and window strategies to bring daylight into a building's interior without heat and glare. Other key elements are the ones that affect the thermal performance includes shading elements, air tightness, wall and roof insulation and roof reflectance, etc.

Objective

A building envelope or an exterior wall in a building is very important as it forms the technical and aesthetic aspect of the building. The energy associated with a building envelope is something which can be easily measured and even addressed the most. As there is growing environmental awareness of protecting the environment and saving on the natural resources, architects, designers, industry and various businesses are curious to find out how the building will perform over a period of time.

This study focuses on evaluating different envelope systems for a case study building and analyzing what impacts did the envelope have on the environment. The reasons for performing the study on an existing building was due to the issues related with the building`s exterior wall system. The exterior wall system is made of Tilt up concrete construction which creates some occupancy and thermal comfort problems. The aim was to evaluate the life cycle performance of the existing wall system and also they are compared with five other types of wall systems to find out which of the wall systems has less impact on the environment. The results from this study will facilitate choosing the right materials and systems for the construction of future buildings.

LITERATURE REVIEW

Generic Elements of LCA

For a standard LCA practice, there are some key elements required to be considered. Some of them are - (Architects, 2010):

Functional unit

The basis for an LCA study is the calculation of environmental impacts for the delivery of specific functions or utilities. In an LCA study, defining of an appropriate functional unit is always a challenge primarily because there is a need to balance the options that may have secondary functions. Conceptually, it is defined so that results from the LCA can be used to promote a substitution of the options. For example, if different materials were manufactured using different vehicle options, most people would not consider this as a barrier to purchase. However, if the vehicle options differed in their durability, efficiency, carrying capacity, speed, range, cost or style, the prospective for product substitution would be limited and the uptake would require some sacrifice or trade-off between different options and the environment. There are many instances in which people are willing to those such trade-offs and where all options needed to be resolved by the decision-maker have positive and negative features.

System boundary

If there is a system being analyzed, then there must be boundaries within which that system could be analyzed. Generally, the system boundary is framed conceptually in terms of the life cycle stages included in the study. For example, a study could include all material inputs involved in the process but exclude capital equipment, infrastructure and services. Alternatively, within the boundaries the system may be described literally through a description of all the processes. However, as LCA can include thousands of unit processes, this is often not meant to be practical. Boundaries could be as tight as the limits of a single unit process, such as the burning of gas extracted from nature, or as broad as the consumption of goods and services by whole populations.

Inputs and outputs

LCAs are constructed through the calculation of inputs and outputs required, or arising as a consequence of, the delivery of the functional unit. The inputs and outputs might be technical processes such as materials, services and processes, elementary flows to and from the environment such as coal, minerals and land use, and/or inputs and outputs to air, water and soil such as carbon dioxide, nitrogen and heavy metals. In absence of these elementary flows in LCAs, there are otherwise no impacts. The number and aggregation of the technical flows vary proportionally with the type of LCA and the system being investigated.

Impact assessment

The analysis of impacts could not be possible if the type and number of indicators used in LCAs vary, hence all the LCAs should have some indicators. Studies claim to consider only a life cycle inventory and do not include impact assessment, however this indicates that energy and greenhouse gases are the focus of the study, or only a very narrow group of emissions or priority pollutants are taken into consideration (e.g. nitrous oxides, sulphur oxides, hydrocarbons and carbon dioxide).

'Bottom-up' process analysis

Bottom-up process analysis refers to process-based modelling that begins at the bottom of the supply chain and puts together the individual unit processes that comprises a product's system. In modern economies, the first stage includes extraction of minerals, production of energy and the system transportation are required. The data that is collected for each of these processes by measurement and modelling of each process at either local, regional or national levels are unique to bottom-up process analysis, although the process model will represent a single process or group of processes analogous to a factory or operation. On the contrary, the unit processes in economic input-output analysis are economic sectors. The unit processes in LCA are connected by virtue of energy and material flows between them.

Therefore, electricity uses coal; timber milling uses electricity and; timber is used to make buildings, etc. The circular nature of the economy is represented by the fact that buildings are used in the extraction of coal. One characteristic feature of bottom-up analysis is its emphasis on major materials and energy flows and the minor and service-oriented inputs are excluded. Based on their mass energy or environmental significance, small material flows may be omitted, as suggested in the ISO standards. For example, where coal-mining operations requires timber framing, it may be excluded from coal production as the impact of timber production and the mass of timber used could be less than 1% of the mass of coal extracted. In this case, timber will be irrelevant in environmental terms compared to energy inputs to coal mining and transport of coal. The relevance of timber used in coal mining as an input to electricity will become even less significant, if the LCA study is expanded so that electricity generation is considered more generally. Process analysis is rich in this type of detail.

Types of LCA used in practice

Process LCA

In a process-based LCA, one specifies the inputs (materials and energy resources) and the outputs (emissions and wastes to the environment) for each step needed to produce a product. The LCA methods implemented in the building construction industry are primarily based on process-based LCA. The different types of process-based LCA methods are:

Cradle-to-Grave

Cradle-to-grave is the full Life Cycle Assessment from manufacture or “cradle” to use phase and disposal phase, “grave.”

Cradle-to-Gate

This includes the assessment of a partial product life cycle from manufacture, “cradle,” to the factory gate, i.e., before it is transported to the consumer. Cradle-to-gate assessments are sometimes the basis for *Environmental Product Declarations (EPDs).* When used for buildings, this would only include the manufacturing and, depending on how the LCA was carried out, the construction stage. Building LCA tools based on assemblies has a starting point for the assessment that might be a collection of cradle-to-gate LCAs completed on major building systems, for example, curtain wall, roof systems, load bearing frames, etc., which are then assembled into a complete cradle-to-grave assessment of the entire building.

Cradle-to-Cradle

This is a specific kind of cradle-to-grave assessment where the end-of-life disposal step for the product is a recycling process. New, Identical or different products are originated from the recycling process. The term cradle-to-cradle often implies that the product under analysis is substantially recycled, thus reducing the impact of using the product in the first place, a work of William McDonough.

Gate-to-Gate

Gate-to-Gate is a partial LCA that examines only one value-added process in the entire production chain, say evaluating the environmental impact due to the construction stage of a building, for example. (Architects, 2010)

Streamlined LCA

Streamlined LCA incorporates a group of approaches designed to simplify and reduce the time, cost and effort involved in conducting an LCA, while it still facilitates accurate and effective decisions. LCA practitioners noted in a North American survey, that a streamlined LCA:

- is simplified, pragmatic, feasible, practical, flexible, fast and easy to use
- represents the most important environmental burdens

- focuses on key impact areas
- limits consideration of effects to first-order impacts
- leaves out some life cycle stages or impact categories
- uses available information to simplify the process
- is less comprehensive
- is more ‘do-able’

Practitioners describe various approaches to streamline LCA, usually involving: narrowing the boundaries of the study, to target specific issues and using readily available data, including the qualitative data.

The principal question that need to be addressed before embarking upon any streamlined LCA comprises of the appropriate level of trade-off of accuracy or depth in results that is acceptable in exchange for the reduced effort in undertaking the evaluation. Quick and dirty LCAs perpetually limit the time spent on data collection by using data that are existing in public databases often already integrated into LCA software. This includes the use of other regional data, proxy processes for data that is not available, and the exclusion of transformation of materials, intermediate transport and so on. The other approach is to reduce the impact indicators and thus reduce the scope of the study and the resources required to undertake it. While reducing the indicators could reduce the data collection, particularly the one on elementary flows, there are two additional tasks that needs to be undertaken. Firstly, careful consideration is required to identify those indicators of primary interest to study where indicators are to be reduced, so that the shortened list of indicators covers the key contestable issues. While the goal and scope can be used to exclude any indicators, the value of the study would be very limited if it does not address basic questions posed by stakeholders. Secondly, the practitioner should comment on and contextualize the results against indicators at the conclusion of the streamlined study. (Architects, 2010)

Input–output and hybrid input–output

Input–output analysis is a top-down economic technique, which uses monetary transactions between the economic sectors rather than physical flows to represent the interrelationships between processes leading to the production of goods and services. In this analysis, direct emissions and resource use arising from within each sector are identified and accumulated as the necessary inputs from each sector. Then in any given sector, these are then calculated to supply final demand. By resolving the infinite and circular nature of the transactions between sectors, input–output analysis effectively traces the supply chain comprehensively. For example, it considers the inputs from transport to make electricity, and the inputs of electricity to make trucks, and the inputs from trucks to make transport, and so on. The limitation of this analysis is the coarse categorization of economic sectors.

In terms of all the different types of goods and services produced in the world, USA’s equivalent input–output table includes about 500 sectors which still represents a problem of gross aggregation. Two solutions to this problem would be to disaggregate the input–output data where more resolution is needed, using more detailed economic data, or to use hybrid techniques where physical flows from process analysis are combined with the hybrid input–output data. (Architects, 2010)

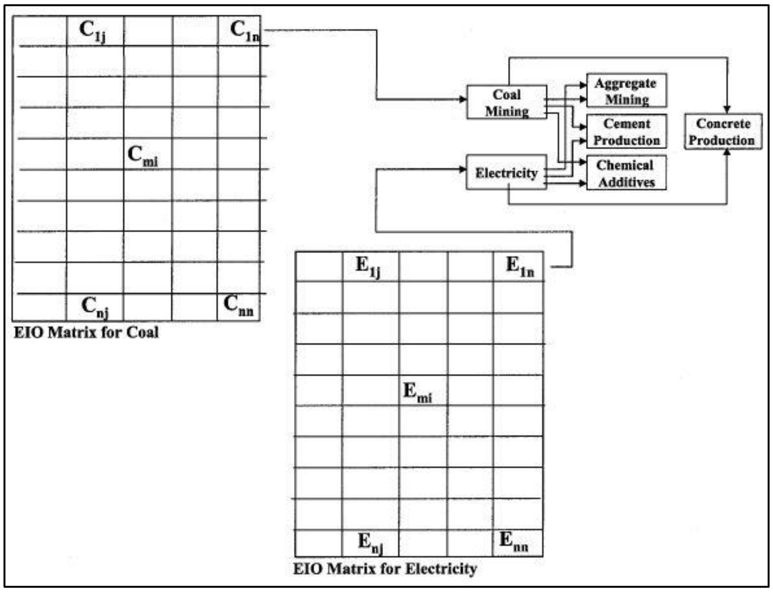


Figure 7: Figure shows the hybrid LCA of ready mix concrete

Studies in LCA

Assessing the environmental impacts of construction and buildings involves more than the simple aggregation of material assessments and individual product. Simultaneously, there are several studies which have attempted to assess complete buildings, building systems, and construction processes. These efforts have often identified that life-cycle phases with the most environmental impacts, have provided a basis for overall building system assessment. Some of these studies include:

(G Keoleian, 2000) evaluated the life-cycle energy use, greenhouse gas emissions, and the costs of a standard residential home in Ann Arbor, Michigan, covering pre-use (materials production and construction) phase, use (including maintenance and improvement) phase, and demolition phases. They established that the use phase accounted for 91% of the total life-cycle energy consumption over a 50-year home life.

They also came up with a model which was functionally equivalent energy efficient house that incorporated 11 energy-efficiency strategies and found that these strategies led to a dramatic reduction in the total life-cycle energy use.

(S Citherlet, 2007) presented a process-based lifecycle assessment of three home designs in Switzerland. In this study, they classified life-cycle environmental impacts into direct and indirect categories; where the direct impacts included all use-related energy consumption impacts; and the indirect impacts included other upstream and downstream impacts from material extraction, production, construction, demolition, etc. The results of the study inferred that direct environmental impacts can be significantly reduced by better insulation and by the use of renewable energy sources.

(Hovarath, 2003) studied the environmental impacts of a concrete-framed office building located in Finland. The authors mentioned that, while previous environmental studies related to buildings have focused either on limited environmental indicators, or on a limited set of life-cycle phases, their study attempted to comprehensively evaluate life-cycle environmental impacts in relation to climate change, acidification, eutrophication, and dispersal of harmful substances. It was also found that electricity and heat use during building operation (use phase) and building material production caused the most significant environmental impact, consistent with the other previous studies. The study also suggested that U.S. buildings might have even higher use-phase impacts because of higher tenant turnover rates and more fossil fuel-based energy generation, and it was recommended to examine case studies from the perspective of various decision makers.

(Gheewala, 2008) conducted an LCA for an office building in Thailand and found that steel and concrete accounted for greatest of the material-related environmental impacts, where the use-phase energy consumption accounted for 52% of total life-cycle impacts.

While the above discussed studies analyzed whole buildings, some studies have focused only on the building subsystems. (Ries, 2004) used a process-based LCA framework to evaluate the environmental impacts of construction and operations of a cogeneration facility to meet the energy requirements of a commercial building. They performed energy simulations to determine the building's energy needs throughout the year. Later the results of the study found that certain cogeneration facilities might have been environmentally preferable over conventional energy production facilities.

(Hutzler, 2005) conducted parallel LCAs and LCCAs to determine the environmental and economic efficiency of various water supply systems for multioccupant buildings from the energy and resource use perspective over a period of 25-year life cycle. They applied the *Building for Environmental and Economic Sustainability (BEES)* software to measure the environmental impacts and off-the-shelf cost databases for economic analysis. It was found that the use of efficient plumbing fixtures and natural gas for water heating was economically and environmentally preferable.

(Glick, 2007) analyzed two heating system solutions a gas forced-air system (GFA) and a solar radiant system (SRS) for a home in Colorado. The analysis included both environmental LCA and LCCA. The study considered the environmental performance indicators as energy use and global warming potential (GWP) and assessed these for manufacturing, construction, use and maintenance, and disposal phases. Life-cycle cost analysis was also performed for the manufacturing and use and maintenance phases. The results of the study suggested that the gas forced-air system is both environmentally and economically preferable to solar radiant system, but a hybrid solution incorporating a gas-fired boiler in the solar radiant system is an overall optimal choice.

LCA Methodology

The LCA methodology is divided into 4 different stages. They are-

- Goal and Scope definition
- Inventory Analysis
- Impact assessment
- Interpretation of Results.

Goal and Scope Definition

This section defines on which product the LCA study is carried on and also the purpose of carrying out the LCA study on that product. According to *International Standard Organization (ISO 14040 1997)* the goal definition incudes stating the intended application of the study, the reason for carrying it out and to whom the results are intended to be communicated. When an LCA study is originated, the purpose of the study is often expressed very vaguely and generally. A problem formulation is specified more clearly before the LCA study is performed.

The functions of Goal and scope is that the context of the study is defined – whom does the study cater to and how are the results to be communicated. There are also some choices made during this phase. During this phase, the choices of what to study are made and governed by the system boundaries of the flow model constructed in subsequent inventory analysis. The types of environmental impacts are considered. There are more or less default list of impacts which are always considered in most of the LCA`s. For example resource use, global warming, acidification and eutrophication, but sometimes LCA`s are limited to covering only certain impacts. The chosen impacts determine the parameters for which data will be collected during the inventory analysis. The next step would be the level of detail in the study and thus the requirements on the data- whether to use the site specific data or the data describes an average over a number of production sites.

Inventory analysis

This phase in LCA methodology means to build a systems model according to the requirements of the goal and scope definition, which is a flow model of a technical system with certain types of system boundaries. The result got is an incomplete mass and energy balance for the system, in the sense that only the environmentally relevant flows are considered, which more or less includes the use of scarce resources and emissions of substances considered harmful. Environmentally indifferent flows such as water vapor emissions from combustion and industrial surplus heat are disregarded. The activities involved in Life cycle inventory analysis are-

1. Construction of flow model according to the system boundary decided on in the goal and scope definition. The flow model is usually represented as a flowchart that shows the activities included in the analyzed system (production, processes, transports and waste management) and the flows between these activities.

2. Data collection for all activities (processes and transports) in the product system. The collected data include inputs and outputs of all activities such as
    - Raw materials, including energy carriers
    - Products and
    - Solid waste and emissions to air and water.

3. Calculation of the amount of resource use and pollutant emission of the system in relation to the functional unit. (Henrikke Baumann, 2004)

Inventory results are often explained as bar charts and other types of graphic representation. The inventory analysis seems very straightforward but usually it is a complicated process by the fact that many technical processes produce more than one product. The environmental load of such processes might be allocated, i.e. portioned between its different products. Allocation complicates life cycle inventories considerably.

Life Cycle Impact Categories

LCA methodologies have Life Cycle Impact categories that vary from system to system. These categories are mappings from quantities of emissions to the environmental impacts that these emissions cause. They can be thought of as a class of environmental issues of concern to which Life Cycle Inventory (LCI) results may be assigned. They have also been established from nationally recognized standards established by the agencies such as the *Environmental Protection Agency, Occupational Safety and Health Administration, and National Institutes of Health*. The impact is usually specified as a ratio of the quantity of the impact per functional unit of the product produced. Each category is an indicator of the contribution of a product to a specific environmental problem. A set of impact categories common to many LCA methods are explained below-

Global Warming Potential (GWP)

Global Warming Potential has been developed to characterize the change in the greenhouse effect due to emissions and absorptions attributable to humans. The unit for measurement is grams equivalent of CO2 per functional unit of product (note that other greenhouse gases, such as methane, are included in this category, thus the term “CO2 equivalent” is an impact and not an emission).

Acidification Potential (AP)

Acidifying compounds emitted in a gaseous state either dissolve in atmospheric water or fixed on solid particles which reach the ecosystems through dissolution in rain. The two compounds principally involved in acidification are sulfur and nitrogen compounds. The unit of measurement is grams of hydrogen ions per functional unit of product.

Eutrophication Potential (EP)

Eutrophication Potential is the addition of mineral nutrients to the soil or water. In both media, the addition of large quantities of mineral nutrients such as nitrogen and phosphorous results in generally undesirable shifts in the number of species in ecosystems and a reduction in ecological diversity. Excess nutrient in water leads to increased biological oxygen demand (BOD) from the dramatic increase in flora that feed on these nutrients, a subsequent reduction in dissolved oxygen levels, and the collapse of fish and other aquatic species. The unit of measurement is grams of nitrogen per functional unit of product.

Fossil Fuel Depletion (FFD)

This impact addresses only the depletion aspect of fossil fuel extraction, not the fact that the extraction itself may generate impacts. The unit for measurement is mega joules (MJ) of fossil-based energy per functional unit of the product. This category helps to demonstrate positive environmental goals, such as reducing the energy needed to produce a product, or producing a product with renewable, non-fossil-based energy.

Smog Formation Potential (SFP)

Under certain climatic conditions, air emissions from industry and fossil-fueled transportation could be trapped at ground level, where they react with sunlight to produce photochemical smog. The contribution of a product or system to smog formation is quantified by this category. The unit of measurement is grams of nitrogen oxide per functional unit of product. This highlights an area where a regional approach to LCA may be appropriate, as certain regions of the world are climatically more susceptible to smog.

Ozone Depletion Potential (ODP)

Emissions from some processes may result in the thinning of the ozone layer, which protects the earth from certain parts of the solar radiation spectrum. Ozone depletion potential measures the extent of this impact for a product or system. The unit of measurement is CFC-11 per functional unit of the product.

Ecological Toxicity (ET)

The ecological toxicity impact measures the potential of a chemical released into the environment to harm terrestrial and aquatic ecosystems. The unit of measurement is grams of 2, 4-dichlorophenoxy-acetic acid per functional unit of product.

Water Use (WU)

Water resource depletion has not been routinely assessed in the recent LCAs, but researchers are beginning to address this issue to account for areas where water is scarce, such as the western United States. The unit of measurement is liters per functional unit.

It should be noted that the impact categories described above is in accordance with TRACI LCIA method used in the Building for Environmental and Economic Stability (BEES®) tool. Other impact categories included but not described here are Habitat Alteration, Criteria Air Pollutants and Human Health, etc.

Life Cycle Impact assessment

Life Cycle Impact Assessment aims to describe, indicate, the impacts of the environmental loads quantified in the inventory analysis. Thus one purpose of the LCIA is to turn the inventory results into more environmentally relevant information, which means the information on impacts on the environment rather than just information on emissions and resource use.

The first step is *classification*- which means that sorting the inventory parameters according to the type of environmental impact they contribute to. The next step would be Characterization- calculations of the relative contributions of the emissions and resource consumptions to each type of environmental impact. For example, all emissions of greenhouse gases may be aggregated into one indicator for acidification. Such calculations are based on scientific models of cause-effect chains in the natural systems. However, these cause-effect models used in LCIA are sometimes simplified. Instead of uncertainties and other limitations of characterization, the numerous result parameters of an LCA may be aggregated into a limited number of impact categories. This could be done in several ways- both formalized and quantitative weighing procedures or through expert panels or with qualitative, verbal argumentation. This cannot be done one based solely on natural science but values must be introduced. Such a weighting method is described as a 'yardstick' with which all environmental problems are measured and they are based on values and preferences concerning environmental goals that may be used to create a weighting system.

Life Cycle Impact Assessment is thus a stepwise aggregation of the information given by the inventory results. Classification and Characterization are compulsory in LCA according to the standard (ISO 14042 2000) whereas weighting could be optional. If no impact assessment is performed, but only an inventory analysis is done, the study is referred to as Life Cycle Inventory analysis (LCIA).

Several methods are used to convert the LCI analysis results (quantities of materials and energy used and resulting emissions) into environmental impacts. Some of the commonly used methods are Eco-indicator 99, EDIP 1997 and IMPACT 2002+. The *Tool for the Reduction and Assessment of Chemical and other environmental Impacts* (TRACI) is an impact assessment tool developed by Environmental Protection Agency (EPA), and it allows the examination of the potential for impacts associated with the raw material usage and chemical releases resulting from the processes involved in producing a product, examine the potential for impacts for a single life cycle stage or the whole life cycle and to compare the results between products or processes (Architects, 2010).

Interpretation of Results

Enhancement of raw results into useful, presentable and final results requires a process that may involve screening of the raw results, identification of critical data and assessments of the importance of missing data. The process of assessing the results in order to draw conclusions in LCA methodology is called interpretation. The term Life Cycle Interpretation is defined in the ISO 14040 standard as the…..

"…. Phase of life cycle assessment in which the findings of the inventory analysis or the impact assessment, or both, are combined consistent with the defined goal and scope in order to reach conclusions and recommendations." (ISO 14040 1997).

Evaluations of the robustness of conclusions drawn in an LCA study are also part of the interpretation phase which typically entail sensitivity analysis, uncertainty analysis, and data quality assessments. LCA studies often produce surprising, unexpected results, and therefore beyond the intended goal and scope. These unexpected results usually offer great potential for learning, and the ability to make use of surprising results is an important element in LCA application. Since LCA is an iterative process, the existence of unexpected results poses a problem, it is always possible to reformulate the goal and scope.

Materials used in Building Envelope

Building Envelope/Wall system/ Façade makes an overall contribution to the technical and aesthetic aspect of a building. The most commonly used building materials for the façade is Concrete, Stone, Glass, Wood and Metal. The following paragraph will explain some of the façade construction technologies. As mentioned above, the study involves description of six different wall systems. They are -

1. Tilt Up Concrete Construction
2. Cast-in-place Concrete Construction
3. Concrete Blocks
4. Steel Stud Construction
5. Curtain Wall Envelope System
6. Insulated Concrete Form Construction

Tilt Up Concrete Wall Construction

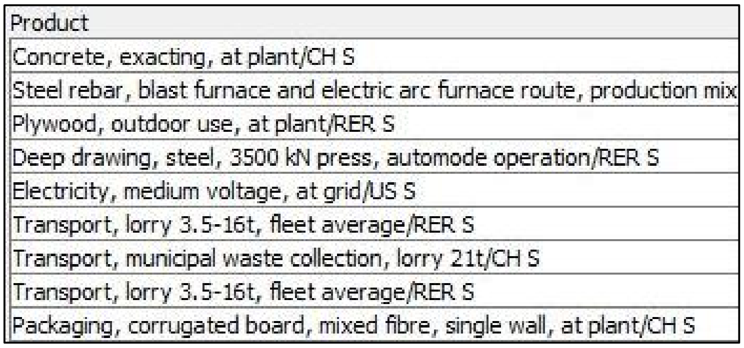
Figure 8: Schindler-Chase house (Rudolf Schindler) is an early example of Tilt-Up concrete construction

Tilt-Up concrete construction is not new; it has been in use since the turn of the century. Over 15% of all industrial buildings are Tilt-Up, ranging in size from 5,000 to over 1.5 million square feet nationwide. They are characterized by their attractiveness, efficiency and longevity. It is one of the rapidly growing industries in the United States with at least 10,000 buildings enclosing more than 650 million square feet are constructed annually. *Tilt-up, tilt-slab or tilt-wall* is a type of building and a construction technique using concrete which is a cost-effective technique with a shorter completion time, poor performance in earthquakes has mandated significant seismic retrofit requirements in older buildings (Wikipedia, Tilt up , 2013). These concrete elements are formed horizontally on a concrete slab, usually the building floor or sometimes a temporary concrete casting surface near the building footprint. Once the concrete has been cured, the concrete elements are “tilted” to vertical position with a crane and braced into the position until the other building components are secured.

Figure 9: A Tilt-Up concrete construction at site. (Source: Wikipedia)

Construction of this envelope system requires significant organization and collaboration on the building site. Site Evaluation, engineering, forming tilt-up panels, steel placement, embeds and inserts, concrete placement, panel erection and panel finishing. Once the casting surface has been cured, forms are built on top. A high quality plywood or fiber board that has at least one smooth face is typically used, although aluminum and steel forms are used. Door, window openings, and other architectural features of any desired shape can be molded into the concrete. Studs, gussets and attachment plates are located within the form for embedding in the concrete. A rebar grid is constructed inside the forms, its size and spacing is generally specified by the engineer. A chemically reactive bond-breaker is sprayed on the form's surfaces to prevent the cast concrete from bonding with the slab. This allows the cast element to separate from the casting surface once it has cured. Improper chemical selection or application will prevent the lifting of the panels, and will entail costly demolition and rework. Concrete is poured with desired thickness and surrounded by steel inserts, embedded features and rebar. Later, these forms are cured, rigging is attached and a crane tilts the panel or lifts the element into place. Cranes are used to tilt the concrete elements from the casting slab to a vertical position. Tilt up walls are very heavy, as much as 300,000 pounds (140 t) or more, engineered to work with the roof structure and/or floor structures to resist all forces that is to function as load-bearing walls.

Table 1: Table shows the Inventory Data for Tilt-Up concrete Wall construction (Source: Simapro)



Product
Concrete, exacting, at plant/CH S
Steel rebar, blast furnace and electric arc furnace route, production mix
Plywood, outdoor use, at plant/RER S
Deep drawing, steel, 3500 kN press, automode operation/RER S
Electricity, medium voltage, at grid/US S
Transport, lorry 3.5-16t, fleet average/RER S
Transport, municipal waste collection, lorry 21t/CH S
Transport, lorry 3.5-16t, fleet average/RER S
Packaging, corrugated board, mixed fibre, single wall, at plant/CH S

These wall panels are either solid concrete, or they may be sandwich-type construction. Insulation could be incorporated into tilt-up to provide energy efficient construction with hard exterior wall surfaces. Walls can range from R-values of about 2 for uninsulated panels up to about 32 for walls containing thicker layers of insulation. As building codes require greater energy efficiency, the thickness of insulation increases. Energy performance is an important part of tilt-up's environmental friendliness that apply to any type of concrete, which offers high thermal mass, and airtight construction. The panelization also means fewer joints and reduced air infiltration. There is potential for recycled content in tilt-up concrete. The wall panels can be demolished and the concrete recycled at the end of its life as it is locally produced. It is durable and low maintenance. (Portland Cement Association, 2013)

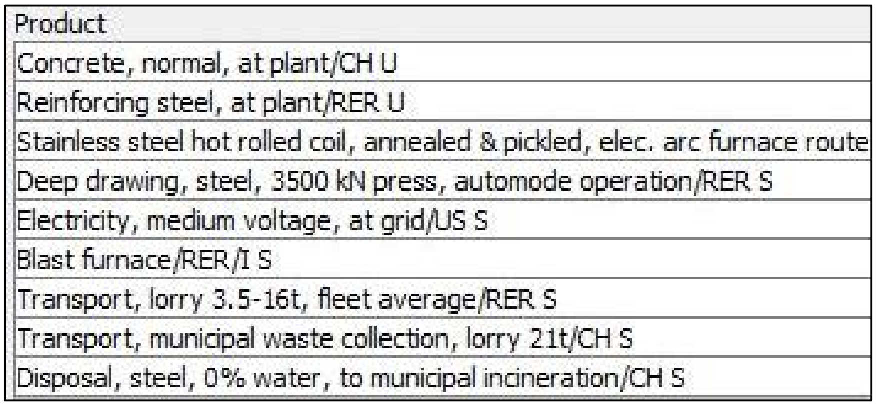
Cast in Place Concrete Wall Construction

Figure 10: Framework for Precast concrete wall (Source: Baruzzini Construction)

Cast-in-Place (CIP) concrete walls are all made with ready mix concrete placed into different wall forms erected on the site. This type of technology was invented by Thomas Edison, generally defined by the buildings structural systems, which has the vertical (gravity) load resistant systems and the lateral (wind and seismic) resistant system. The vertical load resistant systems includes the floor and wall system, whereas the lateral resistant system includes shear walls, braced frames or a combination of all these systems. In the United States, any concrete structure built follows the provisions of the ACI Building Code. The codes not only provides safety requirements but also prescribes serviceability and durability requirements.

The construction of a cast-in-place wall is relatively simple which includes placement of temporary forms and then later placing the reinforcement bars and pouring the ready mix concrete on site. Builders usually place formwork starting from the corner and then fill in between the corners. The reinforcement bars are then erected. With the help of truck chute, bucket or pump concrete is poured into the forms, which are filled at an appropriate rate based on formwork manufacturer recommendations. Door and window openings are made with fasteners around them. The thickness of these walls range from anywhere between 4 to 24 inches. Uninsulated walls are typically 6 to 8 inches thick and walls with insulation are generally thicker when they contain an internal layer of insulation, either the inner or outer wall layer will serve a structural purpose. (Guide, n.d.).

Table 2: Table shows the Inventory Data for Cast in Place concrete Construction (Source: Simapro)



Product
Concrete, normal, at plant/CH U
Reinforcing steel, at plant/RER U
Stainless steel hot rolled coil, annealed & pickled, elec. arc furnace route
Deep drawing, steel, 3500 kN press, automode operation/RER S
Electricity, medium voltage, at grid/US S
Blast furnace/RER/I S
Transport, lorry 3.5-16t, fleet average/RER S
Transport, municipal waste collection, lorry 21t/CH S
Disposal, steel, 0% water, to municipal incineration/CH S

Energy performance of these wall types are good as they consume less energy to heat or cool the space than walls with wood or steel frames. A wall type with thermal mass has the capacity to store warmth and cold which in turn moderates internal temperature fluctuations, slowly transfer the heat through the building and also reduced the loads on the HVAC systems. But energy savings due to thermal performance completely depends on the climate. CIP walls have 10 to 30% better air tightness compared to framed walls as the concrete envelope contains few joints. They also provide consistent interior temperatures for occupants, and increases their comfort. These wall types are also suited to the use of recycled materials- concrete could be made by the use of materials like fly ash or slag to replace the portion of cement.; aggregates could be recycled to reduce the need of virgin aggregate and the steel used for reinforcement can be recycled. (Guide, n.d.)

Concrete Blocks

As the word says, “Concrete Blocks” (CB) are made of concrete. They are large rectangular bricks used in construction, made from cement and aggregate, usually made of sand and fine gravel especially for high sensitivity blocks. The first hollow concrete block was designed in 1890 by Harmon S Palmer in the United States, after 10 years of experimenting and then later he patented the design in 1900. The blocks he designed were of the dimensions 8 inches (20.3 cm) by 10 inches (25.4 cm) by 30 inches (76.2 cm) and were so heavy that a small crane was needed to lift them. (Portland Cement Association, 2013).

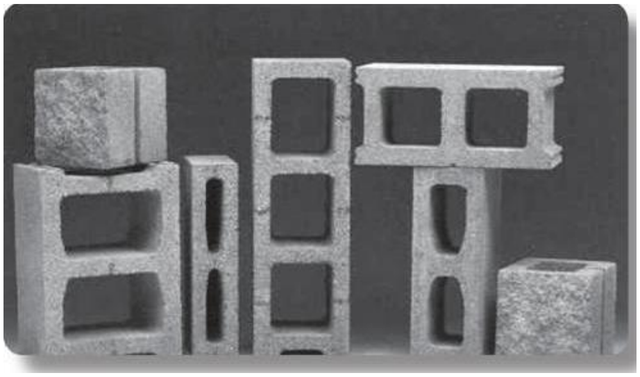


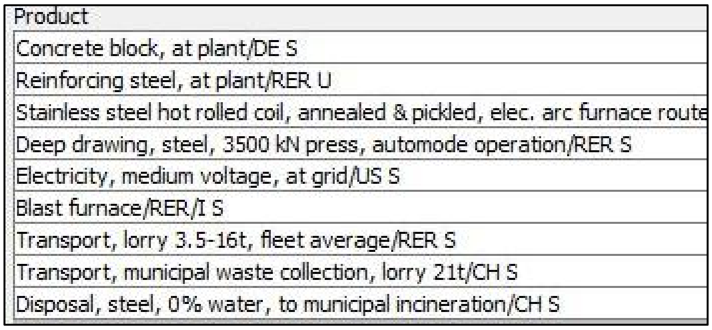
Figure 11: Hollow Concrete Blocks (Source: Building Materials BlogSpot)

The concrete normally used to make concrete blocks is a mixture of powdered Portland cement, water, sand and gravel. This kind of mixture produces a *light* *gray block* with a fine surface texture with a high compressive strength. A typical concrete block weighs between 38 -43lb (17.2 – 19.5kg). The mixture comprises of higher percentage of sand and a lower percentage of gravel and water than the concrete mixtures used for general purposes which produces a very dry, stiff mixture that holds its shape when it is removed from the block mold. There are *light weight concrete blocks* that made by replacing sand and gravel with expanded clay, shale or slate, produced by crushing the raw materials and heating them to about 2000 F (1093 C). (Cavette, 2007)

The shape and sizes of most of the concrete blocks have been standardized to ensure uniform building construction with sizes – 8 X 8 X 16 inches (20.3 X 20.3 X 40.6 cm). This measurement includes room for bead of mortar, and the block itself actually measures 7.63 X 7.63 X 15.63 inches (19.4 X 19.4 X 38.8 cm). The manufacture of these blocks requires constant monitoring to produce blocks with the required properties. (Portland Cement Association, 2013). The raw materials are then weighed electronically before they are placed in the mixer. Ultrasonic sensors are used to measure the trapped water content in the sand and gravel, and the amount of water to be added is automatically compensated. The water may pass through a chiller or heater before it is used where the climate is extreme. When the blocks come out of the machine, their heights are checked with the help of laser beam sensors. The temperatures, pressures, and cycle times are all controlled and recorded automatically to ensure that the blocks are cured properly in the curing kiln.

As these wall systems are exposed to sun and exterior temperatures, they can be heated or cooled, absorb the heat and will radiate the heat to the surrounding components of the wall system. Their thermal performance is purely based on the insulation capacity in the wall cavity or within the backup wall. Even light weight concrete blocks provide considerate amount of thermal mass compared to wall systems such wood frame or steel stud. *Light weight blocks* stores less heat, compared to heavy weight blocks of the same thickness, at the same time release the heat more slowly, which improves the overall thermal performance. In the southern regions of the United States, concrete blocks have been most popular where buildings are subjected to significantly warm and humid climates. It provides a strong and durable structure, withstanding both routine natural wear as well as extraordinary impacts of natural and human disasters.

Table 3: Table shows the Inventory Data for Concrete Block Construction (Source: Simapro)



Product
Concrete block, at plant/DE S
Reinforcing steel, at plant/RER U
Stainless steel hot rolled coil, annealed & pickled, elec. arc furnace route
Deep drawing, steel, 3500 kN press, automode operation/RER S
Electricity, medium voltage, at grid/US S
Blast furnace/RER/I S
Transport, lorry 3.5-16t, fleet average/RER S
Transport, municipal waste collection, lorry 21t/CH S
Disposal, steel, 0% water, to municipal incineration/CH S

These blocks are often manufactured with recycled content. Fly ash, slag cement, or silica fume can substitute for cement, whereas recycled aggregates can replace newly mined gravel. There are even mortar less units available which are “dry-stacked” and are generally held together by a coat of bonding plaster inside and out. Portland cement plaster, or stucco is made from the same material and is sometime considered to be a masonry product.

Curtain Wall System

It can be defined as a thin, any non-load bearing that hangs like a curtain regardless of construction or cladding material, usually made of aluminum frame containing glazing patterns, metal panels or thin stone. The framing which is attached to the building structure does not carry the floor or roof loads of the building. As far as the wind and gravity loads are concerned, they are transferred to the building structure typically to the floor line. These wall systems dates back to the 1930’s when aluminum became available for non-military use. Curtain wall systems are either to manufacturer’s standards or even specialized. (Nik Vigener, PE and Mark A. Brown, 2012)

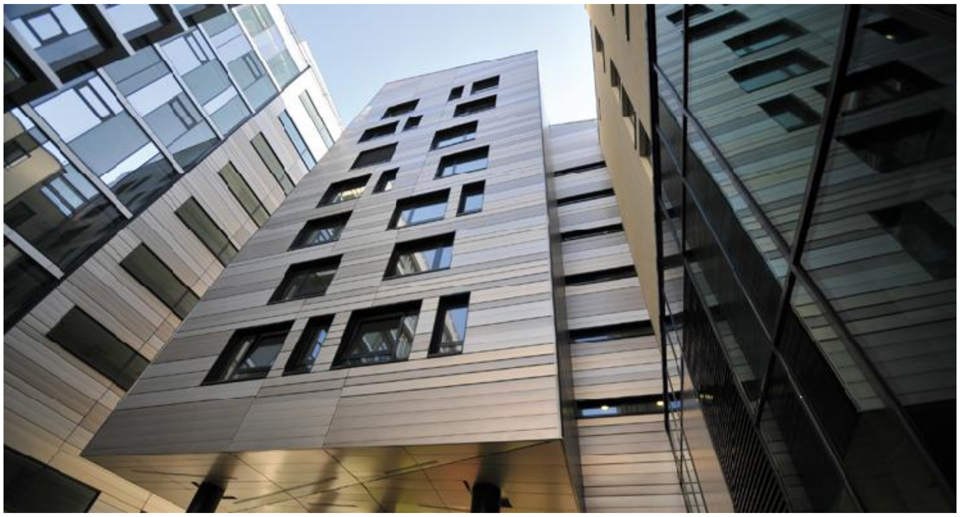


Figure 12: Metal Facade Panel Location: Bratislava Slovakia (Slovak Republic) (Source: Hunter Douglas Facade systems)

Curtain walls can be classified on basis of their fabrication and installation. (Window and Wall systems, n.d.) They are:

Storefront- non-load bearing glazed systems that occur on the ground floor, which includes commercial aluminum entrances, installed between floor slabs and the roof above. The performance requirements for storefront are usually less-stringent, and materials may require frequent maintenance.

Stick wall- These systems are shipped in pieces for field-fabrication, furnished by the manufacturer as “stock lengths: to be cut machines, assembled and sealed in the field. When the frames are assembled, either “shear blocks” are used to connect the vertical and horizontal framing elements, or “screw-spline” construction, and assembly fasteners feed through holes in interlocking vertical stacking mullions into extruded races in horizontals.

I-Beam walls- In this type of Wall system, “I” or “H” shaped structural, vertical back members are set into window openings in the field, with horizontal members and later clipped to verticals. The extruded aluminum`s interior trim is cut and snapped into place at vision areas, once glazing is done. The unexposed spandrel area is left and doesn’t require any finish.

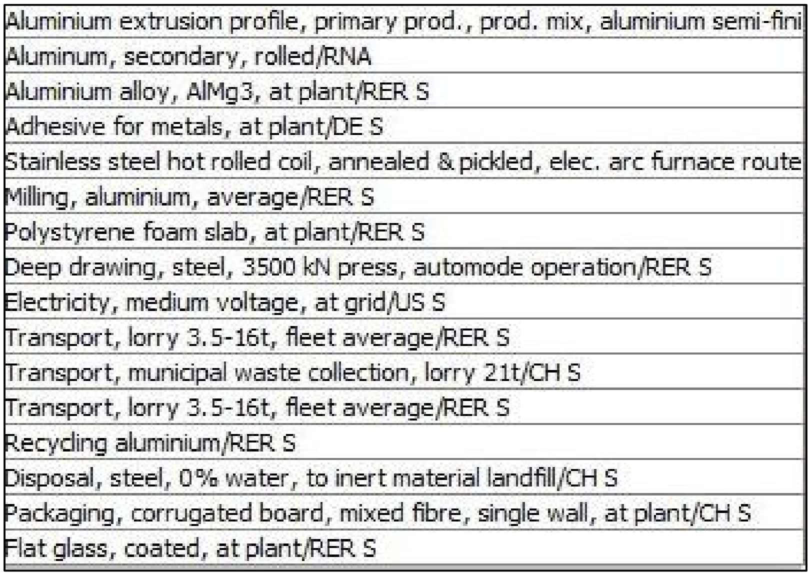
Pressure Walls- When the extruded aluminum plates are screw-applied to compress glass between interior and exterior bedding gaskets, they are called “pressure walls”. To conceal the pressure plate fasteners, a Snap-On cover or “beauty cap” is used. Field assembles or field-glazed curtain wall performs only as good as field workmanship allows, limited by variables such as weather, access, and job site dirt and dust. Seals are necessary for these systems which are designed to drain or “weep” rain penetration from the system back to the exterior.

Unitized Walls- These are *“factory-assembled and glazed”* units which are shipped to the job site. These kind of wall systems are installed in sequential manner around each floor level, moving from the bottom to the top of the building. Sealing fixtures are very limited in Unitized walls, having a translucent silicone sheet or patch, which are field-sealed.

One anchor per mullion is attached to the face of the floor slab. Due to its unique configuration, the horizontal gutter weather-seal is sometimes called “chicken head”. Interlocking unitized curtain wall frame members are weather-stripped to seal to one another both horizontally and vertically. This takes care of the thermal expansion and contraction, inter-story differential movement, and/or seismic movement.

Window Wall-   These systems span from the top of one floor slab to the underside of the slab above. It employs large, side-stacking window units, contained in head and sill receptors known as “starters” which facilitates movement and drainage, with field-applied perimeter sealants. Window wall systems are easily acceptable operable windows, and can be installed non-sequentially.

Table 4: Table shows the Inventory Data for Curtain Wall Construction (Source: Simapro)



Aluminium extrusion profile, primary prod., prod. mix, aluminium semi-fini
Aluminum, secondary, rolled/RNA
Aluminium alloy, AlMg3, at plant/RER S
Adhesive for metals, at plant/DE S
Stainless steel hot rolled coil, annealed & pickled, elec. arc furnace route
Milling, aluminium, average/RER S
Polystyrene foam slab, at plant/RER S
Deep drawing, steel, 3500 kN press, automode operation/RER S
Electricity, medium voltage, at grid/US S
Transport, lorry 3.5-16t, fleet average/RER S
Transport, municipal waste collection, lorry 21t/CH S
Transport, lorry 3.5-16t, fleet average/RER S
Recycling aluminium/RER S
Disposal, steel, 0% water, to inert material landfill/CH S
Packaging, corrugated board, mixed fibre, single wall, at plant/CH S
Flat glass, coated, at plant/RER S

The performance of these systems depends on the type of material used. For example, aluminum is a good conductor of heat so it will have a high heat transfer co-efficient. This shows that there is high heat loss through aluminum curtain wall mullions. To compensate these heat losses- are thermal breaks, barriers between the exterior metal and interior metal, usually made of polyvinyl chloride (PVC). Also, thermal conductivity, use of low-e and spectrally selective glass coatings, can significantly play a role in reducing the HVAC loads in the building. Good design practices ensures durability of the curtain wall systems and they must also be designed for accessibility for maintenance. For low-rise buildings, it is accessed from the ground using equipment with articulated arms, whereas for high-rise buildings, swing stage access for window cleaning, general maintenance and repair work, like glass replacement. Thus, it is always better to use systems that have a good thermal break and high R-value.

Aluminum and Steel systems are typically recycled during their end of life phase. But recycling would become difficult if aluminum is contaminated with sealants, fractured glazing, etc.

Insulated Concrete Forms

Insulated concrete forms are system of formwork for reinforced concrete that stays in a place as a permanent interior and exterior substrate for walls, floors and roofs. These forms are interlocking modular units which are dry-stacked and filled with concrete in between. They form structural walls and floors of building by locking together and commonly called as “Lego” bricks. For both low-rise commercial and high performance residence construction, ICF construction has become common, due to the adoption of more stringent energy efficiency and natural disaster resistant building codes. (Portland Cement Association, 2013) This technique was first developed in Europe following the Second World War as an inexpensive and durable way to rebuild damage structures. In the 1960s the first polystyrene ICF forms were developed, after which these forms have steadily increased.

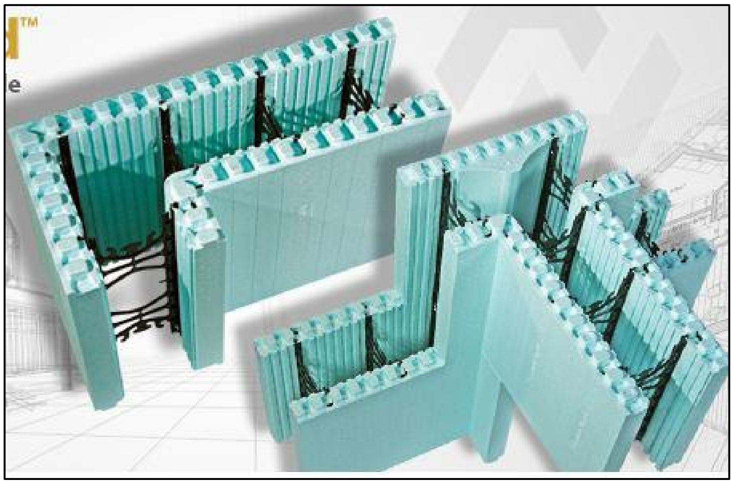


Figure 13: Insulated Concrete Forms (Source: NUDURA Integrated building Technology)

Insulated concrete forms are manufactured from either Polystyrene foam, polyurethane foam, cement-bonded wood fiber, cement-bonded polystyrene beads, or cellular concrete. There are ties that interconnect the two layers of insulated forming material made of either plastic, metal or additional projections of the insulation. Latest trends include hinges into the ties that allows preassembled forms to fold flat or easy, contributing to cost-effective shipping. The method of construction of these forms are pretty simple. First concrete is pumped into the cavity to form the structural elements of the walls. The reinforced steel is added before the concrete is poured for flexural strength. After the concrete has been cured, the forms are left in place permanently, to provide a variety of benefits like thermal performance, acoustic insulation, improved indoor air quality according to the materials used.

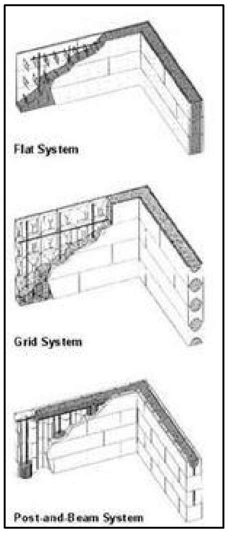
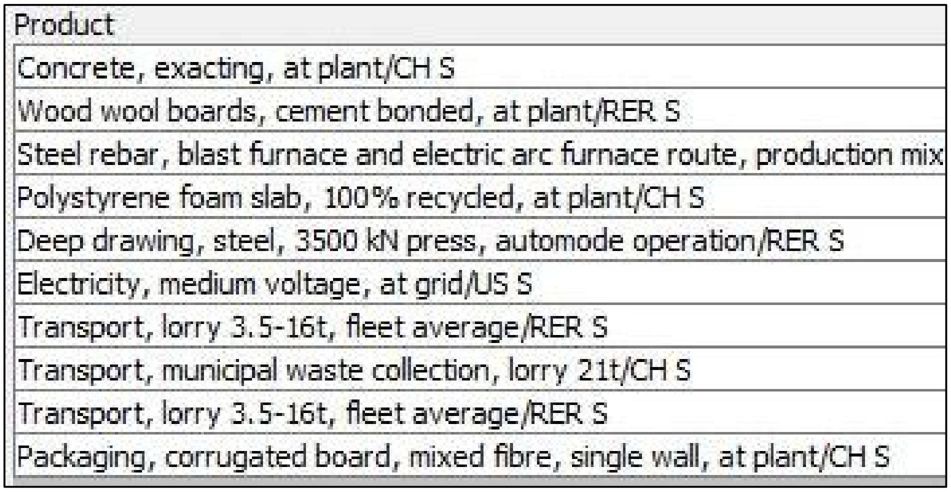


Figure 14: Different Types of ICF systems

ICF systems vary in their design. “Flat” systems yield a continuous thickness of concrete like a conventionally poured wall. “Grid” systems have a waffle pattern where the concrete is thicker at some points than others. “Post and Beam” systems have discrete horizontal beams and columns that are completely condensed in foam insulation. All major ICF wall systems are engineered- designed, code driven and field-proven.

Table 5: Table showing the inventory data of Insulated Concrete Form Wall Construction



Product
Concrete, exacting, at plant/CH S
Wood wool boards, cement bonded, at plant/RER S
Steel rebar, blast furnace and electric arc furnace route, production mix
Polystyrene foam slab, 100% recycled, at plant/CH S
Deep drawing, steel, 3500 kN press, automode operation/RER S
Electricity, medium voltage, at grid/US S
Transport, lorry 3.5-16t, fleet average/RER S
Transport, municipal waste collection, lorry 21t/CH S
Transport, lorry 3.5-16t, fleet average/RER S
Packaging, corrugated board, mixed fibre, single wall, at plant/CH S

ICF are structural wall members that is up to 10 times stronger than wood framed structures. Materials used in making these wall systems like the polystyrene foam or even the poured concrete don’t rot when they get wet. Block sizes are typically in the order of 16 inches high by 48 inches long. The cavities in between these blocks are anywhere between 6 inches to 8 inches depending on what is needed. The thickness of the foam faces also varies between 1-7/8 in to 2-3/4 in. After all finishes are applied, the final wall thickness is greater than 1ft. This results in deeper window sills as the depth of window and door surrounds have to wider than the usual frame wall construction. (Portland Cement Association, 2013)

Greater insulation, tighter construction and temperature-moderating mass of the walls conserve heating and cooling energy much better than conventional wood-frame walls. This reflects the monthly fuel bills. Building ICF walls, saves a lot of trees being destroyed. The concrete used for the construction could be made of out of materials like fly-ash, or slag replacing the cement. Virgin aggregate material can be reduced and replace by crushed concrete. Steel and polystyrene are also recycled.

Steel Stud wall Construction

Steel stud wall systems are used in both residential and commercial construction. A wall stud is defined as a vertical member in the light- frame construction techniques called balloon framing and platforms framing of a buildings wall. Their construction consists of Extruded polystyrene insulation with the joints sealed combined with batt insulation providing a thermal moisture and air barrier wall system. The energy code requirements complies with providing continuous insulation thereby reducing the effect of thermal bridging.

Figure 15: Steel Stud Wall of an Industrial Building (Source: Dreamstime)

Typical components of these systems are C-studs with knockouts and U-shaped tracks.

The high strength-to-weight ratio of light gauge steel maximizes building design flexibility, while providing rigid structural integrity. Metal Studs comes in changing lengths ranging from 8 ft. to 24 ft. with tracks having lengths of 10 ft. (Clark Dietrich Building Systems, 2009)

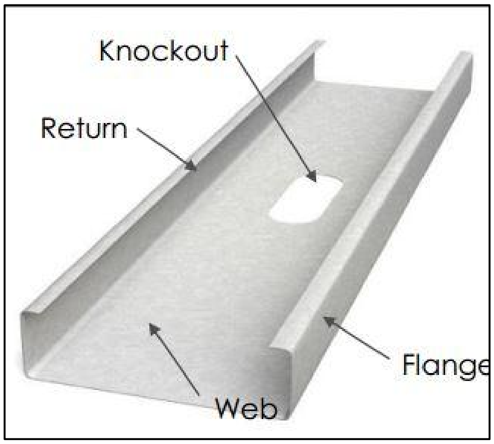


Figure 16: C-Studs

C-Studs

C-studs are also used for in-fill, bypass (balloon), and spandrel framing and are available in a wide range of sizes, flanges, gauges, and yield strengths. Structural steel C-studs are available with web sizes ranging from 2-1/2" to 14". Web depths greater than 14" are typically not available. The flange of the C-stud provides a bearing surface for cladding materials and is a key contributor to the load-bearing capacity of the member. Flanges are available in sizes from 1-3/8" to 3".

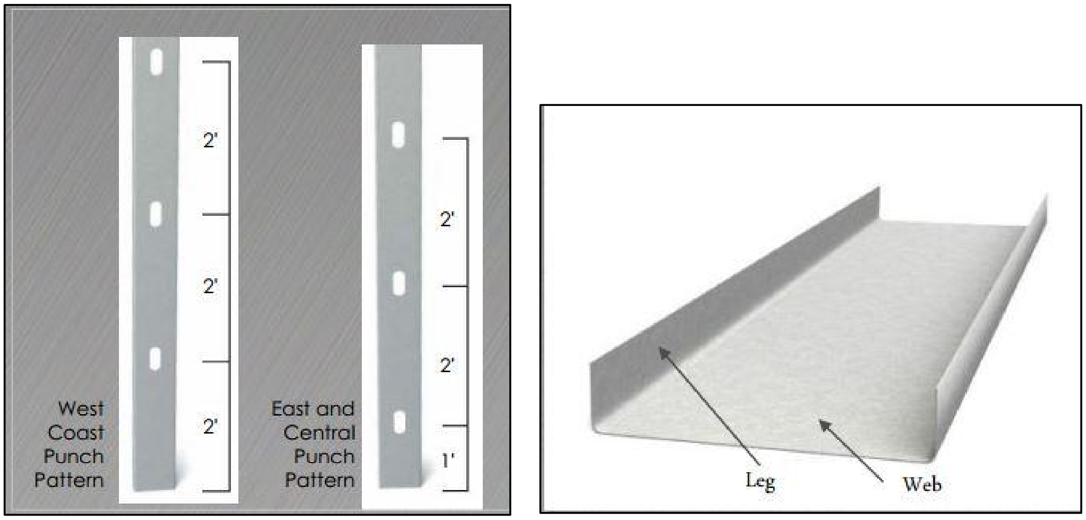


Figure 17: Knockouts and Tracks

Knockouts

C-studs are pre-punched with knockouts at regular intervals to allow rapid installation of electrical conduit, mechanical, and piping. Bridging products are also connected through these knockouts for stud depths 6" or less. Standard knockouts sizes are 1-1/2" x 4" and are punched 12" (East and Central) and 24" (West) from the leading edge and every 24" after that.

Tracks

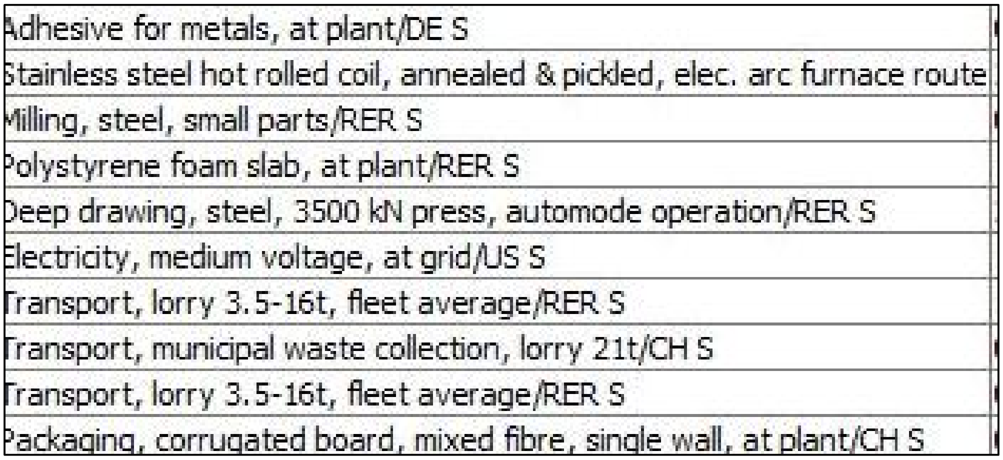
Tracks are U-shaped steel framing components normally used as top and bottom runners to secure wall studs or as head and sill plates at openings. Tracks can also be used to provide end support closures for joists at exterior/ foundation walls or for solid blocking. Standard leg lengths are 1-1/4", however other leg lengths (e.g. 2", 3") are available.

There are three general types of light gauge steel load-bearing wall headers that are commonly used, including:

- Box Beam Headers
- Back-to-Back Headers
- U-Shaped Headers

The first two types of headers are made using C-studs, while the last type is made from preformed U-shaped members.

Table 6: Table showing Inventory Data for Steel Stud Wall Construction (Source: Simapro)



Adhesive for metals, at plant/DE S
Stainless steel hot rolled coil, annealed & pickled, elec. arc furnace route
Milling, steel, small parts/RER S
Polystyrene foam slab, at plant/RER S
Deep drawing, steel, 3500 kN press, automode operation/RER S
Electricity, medium voltage, at grid/US S
Transport, lorry 3.5-16t, fleet average/RER S
Transport, municipal waste collection, lorry 21t/CH S
Transport, lorry 3.5-16t, fleet average/RER S
Packaging, corrugated board, mixed fibre, single wall, at plant/CH S

Thermal performance of exterior steel stud framed walls has always lagged behind that of wood. The critical difference often overshadows steel’s many benefits such as its dimensional consistency, high recycled content, high recyclability, strength, and mold, rot and termite resistance. (Dixon, 2013)

Life Cycle Assessment Tools

LCA tool is defined as an environmental modeling software that develops, presents life cycle inventory (LCI) and life cycle impact assessment (LCIA) results through a laborious analytical process that adheres closely to relevant ISO standards and other accepted LCA guidelines (Life Cycle Assessment, 2001). The most basic tool takes inputs in the form of material take-offs and converts it into mass. Then this mass value is attached to the LCI data available from an LCI database and other sources. This step gives the quantities of inputs and outputs of a product system. The use of resources and releases to air, water, and land associated with the system may be included in the inputs-outputs. LCA tools are classified based on Building Products, Building Assemblies, Whole-Building LCA and user skills- linking user defined or pre-defined unit processes, based on Life Cycle Phases included, and based on region.

Some of the tools which are used for LCA analysis are – Building energy and Environmental Sustainability (BEES), ATHENA impact estimator for buildings, Simapro, GaBi, ATHENA eco-calculator, and some international tools which include Eco-Quantum, Envest, Pharos Framework, Green Foot step, etc. Table showing different types of LCA tools are attached with the Appendix at the end of the report.

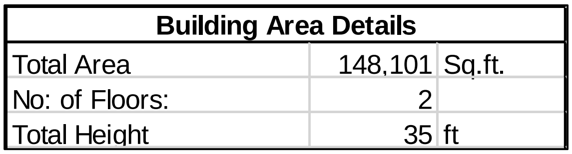
RESEARCH METHODOLOGY

Description of the Case Study

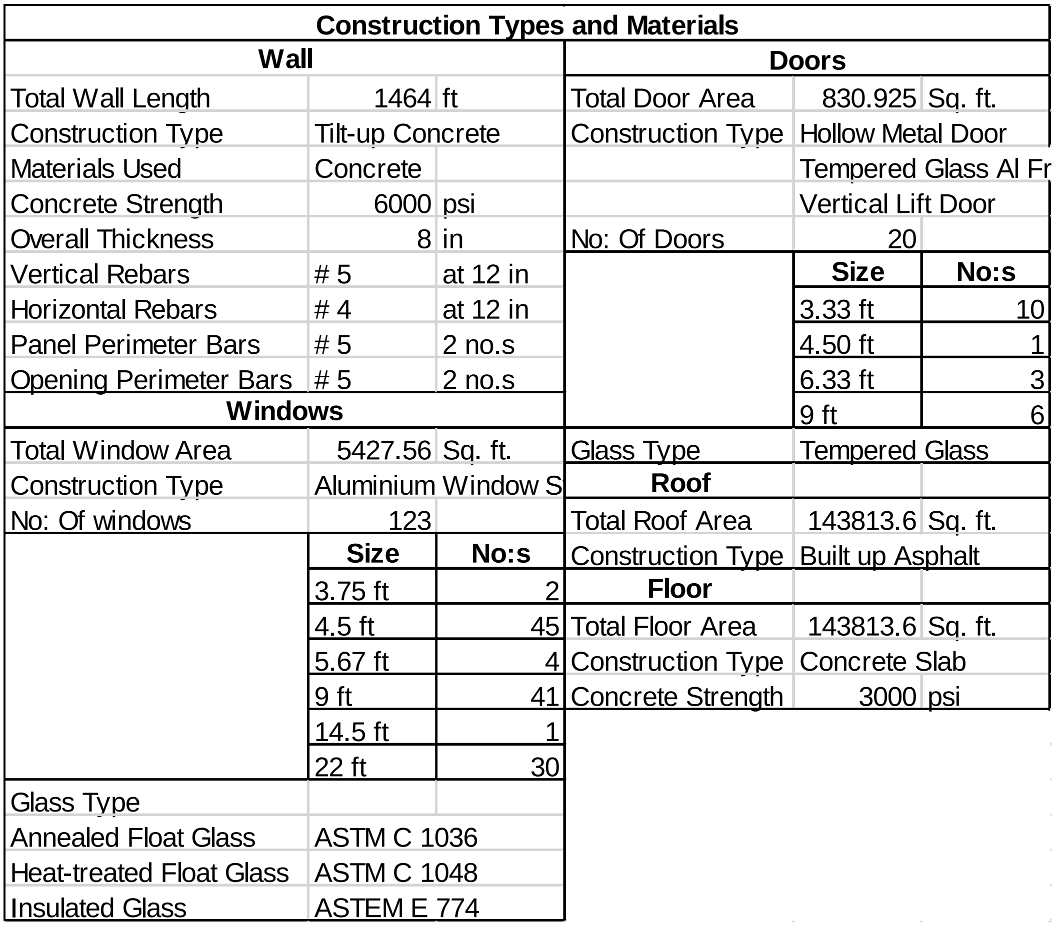
The building selected for the case study is a large scale office building located very close to the ASU campus. The 'University Services Building', located on South Rural Road in Tempe, houses various departments like Facilities Development and Management (FDM) responsible for University facilities, infrastructure and grounds, and manages planning, design, construction, renovation, maintenance and repair at each Arizona State University campus. Departments within FDM include the Office of the University Architect, Capital Programs Management Group, Facilities Management, Administrative Services and Business Operations. The total area of the building was 148,101 sq. ft. spread into two floors. The office space has open-office space planning for a total number of 200 employees. This type of planning makes it easy to re-arrange the spaces in any manner as needed.

The main aim of this study is to evaluate the life cycle environmental impacts associated with the building envelope. The exterior wall or envelope of the building is made of 'Tilt-up Concrete' construction, a method wherein the wall panels are constructed and 'tilt-up' to fit in position. The other details regarding the walls, floors, columns, footings and foundations, doors, windows, etc. are given in Table 7. The mechanical system used in the building are Roof top units. The building also has evaporative coolers in some areas.

Table 7: Table shows the area and construction details of the case study building selected

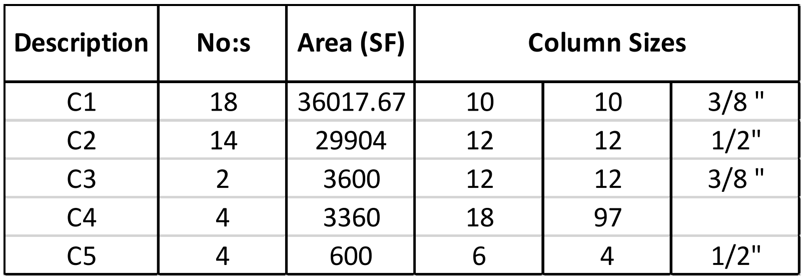


Building Area Details		
Total Area	148,101	Sq.ft.
No: of Floors:	2	
Total Height	35	ft

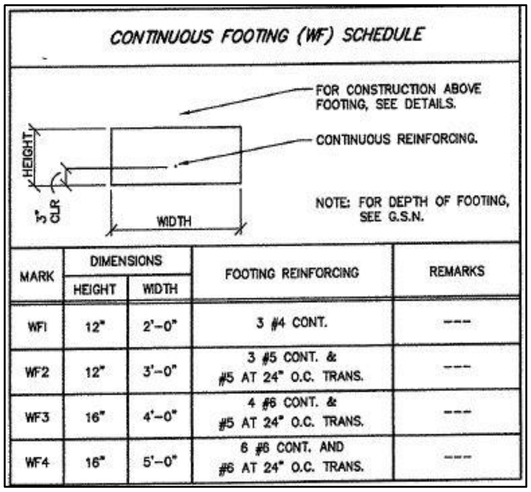


Construction Types and Materials					
Wall			Doors		
Total Wall Length	1464	ft	Total Door Area	830.925	Sq. ft.
Construction Type	Tilt-up Concrete		Construction Type	Hollow Metal Door	
Materials Used	Concrete			Tempered Glass Al Fr	
Concrete Strength	6000	psi		Vertical Lift Door	
Overall Thickness	8	in	No: Of Doors	20	
Vertical Rebars	# 5	at 12 in		Size	No:s
Horizontal Rebars	# 4	at 12 in		3.33 ft	10
Panel Perimeter Bars	# 5	2 no.s		4.50 ft	1
Opening Perimeter Bars	# 5	2 no.s		6.33 ft	3
Windows				9 ft	6
Total Window Area	5427.56	Sq. ft.	Glass Type	Tempered Glass	
Construction Type	Aluminium Window S		Roof		
No: Of windows	123		Total Roof Area	143813.6	Sq. ft.
	Size	No:s	Construction Type	Built up Asphalt	
	3.75 ft	2	Floor		
	4.5 ft	45	Total Floor Area	143813.6	Sq. ft.
	5.67 ft	4	Construction Type	Concrete Slab	
	9 ft	41	Concrete Strength	3000	psi
	14.5 ft	1			
	22 ft	30			
Glass Type					
Annealed Float Glass	ASTM C 1036				
Heat-treated Float Glass	ASTM C 1048				
Insulated Glass	ASTEM E 774				

Table 8: Tables showing the Columns and Footing sizes and area



Description	No:s	Area (SF)	Column Sizes		
C1	18	36017.67	10	10	3/8 "
C2	14	29904	12	12	1/2"
C3	2	3600	12	12	3/8 "
C4	4	3360	18	97	
C5	4	600	6	4	1/2"



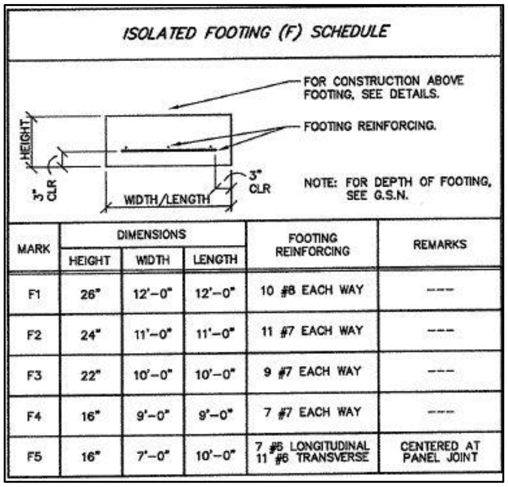
CONTINUOUS FOOTING (WF) SCHEDULE

FOR CONSTRUCTION ABOVE FOOTING, SEE DETAILS.

CONTINUOUS REINFORCING.

NOTE: FOR DEPTH OF FOOTING, SEE G.S.N.

MARK	DIMENSIONS		FOOTING REINFORCING	REMARKS
	HEIGHT	WIDTH		
WF1	12"	2'-0"	3 #4 CONT.	---
WF2	12"	3'-0"	3 #5 CONT. & #5 AT 24" O.C. TRANS.	---
WF3	16"	4'-0"	4 #6 CONT. & #5 AT 24" O.C. TRANS.	---
WF4	16"	5'-0"	6 #6 CONT. AND #6 AT 24" O.C. TRANS.	---



ISOLATED FOOTING (F) SCHEDULE

FOR CONSTRUCTION ABOVE FOOTING, SEE DETAILS.

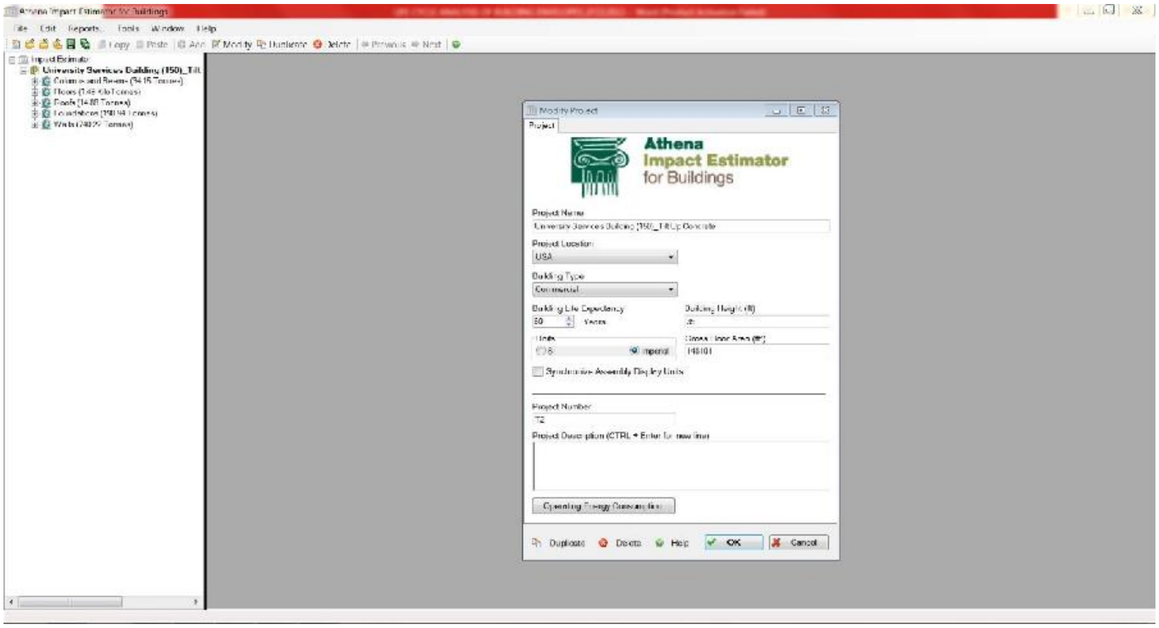
FOOTING REINFORCING.

NOTE: FOR DEPTH OF FOOTING, SEE G.S.N.

MARK	DIMENSIONS			FOOTING REINFORCING	REMARKS
	HEIGHT	WIDTH	LENGTH		
F1	26"	12'-0"	12'-0"	10 #8 EACH WAY	---
F2	24"	11'-0"	11'-0"	11 #7 EACH WAY	---
F3	22"	10'-0"	10'-0"	9 #7 EACH WAY	---
F4	16"	9'-0"	9'-0"	7 #7 EACH WAY	---
F5	16"	7'-0"	10'-0"	7 #6 LONGITUDINAL 11 #6 TRANSVERSE	CENTERED AT PANEL JOINT

Figure 18: Images of the Case Study Building- University Services Building (Tempe, Arizona)

Some of the snapshots from the ATHENA software are attached below.



Project Name: University Services Building (150)_TiltUp Concrete

Project Location: USA

Building Type: Commercial

Building Life Expectancy: 60 Years

Building Height (ft):

Units: ○ SI ● Imperial

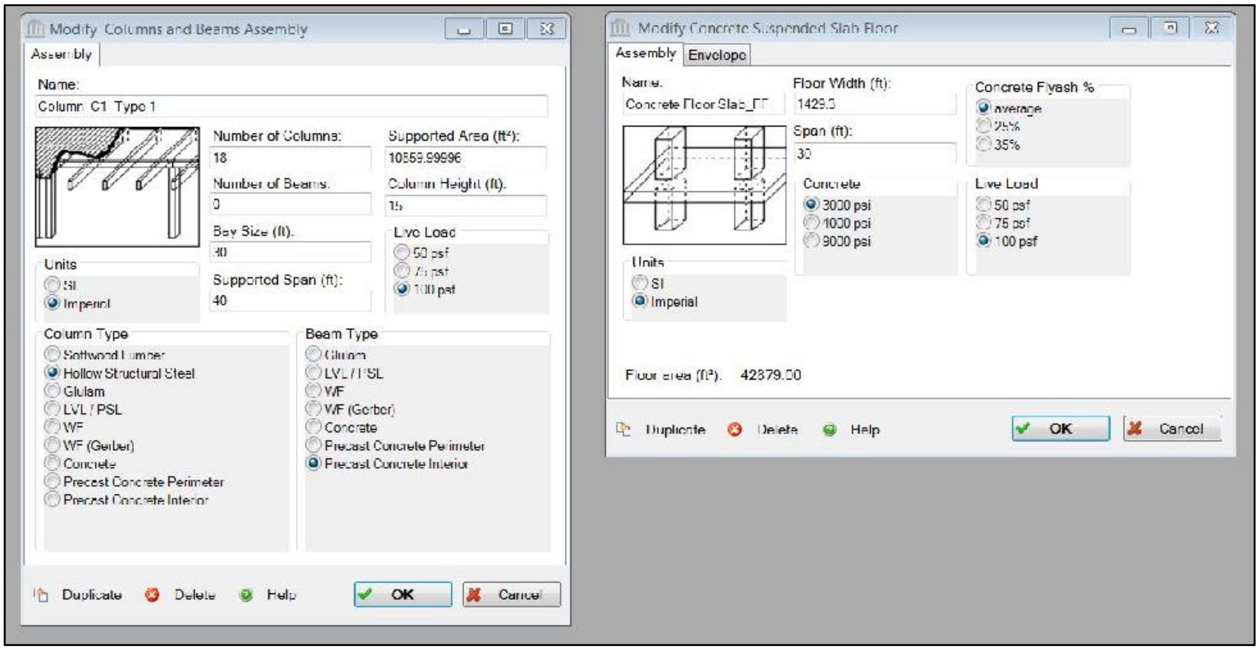
Gross Floor Area (ft²): 148101

☐ Synchronize Assembly Display Units

Project Number: 72

Project Description (CTRL + Enter for new line)

Figure 19: Snapshot from ATHENA software showing the details of some information of the building



Name: Column C1 Type 1
Number of Columns: 18
Supported Area (ft²): 10559.99996
Number of Beams: 0
Column Height (ft): 15
Bay Size (ft): 40
Supported Span (ft): 40

Live Load
○ 50 psf
○ 75 psf
● 100 psf

Units
○ SI
● Imperial

Column Type
○ Softwood Lumber
● Hollow Structural Steel
○ Glulam
○ LVL / PSL
○ WF
○ WF (Gerber)
○ Concrete
○ Precast Concrete Perimeter
○ Precast Concrete Interior

Beam Type
○ Glulam
○ LVL / PSL
○ WF
○ WF (Gerber)
○ Concrete
○ Precast Concrete Perimeter
● Precast Concrete Interior

Name: Concrete Floor Slab_FF
Floor Width (ft): 1429.3
Span (ft): 30

Concrete Flyash %
● average
○ 25%
○ 35%

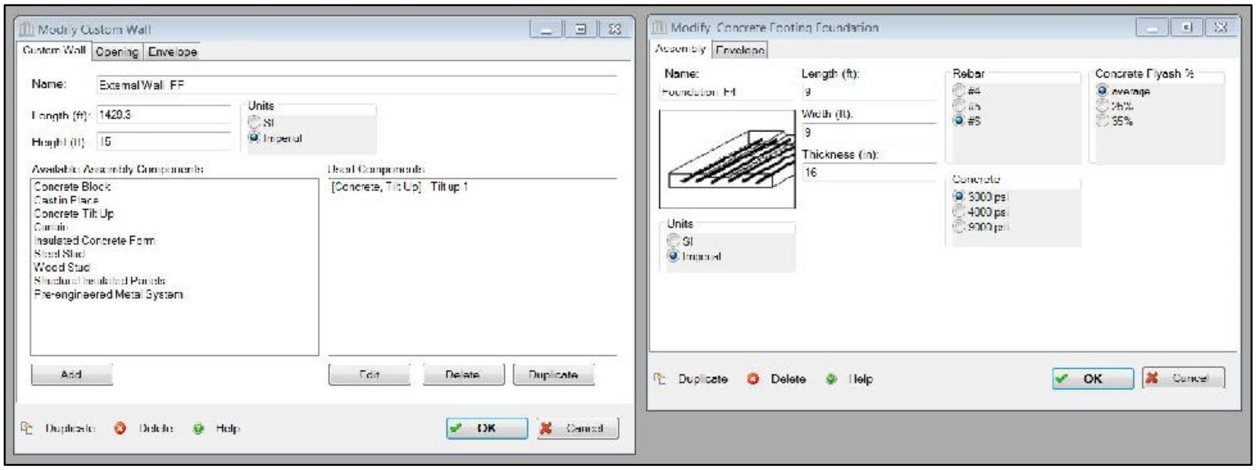
Concrete
● 3000 psi
○ 4000 psi
○ 9000 psi

Live Load
○ 50 psf
○ 75 psf
● 100 psf

Units
○ SI
● Imperial

Floor area (ft²): 42879.00

Figure 20: Snapshot from ATHENA software showing the details of Columns and Floors.



Name: External Wall FF
Length (ft): 1429.3
Height (ft): 15

Units
○ SI
● Imperial

Available Assembly Components:
Concrete Block
Cast in Place
Concrete Tilt Up
Curtain
Insulated Concrete Form
Steel Stud
Wood Stud
Structural Insulated Panels
Pre-engineered Metal System

Used Components:
[Concrete, Tilt Up] Tilt up 1

Name: Foundation F4
Length (ft): 9
Width (ft): 9
Thickness (in): 16

Rebar
○ #4
○ #5
● #6

Concrete Flyash %
● average
○ 25%
○ 35%

Concrete
● 3000 psi
○ 4000 psi
○ 9000 psi

Units
○ SI
● Imperial

Figure 21: Snapshot from ATHENA software showing the details of Exterior Walls and Concrete Footing.

Procedure

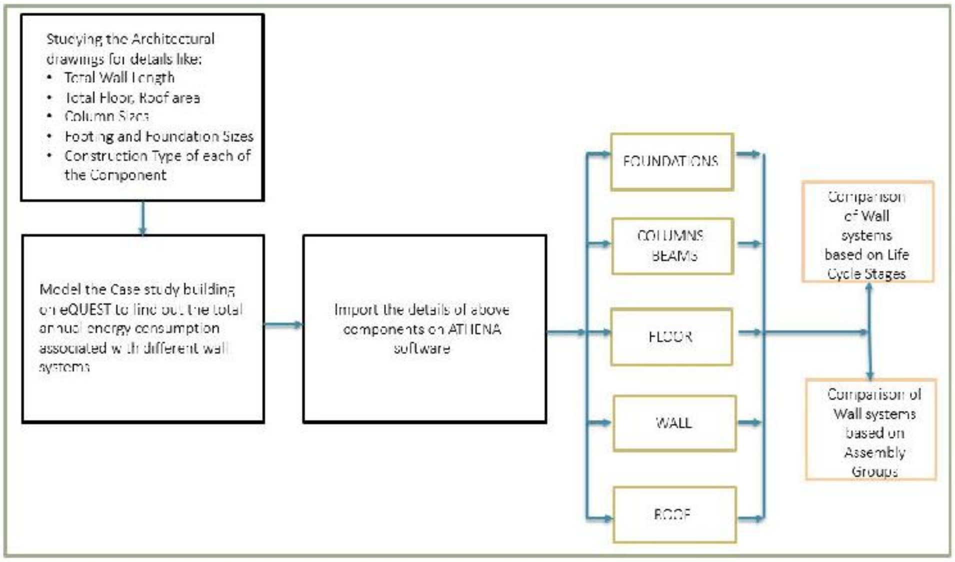


Figure 22: Flowchart showing the steps involved in the Procedure of the research

The flow chart above explains the procedure behind this research study. The architectural drawings were studied to determine construction assembly type and amount for the following categories: Columns and Beams, Intermediate Floors, Exterior Walls, Windows, Interior Walls, and Roof. The software used for the analysis was the life cycle assessment software called the ATHENA Impact estimator for buildings. The software uses Process based LCA and follows database developed by the ATHENA Sustainable Materials Institute, and also the US LCI database. The Life Cycle Impact assessment method used is EPA TRACI.

In order to perform the analysis, in the ‘ATHENA’ software, typical details like the type of building, location, area of the building, building height, etc. were needed to be known. Options to building location are limited to eight cities in Canada and five in the US (Pittsburgh, Minneapolis, Atlanta, Orlando, and New York). The tool tries to identify a region to determine aspects like electrical grid, source of building products, and transportation modes and distances through the location information (ATHENA, 2013). Different tabs are created for each building component, wherein the details like their area, material used and some structural details like columns, footing and foundations sizes are entered. The building`s existing wall system is being compared with five other wall system types – Cast in Place concrete (CIP), Concrete Block (CB), Curtain Wall (CW), Insulated Concrete Form (ICF), and Steel Stud (SS).

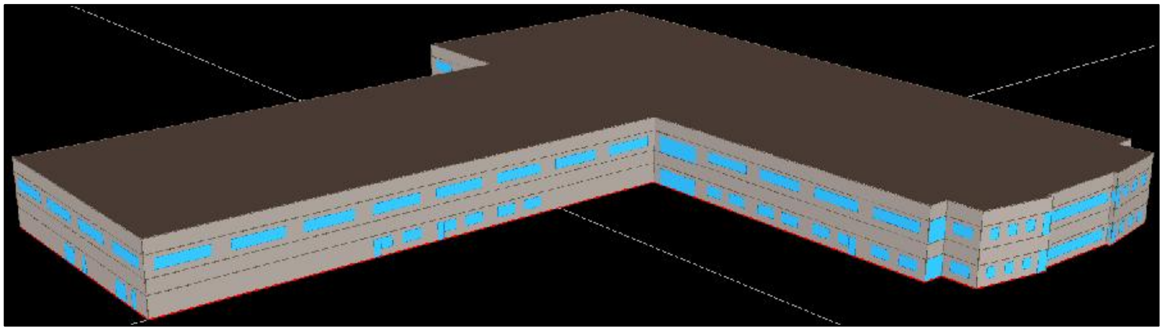


Figure 23: Figure shows the eQUEST model of the case study building to find the energy consumption for different envelope systems

Energy models were developed using the energy modeling software called the eQUEST and the cast study building was simulated for the different types of wall systems chosen. The annual energy consumption was calculated.

Table 9: Table showing the materials used in each of the envelope systems (Source: eQUEST)

Envelope Type	**Units**	**CIP**	**CB**	**CW**			**ICF**				**SS**				**TUC**
Category	**-**	Concrete	Concrete Block Medium Weight	Steel Siding	Fill Insulation	Gypsum	Brick	Polystrene	Concrete 30 lbs	Polystrene	Brick	Batt Insulation	Air Layer	Gypsum	Concrete 140 lb
Material	**-**	Concrete, Heavy Weight, Concrete Filled	8 in Block Concrete Filled	Aluminum Siding	Cellulose, Fill, 3-1/2" (R-13)	Gypusm or Plaster Board, 1/2"	Brick, Face, 3 Inch	Expanded, 3"	Light Weight concrete, 4"	Expanded, 3"	Brick	Mineral Wool/Fiber, Batt, R-11	Air Layer, 3/4" or less Vertical Walls	Gypusm or Plaster Board, 5/8"	Concrete Heavy Weight, Dried
Thickness	**ft**	0.667	0.667	0.005	0.292	0.042	0.25	0.25	0.333	0.25	0.25	0.33	0.9	0.052	0.667
Conductivity	**Btu/h-ft-F**	0.7575	0.4957	26	0.0225	0.0926	0.7576	0.02	0.0751	0.02	0.7576	0.025		0.0926	0.7576
Density	**lb/ft^3**	140	123	480	3	50	130	1.8	30	1.8	130	0.6		50	140
Specific Heat Cap.	**Btu/lb-F**	0.2	0.2	0.1	0.33	0.2	0.22	0.29	0.2	0.29	0.22	0.2		0.2	0.2
Total R Value	**h-ft^2- F/ Btu**	0.88	1.345	13.415			29.768				14.993				0.88

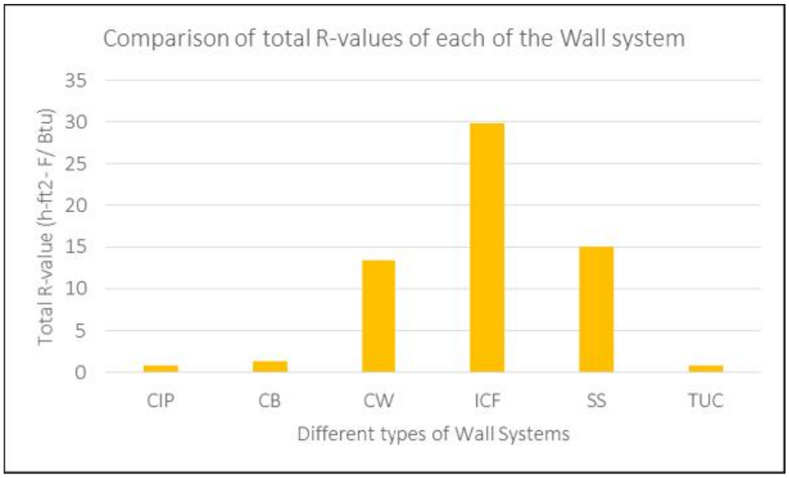


Figure 24: Graph comparing the total R-values between each of the Wall System

Table 9 shows the materials used in each of the wall systems considered, whereas the graph (Figure 20) shows the comparison of the Total R value of each of the wall systems. From the graph, we can see that the Insulated Concrete Forms, Steel Stud and the Curtain Wall systems having R-values as 29.77, 15 and 13.42 h-ft^{2}-° F/Btu. The more the R-value, the better the thermal resistance, which means that a wall system with a higher R-value will transfer comparatively less heat to the interiors compared to a wall system with lesser R-value.

Table 10: Table showing kWh values of the Total Energy Consumption associated with different wall systems (Source: eQUEST)

	CIP	CB	CW	ICF	SS	TUC
Total Annual Energy Consumption (kWh)	1545200	1560200	1536200	1530600	1533900	1568900

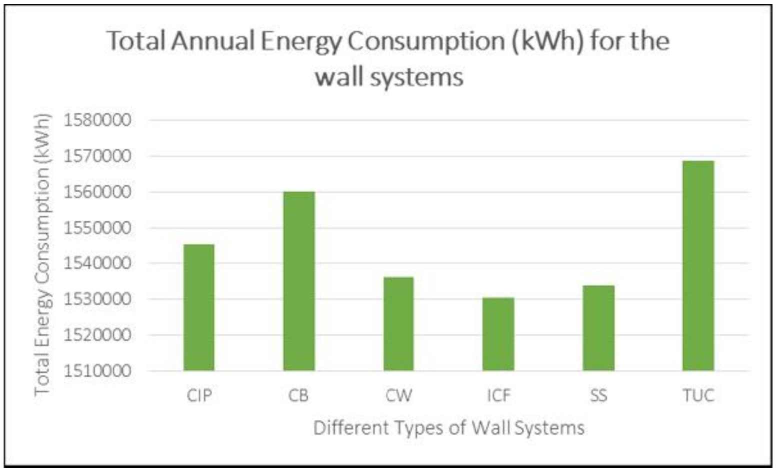


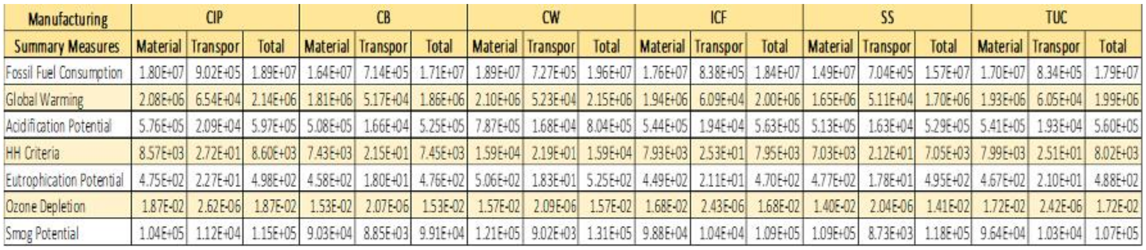
Figure 25: Graph showing the comparison of the Total Energy Consumption (kWh) of the different wall systems (Source: eQUEST)

The wall systems using concrete seem to show more energy consumed compared to the other three systems. Next step the wall systems are compared according to their life cycle stages and within each of the wall systems based on the summary measures. The results were calculated and analyzed.

Results

The Life Cycle stages includes Manufacturing, Construction, Maintenance (Use Phase), End of Life and Operating Energy. The *manufacturing phase* includes details like resource extraction, resource transportation and manufacturing of specific materials, products or building components; *Construction phase* includes product/component transportation from the point of manufacture to the building site and on-site construction activities; *Maintenance or Use phase* Includes life cycle maintenance and replacement activities associated with the structure and envelope components based on building type, location and a user defined life for the building and the *'End-of-Life' phase* includes Simulates demolition energy and final disposition of the materials incorporated in a building at the end of building’s life. (ATHENA, 2013). There are seven impacts categories or Summary measures considered in the software selected from the TRACI impact characterization method created by the US EPA. They are: Fossil Fuel Depletion, Global Warming Potential, Acidification Potential, Human Health Criteria, Eutrophication Potential, Ozone Layer depletion and Smog Potential. (EPA, 2012)

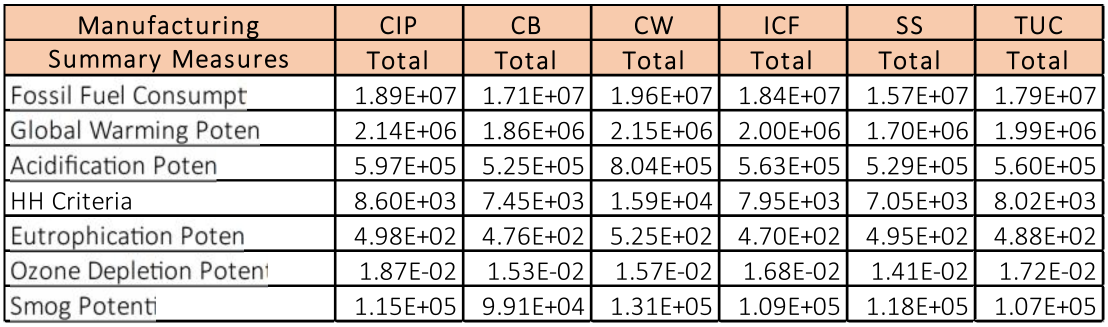
Table 11: Table showing the values of each summary measures of each of the envelope based on the Manufacturing Life Cycle Stage (Source: ATHENA Impact Estimator)



Manufacturing	CIP			CB			CW			ICF			SS			TUC		
Summary Measures	Material	Transpor	Total	Material	Transpor	Total	Material	Transpor	Total	Material	Transpor	Total	Material	Transpor	Total	Material	Transpor	Total
Fossil Fuel Consumption	1.80E+07	9.02E+05	1.89E+07	1.64E+07	7.14E+05	1.71E+07	1.89E+07	7.27E+05	1.96E+07	1.76E+07	8.38E+05	1.84E+07	1.49E+07	7.04E+05	1.57E+07	1.70E+07	8.34E+05	1.79E+07
Global Warming	2.08E+06	6.54E+04	2.14E+06	1.81E+06	5.17E+04	1.86E+06	2.10E+06	5.23E+04	2.15E+06	1.94E+06	6.09E+04	2.00E+06	1.65E+06	5.11E+04	1.70E+06	1.93E+06	6.05E+04	1.99E+06
Acidification Potential	5.76E+05	2.09E+04	5.97E+05	5.08E+05	1.66E+04	5.25E+05	7.87E+05	1.68E+04	8.04E+05	5.44E+05	1.94E+04	5.63E+05	5.13E+05	1.63E+04	5.29E+05	5.41E+05	1.93E+04	5.60E+05
HH Criteria	8.57E+03	2.72E+01	8.60E+03	7.43E+03	2.15E+01	7.45E+03	1.59E+04	2.19E+01	1.59E+04	7.93E+03	2.53E+01	7.95E+03	7.03E+03	2.12E+01	7.05E+03	7.99E+03	2.51E+01	8.02E+03
Eutrophication Potential	4.75E+02	2.27E+01	4.98E+02	4.58E+02	1.80E+01	4.76E+02	5.06E+02	1.83E+01	5.25E+02	4.49E+02	2.11E+01	4.70E+02	4.77E+02	1.78E+01	4.95E+02	4.67E+02	2.10E+01	4.88E+02
Ozone Depletion	1.87E-02	2.62E-06	1.87E-02	1.53E-02	2.07E-06	1.53E-02	1.57E-02	2.09E-06	1.57E-02	1.68E-02	2.43E-06	1.68E-02	1.40E-02	2.04E-06	1.41E-02	1.72E-02	2.42E-06	1.72E-02
Smog Potential	1.04E+05	1.12E+04	1.15E+05	9.03E+04	8.85E+03	9.91E+04	1.21E+05	9.02E+03	1.31E+05	9.88E+04	1.04E+04	1.09E+05	1.09E+05	8.73E+03	1.18E+05	9.64E+04	1.03E+04	1.07E+05

The above table with values shows the manufacturing stage of each of the envelope types considered for the analysis. The results got from the ATHENA software displays the summary measures values based on the material and transport associated with each life cycle stage.

Table 12: Table showing total values of the manufacturing impacts based on the Summary measures

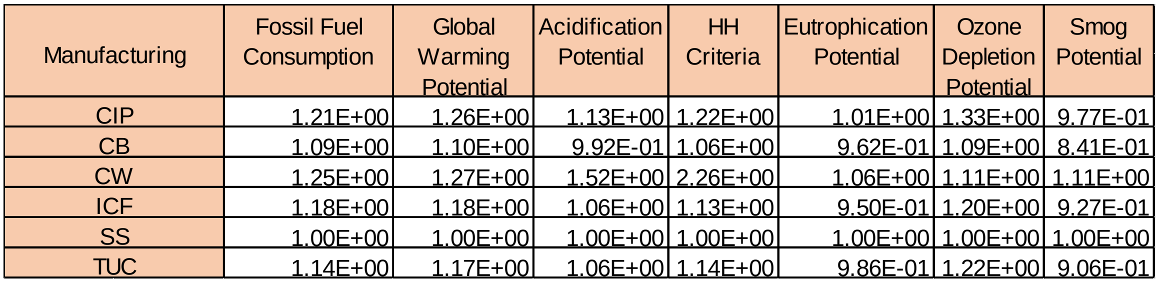


Manufacturing	CIP	CB	CW	ICF	SS	TUC
Summary Measures	Total	Total	Total	Total	Total	Total
Fossil Fuel Consumpt	1.89E+07	1.71E+07	1.96E+07	1.84E+07	1.57E+07	1.79E+07
Global Warming Poten	2.14E+06	1.86E+06	2.15E+06	2.00E+06	1.70E+06	1.99E+06
Acidification Poten	5.97E+05	5.25E+05	8.04E+05	5.63E+05	5.29E+05	5.60E+05
HH Criteria	8.60E+03	7.45E+03	1.59E+04	7.95E+03	7.05E+03	8.02E+03
Eutrophication Poten	4.98E+02	4.76E+02	5.25E+02	4.70E+02	4.95E+02	4.88E+02
Ozone Depletion Potent	1.87E-02	1.53E-02	1.57E-02	1.68E-02	1.41E-02	1.72E-02
Smog Potenti	1.15E+05	9.91E+04	1.31E+05	1.09E+05	1.18E+05	1.07E+05

CIP- Cast In Place; CB- Concrete Block; CW- Curtain Wall; ICF- Insulated Concrete Form; SS- Steel Stud; TUC- Tilt-up Concrete

The above table (Table 8) displays summary measure values of each of the wall system based on the Manufacturing stage as Material and Transport. In order to simplify the number of values, Table 9 was created which had the total impacts of each of the summary measures. But it is found that each of the summary measures has different units, which makes the comparison difficult. So in order to ease that, the wall system which shows least values of summary measures is taken and the other wall systems are compared with it. This process of comparing is called Internal Normalization. So, from Table 9 it is seen that Steel Stud seems to have lesser values compared to the other wall systems. The total value for each of the Summary measure of the other wall system types are divided by the value of Steel Stud wall system.

Table 13: Table showing total values of the manufacturing impacts based on the summary measures after normalization



Manufacturing	Fossil Fuel Consumption	Global Warming Potential	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
CIP	1.21E+00	1.26E+00	1.13E+00	1.22E+00	1.01E+00	1.33E+00	9.77E-01
CB	1.09E+00	1.10E+00	9.92E-01	1.06E+00	9.62E-01	1.09E+00	8.41E-01
CW	1.25E+00	1.27E+00	1.52E+00	2.26E+00	1.06E+00	1.11E+00	1.11E+00
ICF	1.18E+00	1.18E+00	1.06E+00	1.13E+00	9.50E-01	1.20E+00	9.27E-01
SS	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
TUC	1.14E+00	1.17E+00	1.06E+00	1.14E+00	9.86E-01	1.22E+00	9.06E-01

CIP- Cast In Place; CB- Concrete Block; CW- Curtain Wall; ICF- Insulated Concrete Form; SS- Steel Stud; TUC- Tilt-up Concrete

Each of the value for the summary measures calculated using the software has values represented using a scientific notation. To make the results simpler, a ranking is done among the total summary measure values for each of the life cycle stage to find out which wall systems performs the best and worst keeping Steel Stud as a basis to compare.

Table 14: Table showing the rankings for manufacturing stage of each of the wall systems based on the summary measures

Manufacturing	Fossil Fuel Consumpt	Global Warming Potential	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total
CIP	5	5	5	5	5	6	4	35
CB	2	2	1	2	2	2	1	12
CW	6	6	6	6	6	3	6	39
ICF	4	4	4	3	1	4	3	23
SS	1	1	2	1	4	1	5	15
TUC	3	3	3	4	3	5	2	23

CIP- Cast In Place; CB- Concrete Block; CW- Curtain Wall; ICF- Insulated Concrete Form; SS- Steel Stud; TUC- Tilt-up Concrete

The number 1 represent lesser value, so better performing wall system, whereas number 6 represents higher value, a worst performing wall system. Therefore, for manufacturing stage keeping Steel Stud wall system as a basis, the next best performing system was the Concrete Block, and had a total ranking value of 12 which was lesser than 15. Though the values are lesser than the Steel Stud, only two of the summary measures has lower values. On the other hand for Steel Stud, more than 3 summary measures had lower values making the best performing wall system. The worst performing wall system was the Curtain Wall system with a total of 39.

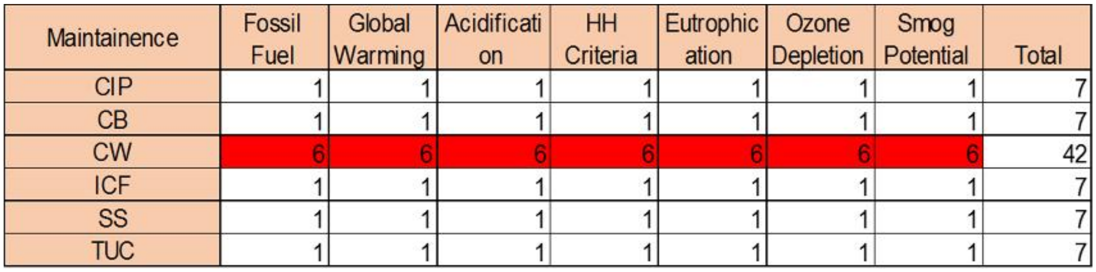
Table 15: Table showing the ranking for Construction Stage each of the wall system based on the summary measures

Construction	Fossil Fuel Consumpt	Global Warming Potential	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total
CIP	6	6	5	5	5	6	5	38
CB	4	3	4	3	4	3	4	25
CW	2	2	2	1	2	2	2	13
ICF	3	4	3	4	3	5	3	25
SS	1	1	1	2	1	1	1	8
TUC	5	5	6	6	6	4	6	38

CIP- Cast In Place; CB- Concrete Block; CW- Curtain Wall; ICF- Insulated Concrete Form; SS- Steel Stud; TUC- Tilt-up Concrete

In the construction stage, Curtain wall system had the next best ranking compared to the Steel Stud with a total of 13. Close to the Curtain wall system was the Insulated concrete form and concrete block having 25 as the total. But looking at the overall construction stage of all the wall systems, the rankings are intermediate. Most of the summary measures have average ranking values ranging from 2-6.

Table 16: Table showing the ranking for Maintainence Stage each of the wall system based on the summary measures

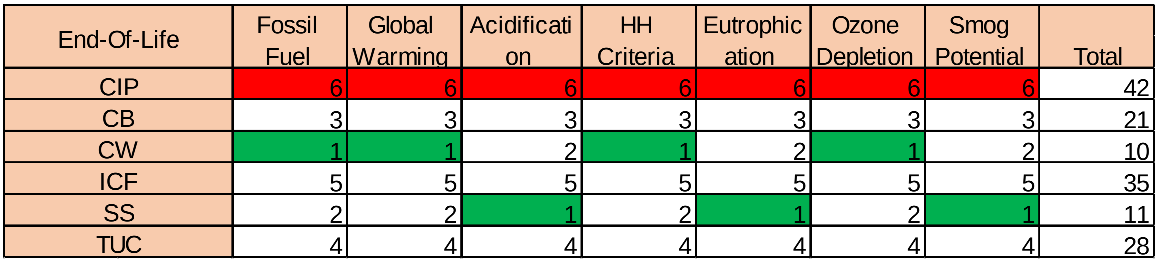


Maintainence	Fossil Fuel	Global Warming	Acidification	HH Criteria	Eutrophication	Ozone Depletion	Smog Potential	Total
CIP	1	1	1	1	1	1	1	7
CB	1	1	1	1	1	1	1	7
CW	6	6	6	6	6	6	6	42
ICF	1	1	1	1	1	1	1	7
SS	1	1	1	1	1	1	1	7
TUC	1	1	1	1	1	1	1	7

CIP- Cast In Place; CB- Concrete Block; CW- Curtain Wall; ICF- Insulated Concrete Form; SS- Steel Stud; TUC- Tilt-up Concrete

In the maintenance stage, it is seen that all the ranking seem to same values for all the wall systems, the worst being for the Curtain Wall system.

Table 17: Table showing the ranking End-of-Life Stage each of the wall system based on the summary measures



End-Of-Life	Fossil Fuel	Global Warming	Acidification	HH Criteria	Eutrophication	Ozone Depletion	Smog Potential	Total
CIP	6	6	6	6	6	6	6	42
CB	3	3	3	3	3	3	3	21
CW	1	1	2	1	2	1	2	10
ICF	5	5	5	5	5	5	5	35
SS	2	2	1	2	1	2	1	11
TUC	4	4	4	4	4	4	4	28

CIP- Cast In Place; CB- Concrete Block; CW- Curtain Wall; ICF- Insulated Concrete Form; SS- Steel Stud; TUC- Tilt-up Concrete

The End-of-Life stage shows Curtain Wall to have the next best ranking in the list, whereas Cast in Place has the worst ranking with a total of 42. Infact, it has 4 out of 7 summary measures with least values, compared to Steel Stud which has just 3 out of 7 summary measures.

Table 18: Table showing the ranking for Operating Energy Stage each of the wall system based on the summary measures

Operating Energy	Fossil Fuel	Global Warming	Acidification	HH Criteria	Eutrophication	Ozone Depletion	Smog Potential	Total
CIP	4	4	4	4	4	4	4	28
CB	5	5	5	5	5	5	5	35
CW	3	3	3	3	3	3	3	21
ICF	1	1	1	1	1	1	1	7
SS	2	2	2	2	2	2	2	14
TUC	6	6	6	6	6	6	6	42

CIP- Cast In Place; CB- Concrete Block; CW- Curtain Wall; ICF- Insulated Concrete Form; SS- Steel Stud; TUC- Tilt-up Concrete

As far the life cycle operating energy is concerned, the Insulated concrete form had the best ranking, and the next best ranking was the Steel Stud with a total of 7 and 14. The Tilt Up concrete had the worst ranking with a total of 42.

Table 19: Table showing the total rankings of all the Life Cycle Stages of the Wall systems

	M	C	Ma	EOL	OE	Total
CIP	5	5	1	6	4	21
CB	2	3	1	3	5	14
CW	6	2	6	2	3	19
ICF	3	4	1	5	1	14
SS	1	1	1	1	2	6
TUC	4	6	1	4	6	21

M-Manufacturing C-Construction Ma-Maintenance EOL-End-Of-Life OE- Operating Energy

CIP- Cast In Place; CB- Concrete Block; CW- Curtain Wall; ICF- Insulated Concrete Form; SS- Steel Stud; TUC- Tilt-up Concrete

To sum up, on the basis of the Steel stud wall system, the concrete block and the Insulated Concrete Form are the next best performing wall systems according to the Life Cycle Stages. This might be due to several reasons. In all the life cycle stages, each of the wall system had different material and transport data associated with it. Due to the unavailability of the data through the ATHENA software, it was difficult to understand what exactly happens in this area. The effects of each of the summary measures can vary among the different wall systems according to the way it was constructed, maintained and recycled/demolished. For example, manufacturing of Insulated Concrete Forms (ICF) consumes lot of energy so it has high impacts, whereas it has the best operating energy next to Steel Stud due to amount of heat transfer through the wall into the building.

When all the Life Cycle Stages are compared, it is found that the maintenance Phase or Use phase has the best ranking. By definition, *Maintenance or Use phase* includes life cycle maintenance and replacement activities associated with the structure and envelope components based on building type, location and a user defined life for the building (ATHENA, 2013). But the software doesn't define what processes are considered in this phase. By theory we know that each of the wall systems has its own way of maintenance. From table 15 we can infer that Curtain Wall had the next best performance, but it might not be true that Curtain wall could be maintained with less impacts. Whereas the other wall systems like Insulated Concrete Forms, Steel Stud and Concrete Block have some average rankings inferring that the effects due to maintenance is tolerable, but very uncertain due to the unavailability of some data. So each of the wall system has its own advantages and disadvantages.

Comparison based on the Assembly groups

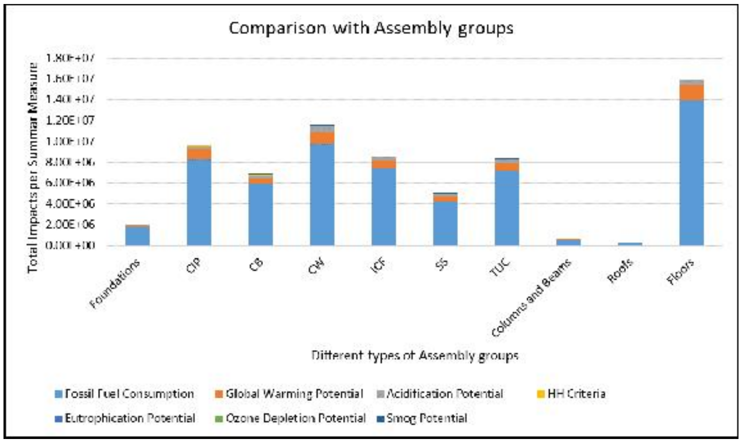


Figure 26: Graph showing all assembly groups with their total impact values

When comparing the total impacts of the summary measures, the columns, roofs and Foundations seem to have lesser impact due to the summary measure. But the main aim of the research study is to just study the different wall systems, so the same building was evaluated for the wall systems and other parameters remained the same. So, we are not considering the other assembly group, but comparing the wall systems on basis of the summary measures. The same procedure – Internal Normalization is followed to find out the results.

Table 20: Table showing the ranking of the different wall systems based on the summary measures

Summary Measures	Fossil Fuel Consumption	Global Warming Potential	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion Potentia	Smog Potential	Total
CIP	5	5	5	5	5	6	5	36
CB	2	2	1	2	2	2	1	12
CW	6	6	6	6	6	3	6	39
ICF	4	3	3	3	1	4	2	20
SS	1	1	2	1	3	1	4	13
TUC	3	4	4	4	4	5	3	27

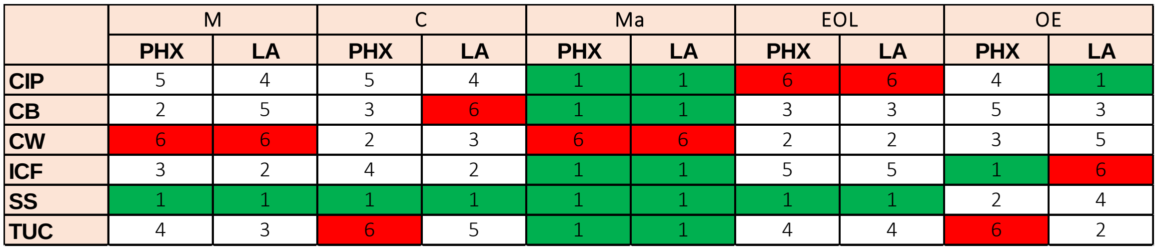
CIP- Cast In Place; CB- Concrete Block; CW- Curtain Wall; ICF- Insulated Concrete Form; SS- Steel Stud; TUC- Tilt-up Concrete

When comparing the different wall systems based on the summary measures with Steel Stud as the basis, the concrete block wall system is closest to Steel Stud system. Though the Concrete Block is one number lesser in total compared to Steel Stud, Steel Stud has the least for at least four of the seven categories making it a better performing wall system. The next closest in ranking was the Insulated Concrete Form which has a total of 20, but the ranking for each of its summary measure was average. The worst performing was the Curtain wall system having a total of 39 and also having higher values for 6 out of 7 categories.

Sensitivity Analysis

For Sensitivity analysis, the climate data was changed from Phoenix to Los Angeles to check the environmental performance of the wall systems. The comparison was done used the Internal Normalization method.

Table 21: Table showing comparisons in rankings of various wall systems based on their Life Cycle Stages for Los Angeles and Phoenix



	M		C		Ma		EOL		OE	
	PHX	**LA**	**PHX**	**LA**	**PHX**	**LA**	**PHX**	**LA**	**PHX**	**LA**
CIP	5	4	5	4	1	1	6	6	4	1
CB	2	5	3	6	1	1	3	3	5	3
CW	6	6	2	3	6	6	2	2	3	5
ICF	3	2	4	2	1	1	5	5	1	6
SS	1	1	1	1	1	1	1	1	2	4
TUC	4	3	6	5	1	1	4	4	6	2

M-Manufacturing C-Construction Ma-Maintenance EOL-End-Of-Life OE- Operating Energy

CIP- Cast In Place; CB- Concrete Block; CW- Curtain Wall; ICF- Insulated Concrete Form; SS- Steel Stud; TUC- Tilt-up Concrete

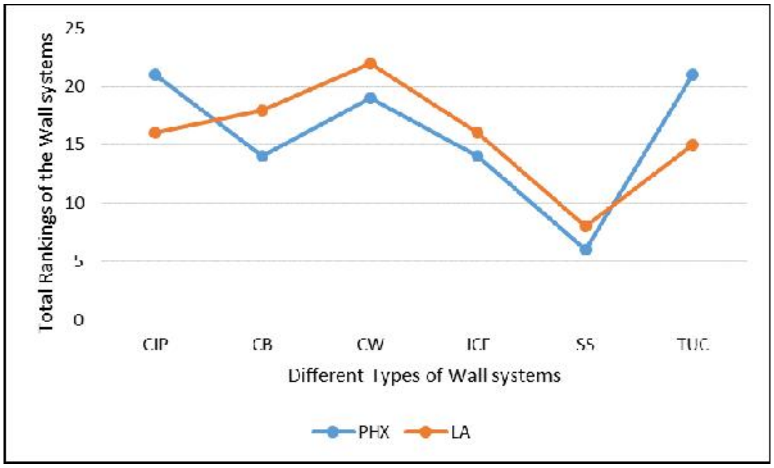


Figure 27: Graph showing the comparison in total ranking of the different wall systems for both climate types

When compared on the basis of Life Cycle Stages, it was seen that Steel Stud has the least value for the impacts. This result was the same as got for a climate type like phoenix, but value was more than Phoenix. This might be due to the difference in the climate types. Phoenix, being hot and dry will require some amount of insulation in the building to filter the excess amount of heat entering into the building, whereas Los Angeles comparatively has a cooler climate where little or no insulation is needed. The wall systems using concrete like Cast in Place, Insulated Concrete Form Tilt Up concrete and Concrete Block ranks almost the same. But in Phoenix, concrete related wall systems had average ranking and had higher values than one found in Los Angeles (Figure 28). This depends on the property of the material to react to the weather. In cold climate, concrete might take time to set and also for heat to enter the wall system making the interiors warm enough to stay. But in hot climates like Phoenix, concrete sets in quickly, heat transfer is very fast making the interiors hot. However, adding insulation layers might increase the thermal resistance making the wall system to perform well.

Table 22: Table showing the comparison in rankings of various wall systems based on their summary measures for Los Angeles and Phoenix

	Fossil Fuel Consumption		Global Warming Potential		Acidification Potential		HH Criteria		Eutrophication Potential		Ozone Depletion Potential		Smog Potential	
	PHX	LA	PHX	LA	PHX	LA	PHX	LA	PHX	LA	PHX	LA	PHX	LA
CIP	5	4	5	4	5	4	5	5	5	4	6	6	5	5
CB	2	6	2	5	1	5	2	4	2	6	2	4	1	4
CW	6	5	6	6	6	6	6	6	6	5	3	2	6	6
ICF	4	3	3	2	3	2	3	2	1	1	4	3	2	2
SS	1	1	1	1	2	1	1	1	3	2	1	1	4	1
TUC	5	2	4	3	4	3	4	3	4	3	5	5	3	3

M-Manufacturing C-Construction Ma-Maintenance EOL-End-Of-Life OE- Operating Energy

CIP- Cast In Place; CB- Concrete Block; CW- Curtain Wall; ICF- Insulated Concrete Form; SS- Steel Stud; TUC- Tilt-up Concrete

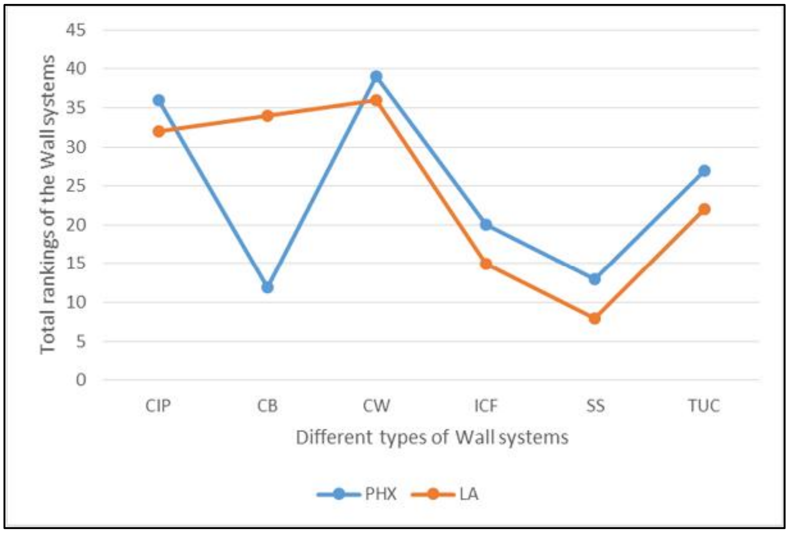


Figure 28: Graph showing comparison of rankings of different wall systems based on the Summary measures

As per the summary measures, the insulated concrete form is best ranking wall system next to the Steel Stud system, having all summary measures with above average rankings. The ranking totals for other wall systems are higher than phoenix`s values. However, Curtain wall has been ranked the worst performing wall system in both the climate types.

Conclusions

From the analysis, we can infer that every wall system has its own advantages and disadvantages in each of their life cycle stages. If one has very good manufacturing performance, its end of life is poor. If other performs well with maintenance, their operational energy is high, etc. An envelope which has closely satisfied almost all the life cycle stages was the Steel Stud envelope, irrespective of the climate. The next best performing wall system which had less impacts on the environment was Insulated Concrete Form and the Concrete Block. As far as the existing construction in the building which was Tilt-Up concrete Construction was concerned, it was ranked the last with having below average rankings for each of the life cycle stages. So it is recommended to use any type of wall system with little or more insulation along with or without concrete to perform better as well as having less impact on the environment.

Comparison as per the summary measures, yielded almost the same results. But as far as summary measures affecting a building are concerned, Fossil Fuel Consumption, Global Warming Potential and Ozone Depletion Potential contribute the most. The graph below shows a comparison in the rankings for the different wall systems based on three of the summary measures. The rankings for each of the summary measures were almost the same. There are lot of gases involved in the three of these summary measures. Analyzing and comparing each of them would be tedious task. But in overall ranking of each of the summary measures we can infer that Steel Stud and Concrete Block have less impact as they rank 1 and 2 respectively. This also shows that the different types of gases used and their quantities for the two wall systems are comparatively lesser than the others.

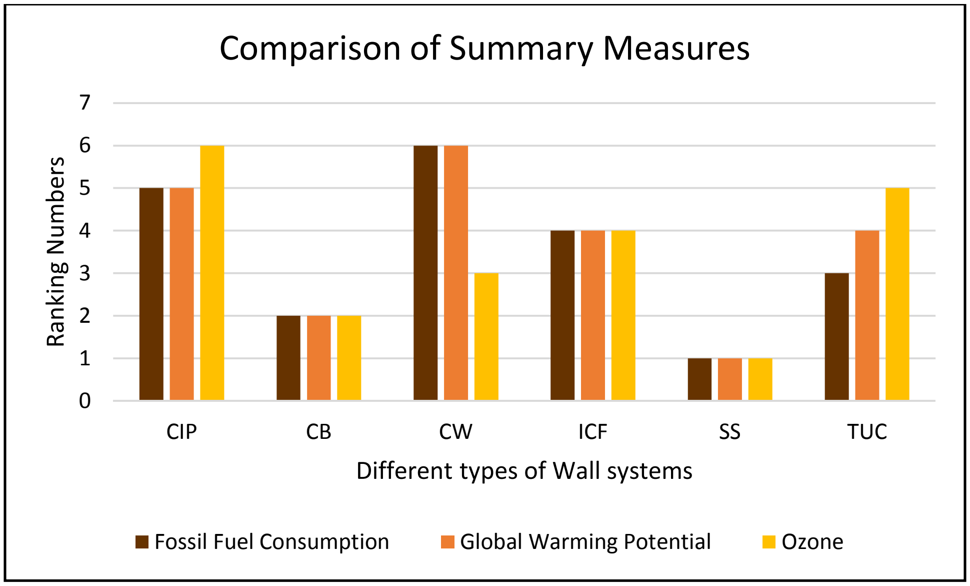


Figure 29: Graph showing comparison of summary measures of different types of Wall systems

CIP- Cast In Place; CB- Concrete Block; CW- Curtain Wall; ICF- Insulated Concrete Form; SS-Steel Stud; TUC- Tilt-up Concrete

The Sensitivity analysis which was performed for another climate type like Los Angeles shows almost the same hierarchy as Phoenix, expect that total rankings are different. This might be due to the differences in the climate typologies and also the physical properties of the materials to adjust to weather conditions.

Limitations

Any research study cannot be done perfect, unless the quality of data is available. The same goes with a Life Cycle Assessment, which is a time consuming task, cannot be made perfect unless each and every data is available to perform the LCA study. This research study had some data regarding the material and transport of each of the life cycle stage was not accessible in the software. Probably availability of the same, the results could have been even more different and justified. The climate and electricity grid data associated with the software has data for very limited locations in the US, which makes it difficult for the analysis. Phoenix was not listed location in the software, instead a general data named ‘USA’ was selected, which had averaged out the electricity grid and climate data. Lastly, another weakness of this tool is that at present it has limited options for designing a wall assembly. Most of the conventional wall assemblies can be created within the tool, but options to create a high-performance wall are not available yet. However, it would be very useful a tool wherein architects can customize an infinite variety of wall assemblies and have an impact number generated by a more dynamic version of the tool.

Future Work

Future work may include Life Cycle Costing comparison for each of the Wall systems. The research could also be extended to other high performance building wall systems like innovative glazing systems, green walls, Phase change materials, etc. During the course of this analysis, a tedious job involved in working with different software’s in order to collect data and import it on to the ATHENA software. Instead considering a software which might at least incorporate some of the features together and lessen the use of variety of software’s would be more helpful. This particular analysis was done for only one of the building, the sane could be tried on different sizes of office buildings with different assembly materials. By doing this, it could make it more interesting and also help ASU with some do-able solutions to improvise on the new buildings in the future.

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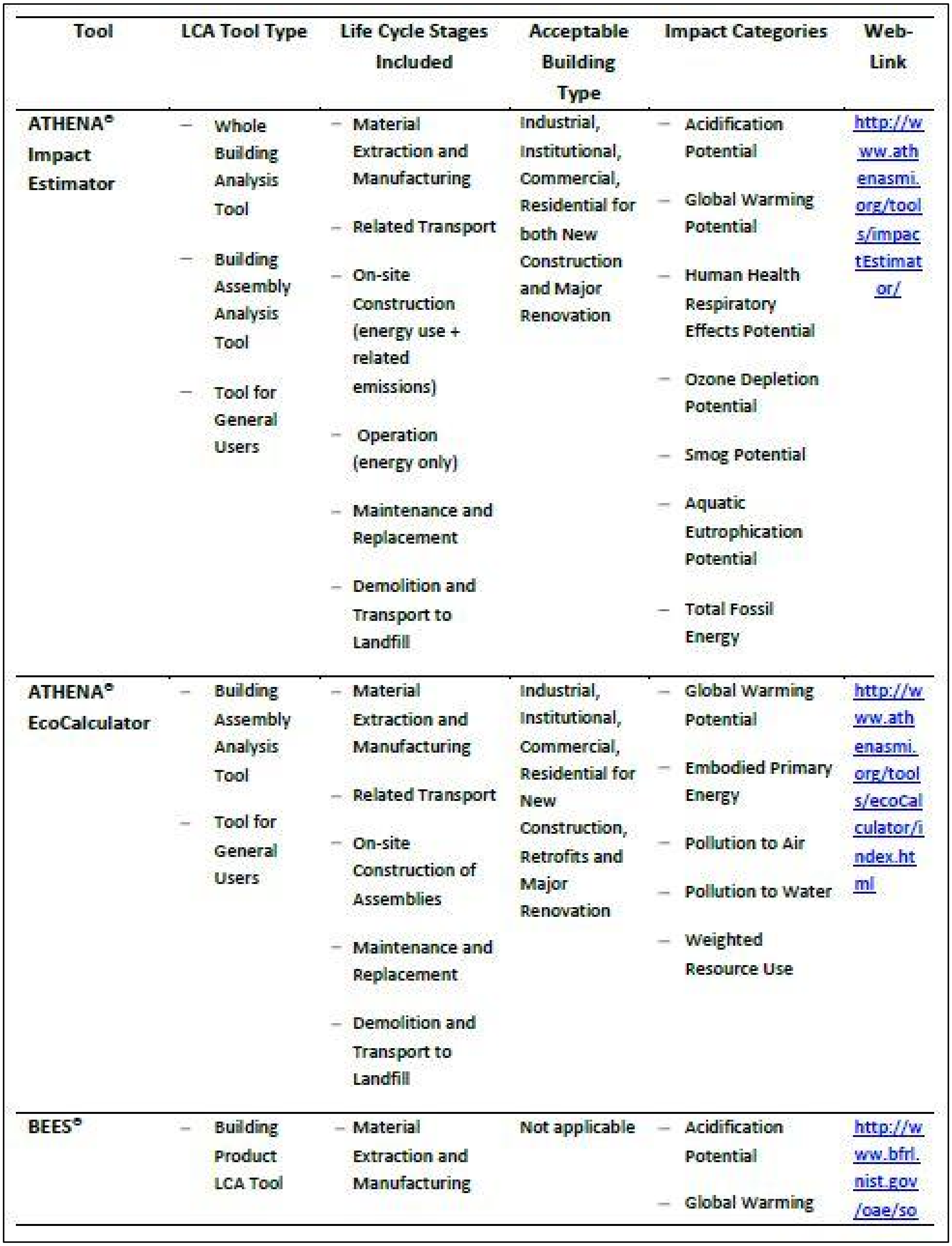
APPENDIX

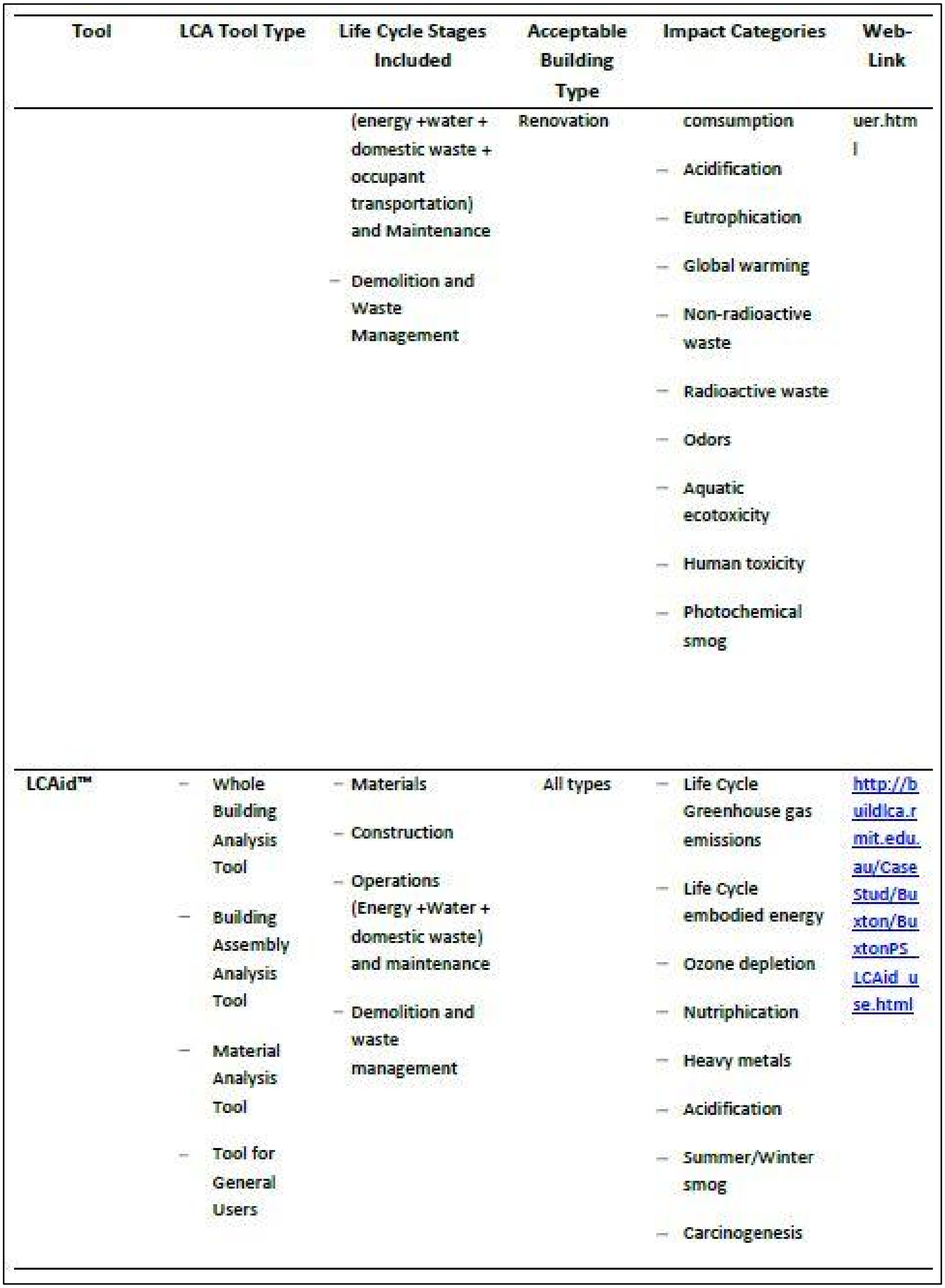
TYPES OF LCA TOOLS

(Architects, 2010)

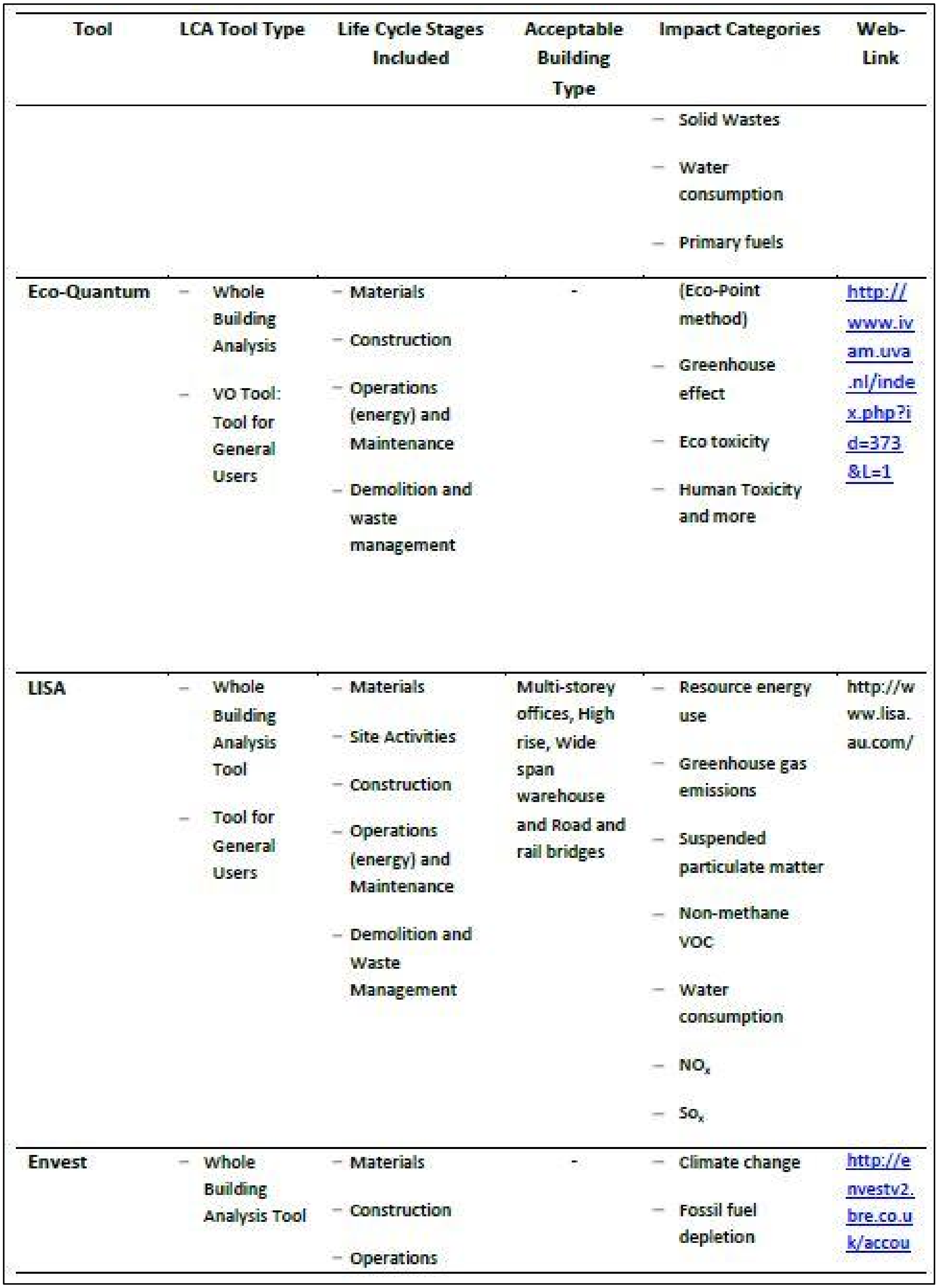


Tool	LCA Tool Type	Life Cycle Stages Included	Acceptable Building Type	Impact Categories	Web-Link
ATHENA® Impact Estimator	– Whole Building Analysis Tool – Building Assembly Analysis Tool – Tool for General Users	– Material Extraction and Manufacturing – Related Transport – On-site Construction (energy use + related emissions) – Operation (energy only) – Maintenance and Replacement – Demolition and Transport to Landfill	Industrial, Institutional, Commercial, Residential for both New Construction and Major Renovation	– Acidification Potential – Global Warming Potential – Human Health Respiratory Effects Potential – Ozone Depletion Potential – Smog Potential – Aquatic Eutrophication Potential – Total Fossil Energy	http://www.athenasmi.org/tools/impactEstimator/
ATHENA® EcoCalculator	– Building Assembly Analysis Tool – Tool for General Users	– Material Extraction and Manufacturing – Related Transport – On-site Construction of Assemblies – Maintenance and Replacement – Demolition and Transport to Landfill	Industrial, Institutional, Commercial, Residential for New Construction, Retrofits and Major Renovation	– Global Warming Potential – Embodied Primary Energy – Pollution to Air – Pollution to Water – Weighted Resource Use	http://www.athenasmi.org/tools/ecoCalculator/index.html
BEES®	– Building Product LCA Tool	– Material Extraction and Manufacturing	Not applicable	– Acidification Potential – Global Warming	http://www.bfrl.nist.gov/oae/so

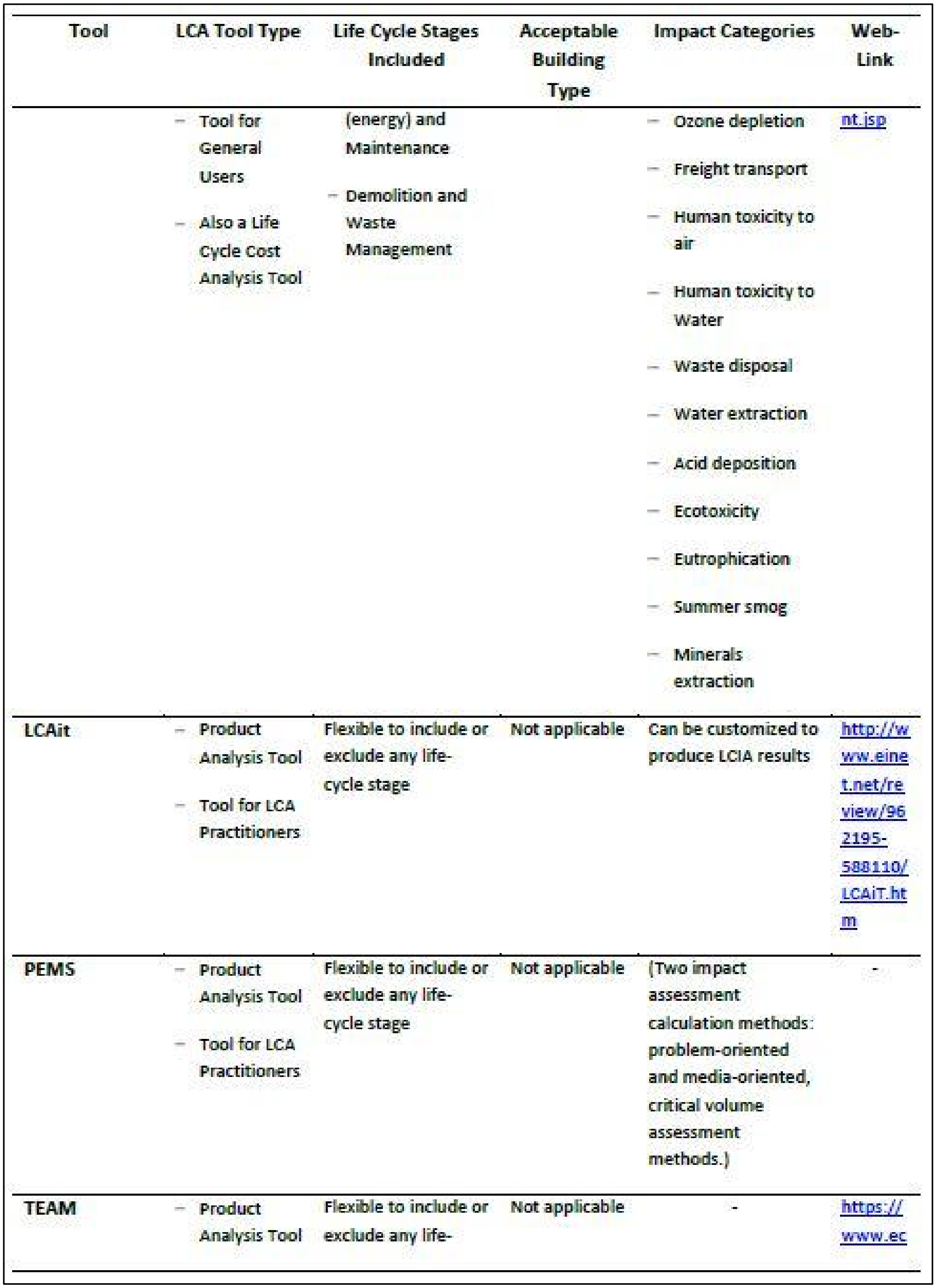
Tool	LCA Tool Type	Life Cycle Stages Included	Acceptable Building Type	Impact Categories	Web-Link
	– Tool for General Users – Also a Life Cycle Cost Analysis Tool	– Transportation – Installation – Maintenance – Recycling and Waste Management		Potential – Eutrophication Fossil Fuel Depletion Indoor Air Quality – Habitat Alteration – Water Intake – Criteria Air Pollutants – Human Health – Smog Formation Potential – Ozone Depletion Potential – Ecological Toxicity	ftware/BEES/bees.html
EIO-LCA	– Embodied Energy Tool	– Material Extraction and Manufacturing – Transportation (Use phase and end of life impacts not directly included)	Residential, Commercial, Institutional, Industrial, Highway and Bridge Construction, Water and Sewer Pipeline Construction, Maintenance and Repair	Not Applicable	http://www.eiolca.net/index.html
EQUER	– Whole Building Analysis Tool	– Material Extraction and manufacturing – Construction – Operation	Industrial, Institutional, Commercial, Residential for both New Construction and Major	– Exhaust of abiotic resources – Primary energy consumption – Water	http://www.cenerg.ensmp.fr/english/logiciel/indexeq



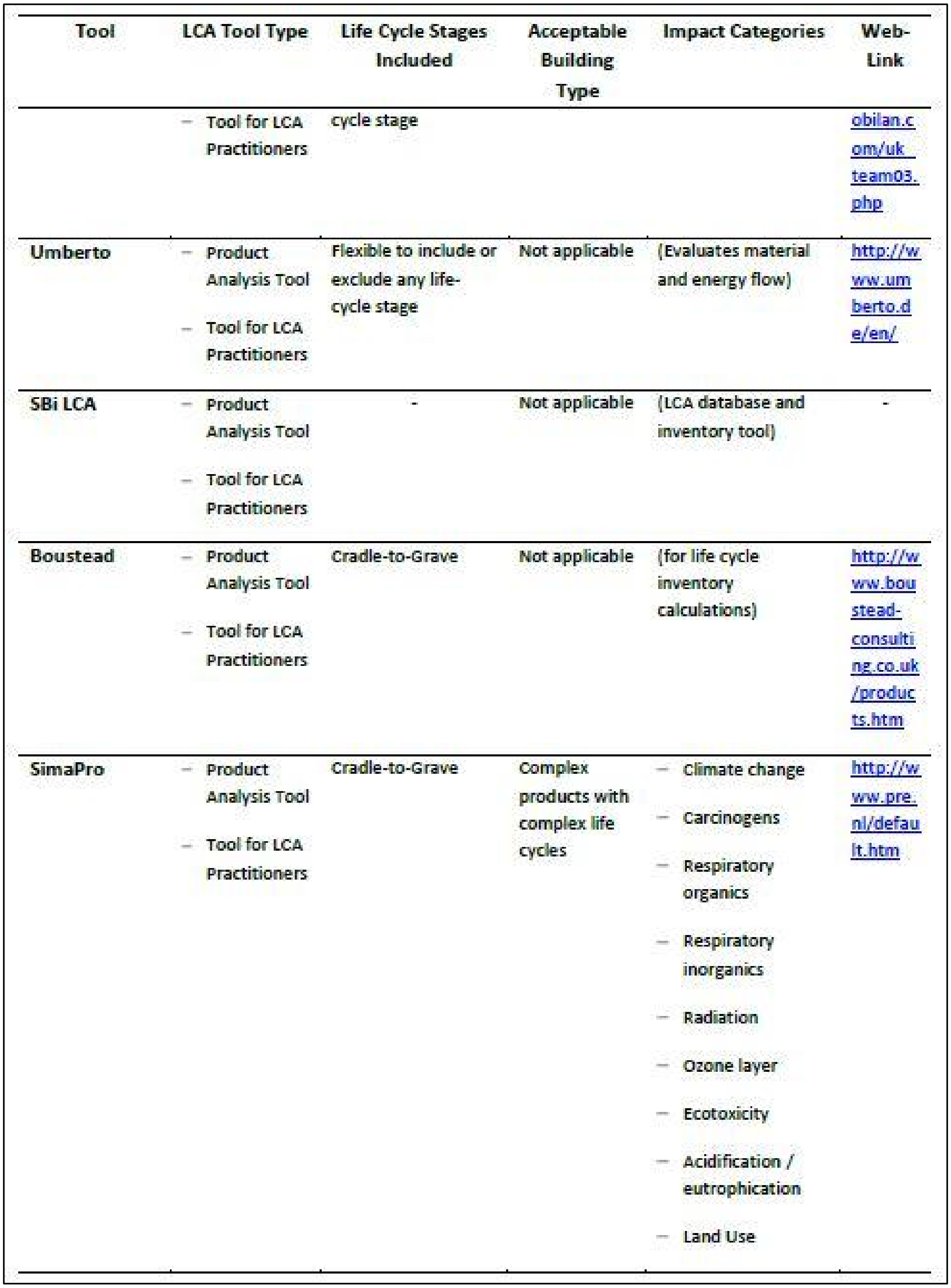
Tool	LCA Tool Type	Life Cycle Stages Included	Acceptable Building Type	Impact Categories	Web-Link
		(energy +water + domestic waste + occupant transportation) and Maintenance – Demolition and Waste Management	Renovation	comsumption – Acidification – Eutrophication – Global warming – Non-radioactive waste – Radioactive waste – Odors – Aquatic ecotoxicity – Human toxicity – Photochemical smog	uer.html
LCAid™	– Whole Building Analysis Tool – Building Assembly Analysis Tool – Material Analysis Tool – Tool for General Users	– Materials – Construction – Operations (Energy +Water + domestic waste) and maintenance – Demolition and waste management	All types	– Life Cycle Greenhouse gas emissions – Life Cycle embodied energy – Ozone depletion – Nutriphication – Heavy metals – Acidification – Summer/Winter smog – Carcinogenesis	http://buildlca.rmit.edu.au/CaseStud/Buxton/BuxtonPS_LCAid_use.html



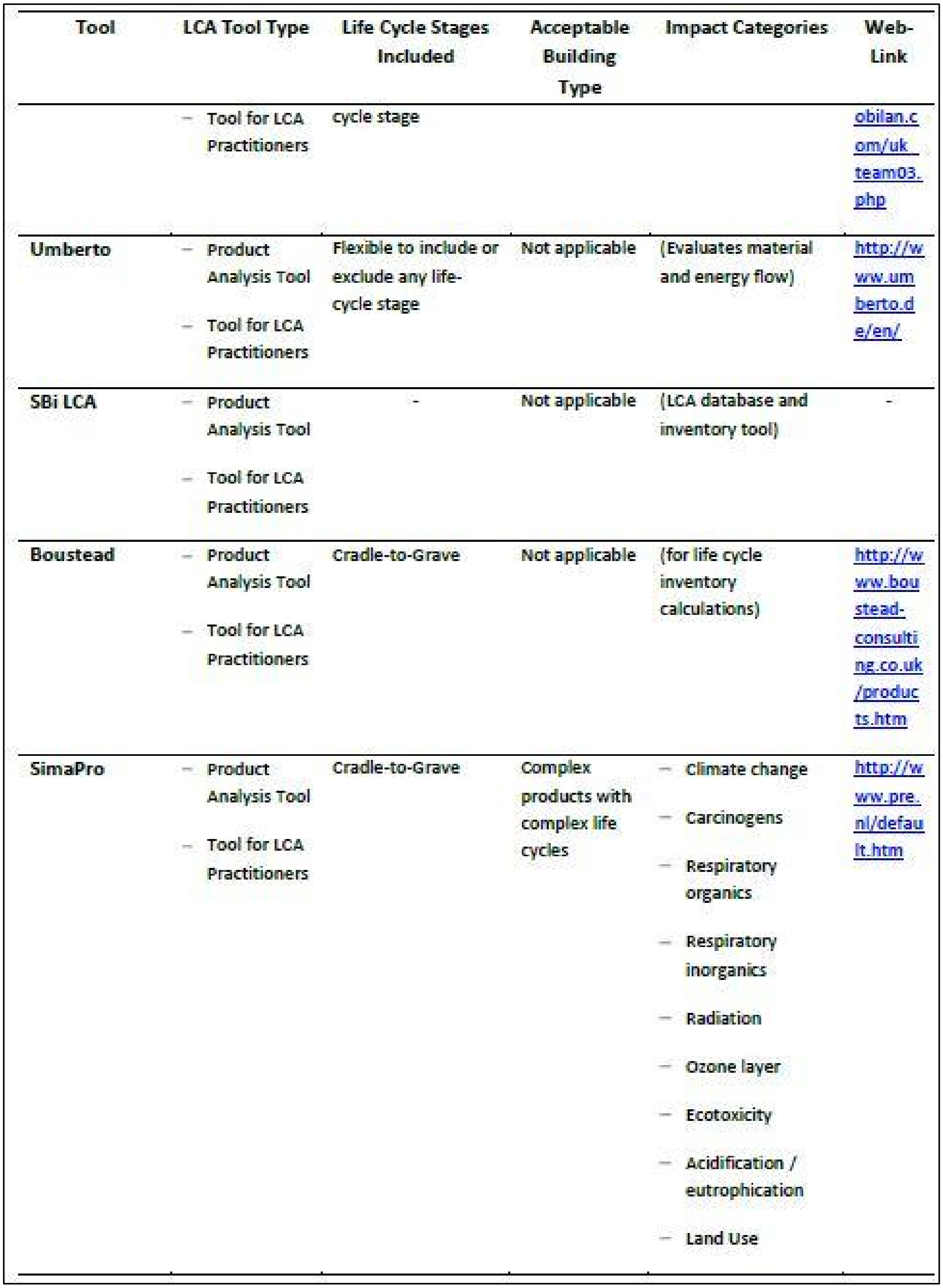
Tool	LCA Tool Type	Life Cycle Stages Included	Acceptable Building Type	Impact Categories	Web-Link
				– Solid Wastes – Water consumption – Primary fuels	
Eco-Quantum	– Whole Building Analysis – VO Tool: Tool for General Users	– Materials – Construction – Operations (energy) and Maintenance – Demolition and waste management	-	(Eco-Point method) – Greenhouse effect – Eco toxicity – Human Toxicity and more	http://www.ivam.uva.nl/index.php?id=373&L=1
LISA	– Whole Building Analysis Tool – Tool for General Users	– Materials – Site Activities – Construction – Operations (energy) and Maintenance – Demolition and Waste Management	Multi-storey offices, High rise, Wide span warehouse and Road and rail bridges	– Resource energy use – Greenhouse gas emissions – Suspended particulate matter – Non-methane VOC – Water consumption – NO_x – So_x	http://www.lisa.au.com/
Envest	– Whole Building Analysis Tool	– Materials – Construction – Operations	-	– Climate change – Fossil fuel depletion	http://envestv2.bre.co.uk/accou



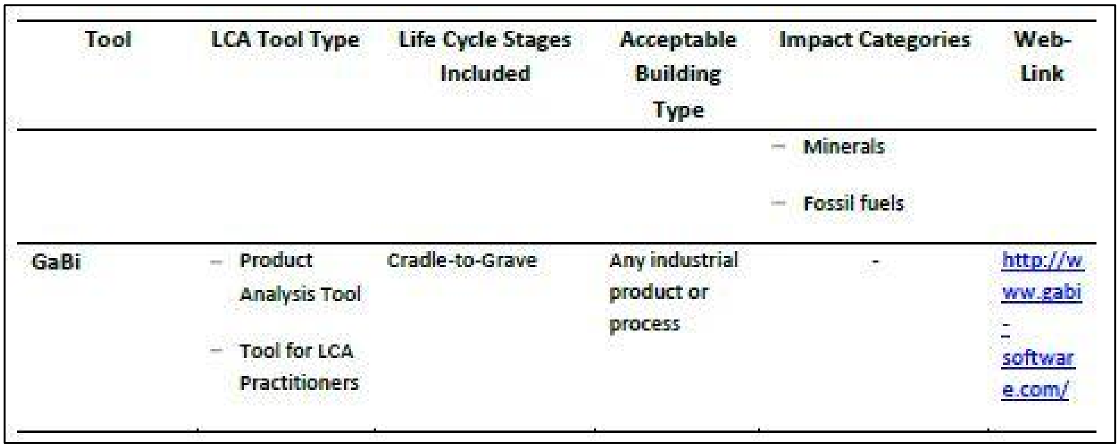
Tool	LCA Tool Type	Life Cycle Stages Included	Acceptable Building Type	Impact Categories	Web-Link
	– Tool for General Users – Also a Life Cycle Cost Analysis Tool	(energy) and Maintenance – Demolition and Waste Management		– Ozone depletion – Freight transport – Human toxicity to air – Human toxicity to Water – Waste disposal – Water extraction – Acid deposition – Ecotoxicity – Eutrophication – Summer smog – Minerals extraction	nt.jsp
LCAit	– Product Analysis Tool – Tool for LCA Practitioners	Flexible to include or exclude any life-cycle stage	Not applicable	Can be customized to produce LCIA results	http://www.einet.net/review/962195-588110/LCAiT.htm
PEMS	– Product Analysis Tool – Tool for LCA Practitioners	Flexible to include or exclude any life-cycle stage	Not applicable	(Two impact assessment calculation methods: problem-oriented and media-oriented, critical volume assessment methods.)	-
TEAM	– Product Analysis Tool	Flexible to include or exclude any life-	Not applicable	-	https://www.ec



Tool	LCA Tool Type	Life Cycle Stages Included	Acceptable Building Type	Impact Categories	Web-Link
	– Tool for LCA Practitioners	cycle stage			obilan.com/uk_team03.php
Umberto	– Product Analysis Tool – Tool for LCA Practitioners	Flexible to include or exclude any life-cycle stage	Not applicable	(Evaluates material and energy flow)	http://www.umberto.de/en/
SBi LCA	– Product Analysis Tool – Tool for LCA Practitioners	-	Not applicable	(LCA database and inventory tool)	-
Boustead	– Product Analysis Tool – Tool for LCA Practitioners	Cradle-to-Grave	Not applicable	(for life cycle inventory calculations)	http://www.boustead-consulting.co.uk/products.htm
SimaPro	– Product Analysis Tool – Tool for LCA Practitioners	Cradle-to-Grave	Complex products with complex life cycles	– Climate change – Carcinogens – Respiratory organics – Respiratory inorganics – Radiation – Ozone layer – Ecotoxicity – Acidification / eutrophication – Land Use	http://www.pre.nl/default.htm



Tool	LCA Tool Type	Life Cycle Stages Included	Acceptable Building Type	Impact Categories	Web-Link
	– Tool for LCA Practitioners	cycle stage			obilan.com/ukteam03.php
Umberto	– Product Analysis Tool – Tool for LCA Practitioners	Flexible to include or exclude any life-cycle stage	Not applicable	(Evaluates material and energy flow)	http://www.umberto.de/en/
SBi LCA	– Product Analysis Tool – Tool for LCA Practitioners	-	Not applicable	(LCA database and inventory tool)	-
Boustead	– Product Analysis Tool – Tool for LCA Practitioners	Cradle-to-Grave	Not applicable	(for life cycle inventory calculations)	http://www.boustead-consulting.co.uk/products.htm
SimaPro	– Product Analysis Tool – Tool for LCA Practitioners	Cradle-to-Grave	Complex products with complex life cycles	– Climate change – Carcinogens – Respiratory organics – Respiratory inorganics – Radiation – Ozone layer – Ecotoxicity – Acidification / eutrophication – Land Use	http://www.pre.nl/default.htm



Tool	LCA Tool Type	Life Cycle Stages Included	Acceptable Building Type	Impact Categories	Web-Link
				– Minerals – Fossil fuels	
GaBi	– Product Analysis Tool – Tool for LCA Practitioners	Cradle-to-Grave	Any industrial product or process	-	http://www.gabi-software.com/

CALCULATIONS OF WALL SYSTEMS FOR PHOENIX CLIMATE FROM ATHENA SOFTWARE

Based on life cycle stages

Manufacturing	CIP	CB	CW	ICF	SS	TUC
Fossil Fuel Consumption	1.21E+00	1.09E+00	1.25E+00	1.18E+00	1.00E+00	1.14E+00
Global Warming Potential	1.26E+00	1.10E+00	1.27E+00	1.18E+00	1.00E+00	1.17E+00
Acidification Potential	1.13E+00	9.92E-01	1.52E+00	1.06E+00	1.00E+00	1.06E+00
HH Criteria	1.22E+00	1.06E+00	2.26E+00	1.13E+00	1.00E+00	1.14E+00
Eutrophication Potential	1.01E+00	9.62E-01	1.06E+00	9.50E-01	1.00E+00	9.86E-01
Ozone Depletion Potential	1.33E+00	1.09E+00	1.11E+00	1.20E+00	1.00E+00	1.22E+00
Smog Potential	9.77E-01	8.41E-01	1.11E+00	9.27E-01	1.00E+00	9.06E-01

Construction	CIP	CB	CW	ICF	SS	TUC
Fossil Fuel Consumption	1.32E+00	1.08E+00	1.03E+00	1.08E+00	1.00E+00	1.32E+00
Global Warming Potential	1.31E+00	1.07E+00	1.03E+00	1.07E+00	1.00E+00	1.30E+00
Acidification Potential	1.37E+00	1.07E+00	1.02E+00	1.06E+00	1.00E+00	1.44E+00
HH Criteria	1.24E+00	1.02E+00	9.85E-01	1.04E+00	1.00E+00	1.27E+00
Eutrophication Potential	1.39E+00	1.09E+00	1.04E+00	1.07E+00	1.00E+00	1.46E+00
Ozone Depletion Potential	1.22E+00	1.09E+00	1.08E+00	1.15E+00	1.00E+00	1.15E+00
Smog Potential	1.40E+00	1.09E+00	1.04E+00	1.07E+00	1.00E+00	1.49E+00

Maintainence	CIP	CB	CW	ICF	SS	TUC
Fossil Fuel Consumption	1.00E+00	1.00E+00	1.58E+00	1.00E+00	1.00E+00	1.00E+00
Global Warming Potential	1.00E+00	1.00E+00	1.91E+00	1.00E+00	1.00E+00	1.00E+00
Acidification Potential	1.00E+00	1.00E+00	1.57E+00	1.00E+00	1.00E+00	1.00E+00
HH Criteria	1.00E+00	1.00E+00	2.44E+00	1.00E+00	1.00E+00	1.00E+00
Eutrophication Potential	1.00E+00	1.00E+00	2.05E+00	1.00E+00	1.00E+00	1.00E+00
Ozone Depletion Potential	1.00E+00	1.00E+00	1.17E+00	1.00E+00	1.00E+00	1.00E+00
Smog Potential	1.00E+00	1.00E+00	2.10E+00	1.00E+00	1.00E+00	1.00E+00

End-Of-Life	CIP	CB	CW	ICF	SS	TUC
Fossil Fuel Consumption	1.27E+00	1.02E+00	9.97E-01	1.19E+00	1.00E+00	1.18E+00
Global Warming Potential	1.27E+00	1.03E+00	9.98E-01	1.19E+00	1.00E+00	1.18E+00
Acidification Potential	1.27E+00	1.07E+00	1.02E+00	1.18E+00	1.00E+00	1.18E+00
HH Criteria	1.28E+00	1.02E+00	9.94E-01	1.19E+00	1.00E+00	1.18E+00
Eutrophication Potential	1.27E+00	1.07E+00	1.02E+00	1.18E+00	1.00E+00	1.18E+00
Ozone Depletion Potential	1.27E+00	1.03E+00	9.98E-01	1.19E+00	1.00E+00	1.18E+00
Smog Potential	1.27E+00	1.10E+00	1.03E+00	1.18E+00	1.00E+00	1.18E+00

Operating Energy	CIP	CB	CW	ICF	SS	TUC
Fossil Fuel Consumption	1.01E+00	1.02E+00	1.00E+00	9.98E-01	1.00E+00	1.02E+00
Global Warming Potential	1.01E+00	1.02E+00	1.00E+00	9.98E-01	1.00E+00	1.02E+00
Acidification Potential	1.01E+00	1.02E+00	1.00E+00	9.98E-01	1.00E+00	1.02E+00
HH Criteria	1.01E+00	1.02E+00	1.00E+00	9.98E-01	1.00E+00	1.02E+00
Eutrophication Potential	1.01E+00	1.02E+00	1.00E+00	9.98E-01	1.00E+00	1.02E+00
Ozone Depletion Potential	1.01E+00	1.02E+00	1.00E+00	9.98E-01	1.00E+00	1.02E+00
Smog Potential	1.01E+00	1.02E+00	1.00E+00	9.98E-01	1.00E+00	1.02E+00

Manufacturing	Fossil Fuel Consumption	Global Warming Potential	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
CIP	1.21E+00	1.26E+00	1.13E+00	1.22E+00	1.01E+00	1.33E+00	9.77E-01
CB	1.09E+00	1.10E+00	9.92E-01	1.06E+00	9.62E-01	1.09E+00	8.41E-01
CW	1.25E+00	1.27E+00	1.52E+00	2.26E+00	1.06E+00	1.11E+00	1.11E+00
ICF	1.18E+00	1.18E+00	1.06E+00	1.13E+00	9.50E-01	1.20E+00	9.27E-01
SS	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
TUC	1.14E+00	1.17E+00	1.06E+00	1.14E+00	9.86E-01	1.22E+00	9.06E-01

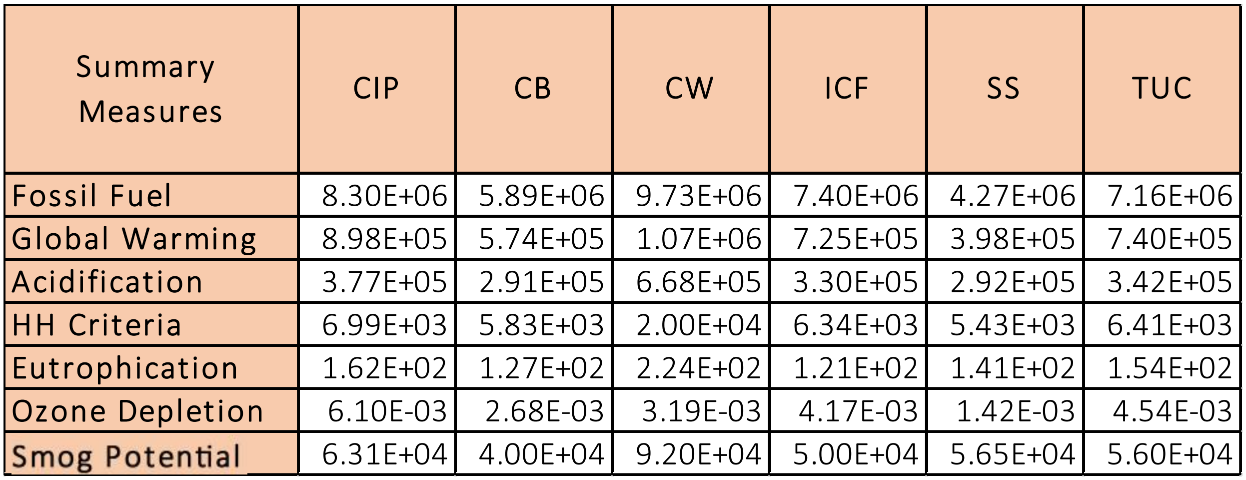
Construction	Fossil Fuel Consumption	Global Warming Potential	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
CIP	1.32E+00	1.31E+00	1.37E+00	1.24E+00	1.39E+00	1.22E+00	1.40E+00
CB	1.08E+00	1.07E+00	1.07E+00	1.02E+00	1.09E+00	1.09E+00	1.09E+00
CW	1.03E+00	1.03E+00	1.02E+00	9.85E-01	1.04E+00	1.08E+00	1.04E+00
ICF	1.08E+00	1.07E+00	1.06E+00	1.04E+00	1.07E+00	1.15E+00	1.07E+00
SS	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
TUC	1.32E+00	1.30E+00	1.44E+00	1.27E+00	1.46E+00	1.15E+00	1.49E+00

Maintainence	Fossil Fuel Consumption	Global Warming	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion	Smog Potential
CIP	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
CB	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
CW	1.58E+00	1.91E+00	1.57E+00	2.44E+00	2.05E+00	1.17E+00	2.10E+00
ICF	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SS	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
TUC	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00

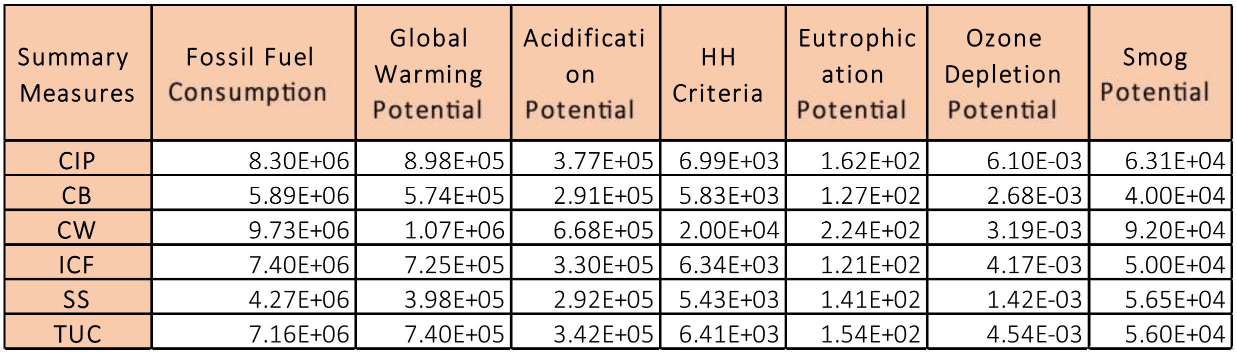
End-Of-Life	Fossil Fuel Consumption	Global Warming	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion	Smog Potential
CIP	1.27E+00	1.27E+00	1.27E+00	1.28E+00	1.27E+00	1.27E+00	1.27E+00
CB	1.02E+00	1.03E+00	1.07E+00	1.02E+00	1.07E+00	1.03E+00	1.10E+00
CW	9.97E-01	9.98E-01	1.02E+00	9.94E-01	1.02E+00	9.98E-01	1.03E+00
ICF	1.19E+00	1.19E+00	1.18E+00	1.19E+00	1.18E+00	1.19E+00	1.18E+00
SS	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
TUC	1.18E+00	1.18E+00	1.18E+00	1.18E+00	1.18E+00	1.18E+00	1.18E+00

Operating Energy	Fossil Fuel Consumption	Global Warming	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion	Smog Potential
CIP	1.01E+00	1.01E+00	1.01E+00	1.01E+00	1.01E+00	1.01E+00	1.01E+00
CB	1.02E+00	1.02E+00	1.02E+00	1.02E+00	1.02E+00	1.02E+00	1.02E+00
CW	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
ICF	9.98E-01	9.98E-01	9.98E-01	9.98E-01	9.98E-01	9.98E-01	9.98E-01
SS	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
TUC	1.02E+00	1.02E+00	1.02E+00	1.02E+00	1.02E+00	1.02E+00	1.02E+00

Based on Summary Measures



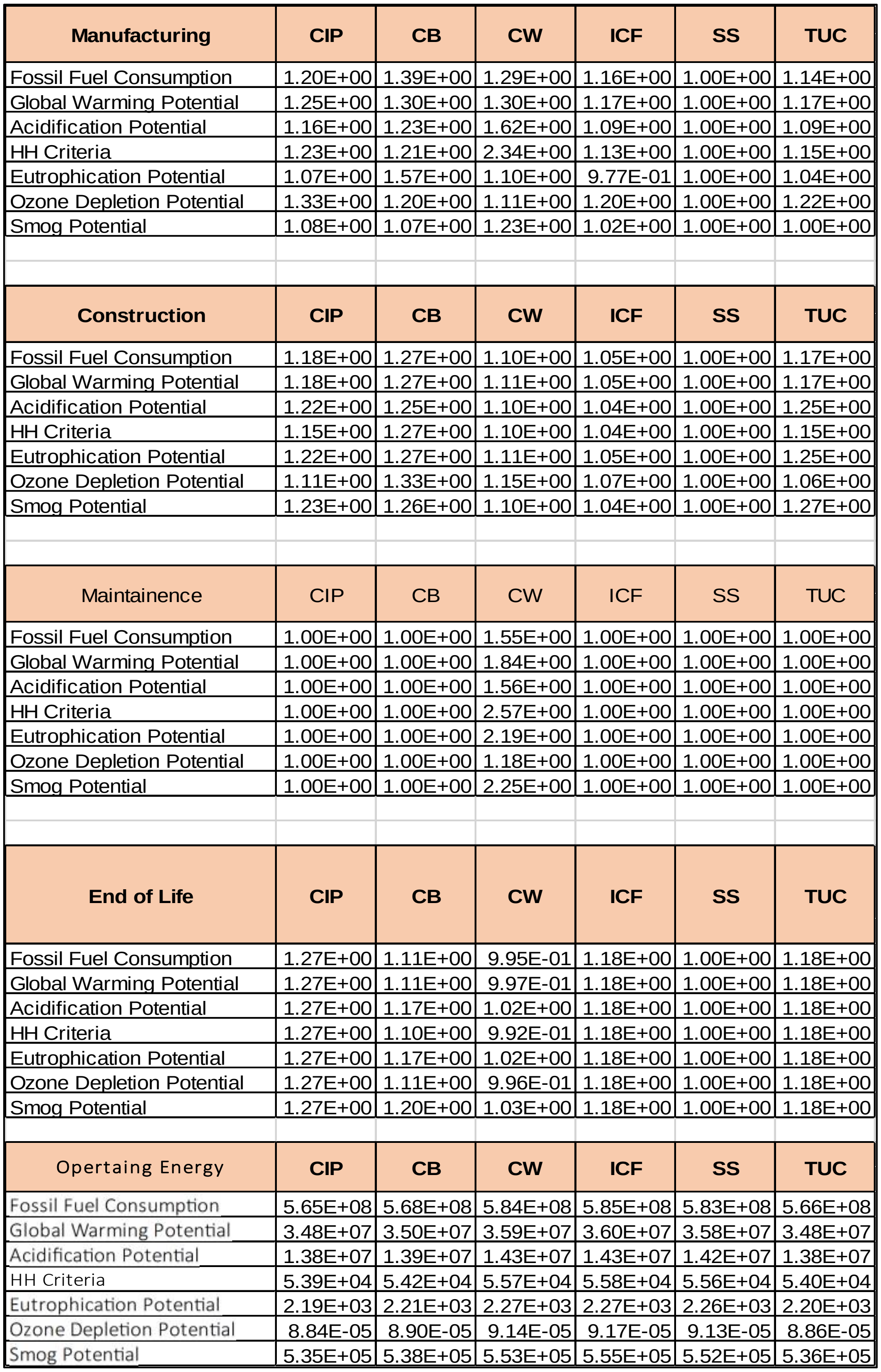
Summary Measures	CIP	CB	CW	ICF	SS	TUC
Fossil Fuel	8.30E+06	5.89E+06	9.73E+06	7.40E+06	4.27E+06	7.16E+06
Global Warming	8.98E+05	5.74E+05	1.07E+06	7.25E+05	3.98E+05	7.40E+05
Acidification	3.77E+05	2.91E+05	6.68E+05	3.30E+05	2.92E+05	3.42E+05
HH Criteria	6.99E+03	5.83E+03	2.00E+04	6.34E+03	5.43E+03	6.41E+03
Eutrophication	1.62E+02	1.27E+02	2.24E+02	1.21E+02	1.41E+02	1.54E+02
Ozone Depletion	6.10E-03	2.68E-03	3.19E-03	4.17E-03	1.42E-03	4.54E-03
Smog Potential	6.31E+04	4.00E+04	9.20E+04	5.00E+04	5.65E+04	5.60E+04



Summary Measures	Fossil Fuel Consumption	Global Warming Potential	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
CIP	8.30E+06	8.98E+05	3.77E+05	6.99E+03	1.62E+02	6.10E-03	6.31E+04
CB	5.89E+06	5.74E+05	2.91E+05	5.83E+03	1.27E+02	2.68E-03	4.00E+04
CW	9.73E+06	1.07E+06	6.68E+05	2.00E+04	2.24E+02	3.19E-03	9.20E+04
ICF	7.40E+06	7.25E+05	3.30E+05	6.34E+03	1.21E+02	4.17E-03	5.00E+04
SS	4.27E+06	3.98E+05	2.92E+05	5.43E+03	1.41E+02	1.42E-03	5.65E+04
TUC	7.16E+06	7.40E+05	3.42E+05	6.41E+03	1.54E+02	4.54E-03	5.60E+04

CALCULATIONS OF THE WALL SYSTEMS FOR LOS ANGELES FROM THE ATHENA SOFTWARE

Bases on Life Cycle Stages



Manufacturing	**CIP**	**CB**	**CW**	**ICF**	**SS**	**TUC**
Fossil Fuel Consumption	1.20E+00	1.39E+00	1.29E+00	1.16E+00	1.00E+00	1.14E+00
Global Warming Potential	1.25E+00	1.30E+00	1.30E+00	1.17E+00	1.00E+00	1.17E+00
Acidification Potential	1.16E+00	1.23E+00	1.62E+00	1.09E+00	1.00E+00	1.09E+00
HH Criteria	1.23E+00	1.21E+00	2.34E+00	1.13E+00	1.00E+00	1.15E+00
Eutrophication Potential	1.07E+00	1.57E+00	1.10E+00	9.77E-01	1.00E+00	1.04E+00
Ozone Depletion Potential	1.33E+00	1.20E+00	1.11E+00	1.20E+00	1.00E+00	1.22E+00
Smog Potential	1.08E+00	1.07E+00	1.23E+00	1.02E+00	1.00E+00	1.00E+00

Construction	**CIP**	**CB**	**CW**	**ICF**	**SS**	**TUC**
Fossil Fuel Consumption	1.18E+00	1.27E+00	1.10E+00	1.05E+00	1.00E+00	1.17E+00
Global Warming Potential	1.18E+00	1.27E+00	1.11E+00	1.05E+00	1.00E+00	1.17E+00
Acidification Potential	1.22E+00	1.25E+00	1.10E+00	1.04E+00	1.00E+00	1.25E+00
HH Criteria	1.15E+00	1.27E+00	1.10E+00	1.04E+00	1.00E+00	1.15E+00
Eutrophication Potential	1.22E+00	1.27E+00	1.11E+00	1.05E+00	1.00E+00	1.25E+00
Ozone Depletion Potential	1.11E+00	1.33E+00	1.15E+00	1.07E+00	1.00E+00	1.06E+00
Smog Potential	1.23E+00	1.26E+00	1.10E+00	1.04E+00	1.00E+00	1.27E+00

Maintainence	CIP	CB	CW	ICF	SS	TUC
Fossil Fuel Consumption	1.00E+00	1.00E+00	1.55E+00	1.00E+00	1.00E+00	1.00E+00
Global Warming Potential	1.00E+00	1.00E+00	1.84E+00	1.00E+00	1.00E+00	1.00E+00
Acidification Potential	1.00E+00	1.00E+00	1.56E+00	1.00E+00	1.00E+00	1.00E+00
HH Criteria	1.00E+00	1.00E+00	2.57E+00	1.00E+00	1.00E+00	1.00E+00
Eutrophication Potential	1.00E+00	1.00E+00	2.19E+00	1.00E+00	1.00E+00	1.00E+00
Ozone Depletion Potential	1.00E+00	1.00E+00	1.18E+00	1.00E+00	1.00E+00	1.00E+00
Smog Potential	1.00E+00	1.00E+00	2.25E+00	1.00E+00	1.00E+00	1.00E+00

End of Life	**CIP**	**CB**	**CW**	**ICF**	**SS**	**TUC**
Fossil Fuel Consumption	1.27E+00	1.11E+00	9.95E-01	1.18E+00	1.00E+00	1.18E+00
Global Warming Potential	1.27E+00	1.11E+00	9.97E-01	1.18E+00	1.00E+00	1.18E+00
Acidification Potential	1.27E+00	1.17E+00	1.02E+00	1.18E+00	1.00E+00	1.18E+00
HH Criteria	1.27E+00	1.10E+00	9.92E-01	1.18E+00	1.00E+00	1.18E+00
Eutrophication Potential	1.27E+00	1.17E+00	1.02E+00	1.18E+00	1.00E+00	1.18E+00
Ozone Depletion Potential	1.27E+00	1.11E+00	9.96E-01	1.18E+00	1.00E+00	1.18E+00
Smog Potential	1.27E+00	1.20E+00	1.03E+00	1.18E+00	1.00E+00	1.18E+00

Opertaing Energy	**CIP**	**CB**	**CW**	**ICF**	**SS**	**TUC**
Fossil Fuel Consumption	5.65E+08	5.68E+08	5.84E+08	5.85E+08	5.83E+08	5.66E+08
Global Warming Potential	3.48E+07	3.50E+07	3.59E+07	3.60E+07	3.58E+07	3.48E+07
Acidification Potential	1.38E+07	1.39E+07	1.43E+07	1.43E+07	1.42E+07	1.38E+07
HH Criteria	5.39E+04	5.42E+04	5.57E+04	5.58E+04	5.56E+04	5.40E+04
Eutrophication Potential	2.19E+03	2.21E+03	2.27E+03	2.27E+03	2.26E+03	2.20E+03
Ozone Depletion Potential	8.84E-05	8.90E-05	9.14E-05	9.17E-05	9.13E-05	8.86E-05
Smog Potential	5.35E+05	5.38E+05	5.53E+05	5.55E+05	5.52E+05	5.36E+05

Manufacturing	Fossil Fuel Consumpt	Global Warming Potential	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
CIP	1.20E+00	1.25E+00	1.16E+00	1.23E+00	1.07E+00	1.33E+00	1.08E+00
CB	1.39E+00	1.30E+00	1.23E+00	1.21E+00	1.57E+00	1.20E+00	1.07E+00
CW	1.29E+00	1.30E+00	1.62E+00	2.34E+00	1.10E+00	1.11E+00	1.23E+00
ICF	1.16E+00	1.17E+00	1.09E+00	1.13E+00	9.77E-01	1.20E+00	1.02E+00
SS	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
TUC	1.14E+00	1.17E+00	1.09E+00	1.15E+00	1.04E+00	1.22E+00	1.00E+00

Construction	Fossil Fuel Consumpt	Global Warming Potential	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
CIP	1.18E+00	1.18E+00	1.22E+00	1.15E+00	1.22E+00	1.11E+00	1.23E+00
CB	1.27E+00	1.27E+00	1.25E+00	1.27E+00	1.27E+00	1.33E+00	1.26E+00
CW	1.10E+00	1.11E+00	1.10E+00	1.10E+00	1.11E+00	1.15E+00	1.10E+00
ICF	1.05E+00	1.05E+00	1.04E+00	1.04E+00	1.05E+00	1.07E+00	1.04E+00
SS	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
TUC	1.17E+00	1.17E+00	1.25E+00	1.15E+00	1.25E+00	1.06E+00	1.27E+00

Maintainence	Fossil Fuel Consumpt	Global Warming Potential	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
CIP	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
CB	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
CW	1.55E+00	1.84E+00	1.56E+00	2.57E+00	2.19E+00	1.18E+00	2.25E+00
ICF	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SS	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
TUC	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00

End of Life	Fossil Fuel Consumpt	Global Warming Potential	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
CIP	1.27E+00	1.27E+00	1.27E+00	1.27E+00	1.27E+00	1.27E+00	1.27E+00
CB	1.11E+00	1.11E+00	1.17E+00	1.10E+00	1.17E+00	1.11E+00	1.20E+00
CW	9.95E-01	9.97E-01	1.02E+00	9.92E-01	1.02E+00	9.96E-01	1.03E+00
ICF	1.18E+00	1.18E+00	1.18E+00	1.18E+00	1.18E+00	1.18E+00	1.18E+00
SS	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
TUC	1.18E+00	1.18E+00	1.18E+00	1.18E+00	1.18E+00	1.18E+00	1.18E+00

Operating Energy	Fossil Fuel Consumpt	Global Warming Potential	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
CIP	5.65E+08	3.48E+07	1.38E+07	5.39E+04	2.19E+03	8.84E-05	5.35E+05
CB	5.68E+08	3.50E+07	1.39E+07	5.42E+04	2.21E+03	8.90E-05	5.38E+05
CW	5.84E+08	3.59E+07	1.43E+07	5.57E+04	2.27E+03	9.14E-05	5.53E+05
ICF	5.85E+08	3.60E+07	1.43E+07	5.58E+04	2.27E+03	9.17E-05	5.55E+05
SS	5.83E+08	3.58E+07	1.42E+07	5.56E+04	2.26E+03	9.13E-05	5.52E+05
TUC	5.66E+08	3.48E+07	1.38E+07	5.40E+04	2.20E+03	8.86E-05	5.36E+05

Based on Summary Measures

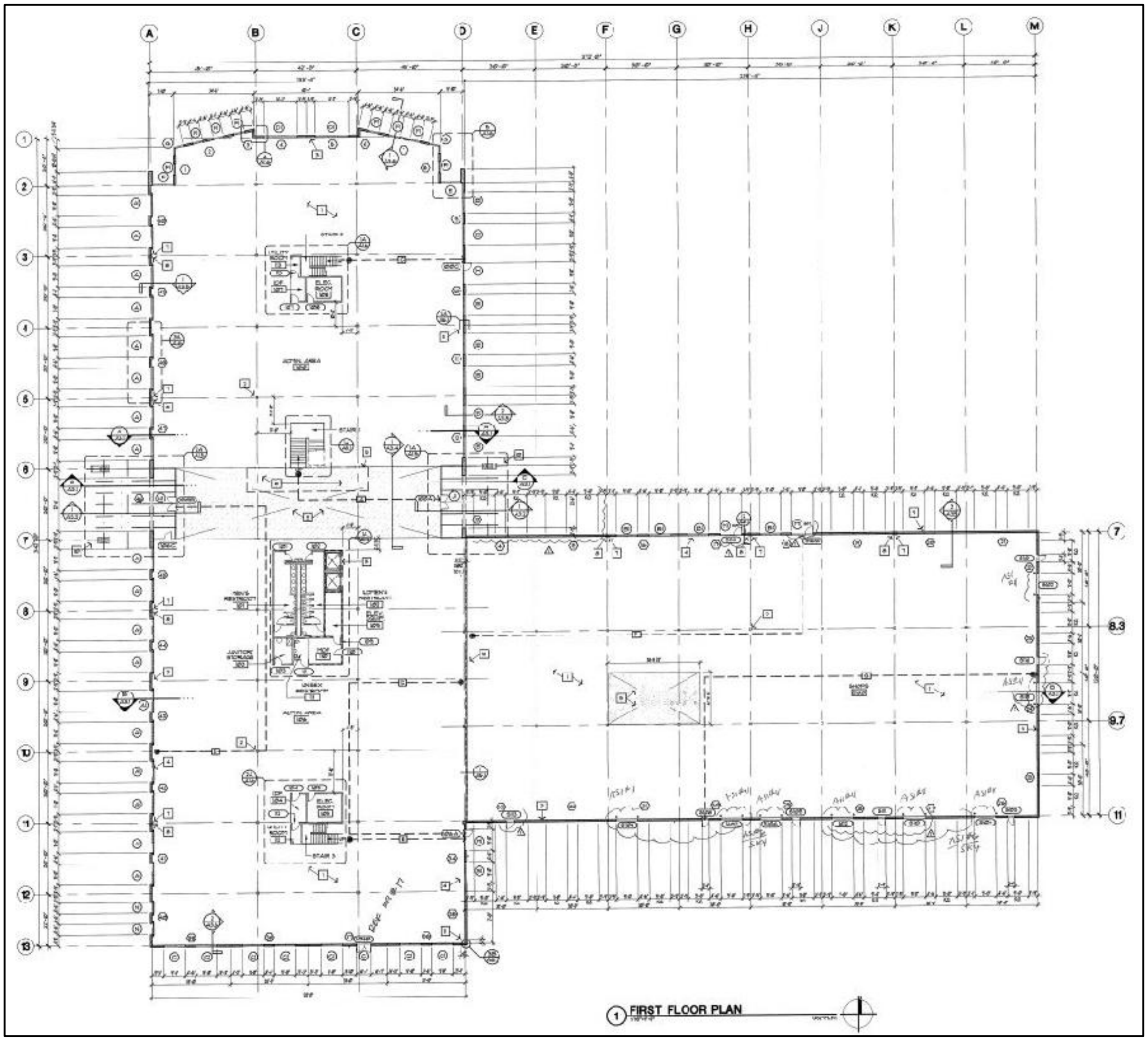
Summary Measures	CIP	CB	CW	ICF	SS	TUC
Fossil Fuel Consumption	1.71E+00	2.24E+00	2.15E+00	1.52E+00	1.00E+00	1.50E+00
Global Warming Potential	1.98E+00	2.14E+00	2.52E+00	1.62E+00	1.00E+00	1.66E+00
Acidification Potential	1.33E+00	1.44E+00	2.39E+00	1.17E+00	1.00E+00	1.21E+00
HH Criteria	1.32E+00	1.29E+00	3.96E+00	1.19E+00	1.00E+00	1.20E+00
Eutrophication Potential	1.36E+00	3.11E+00	1.81E+00	9.61E-01	1.00E+00	1.27E+00
Ozone Depletion Potential	4.34E+00	3.03E+00	2.27E+00	2.96E+00	1.00E+00	3.22E+00
Smog Potential	1.35E+00	1.34E+00	2.02E+00	1.09E+00	1.00E+00	1.20E+00

Summary Measures	Fossil Fuel Consum	Global Warming	Acidification Potential	HH Criteria	Eutrophication Potential	Ozone Depletion	Smog Potential
CIP	1.71E+00	1.98E+00	1.33E+00	1.32E+00	1.36E+00	4.34E+00	1.35E+00
CB	2.24E+00	2.14E+00	1.44E+00	1.29E+00	3.11E+00	3.03E+00	1.34E+00
CW	2.15E+00	2.52E+00	2.39E+00	3.96E+00	1.81E+00	2.27E+00	2.02E+00
ICF	1.52E+00	1.62E+00	1.17E+00	1.19E+00	9.61E-01	2.96E+00	1.09E+00
SS	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
TUC	1.50E+00	1.66E+00	1.21E+00	1.20E+00	1.27E+00	3.22E+00	1.20E+00

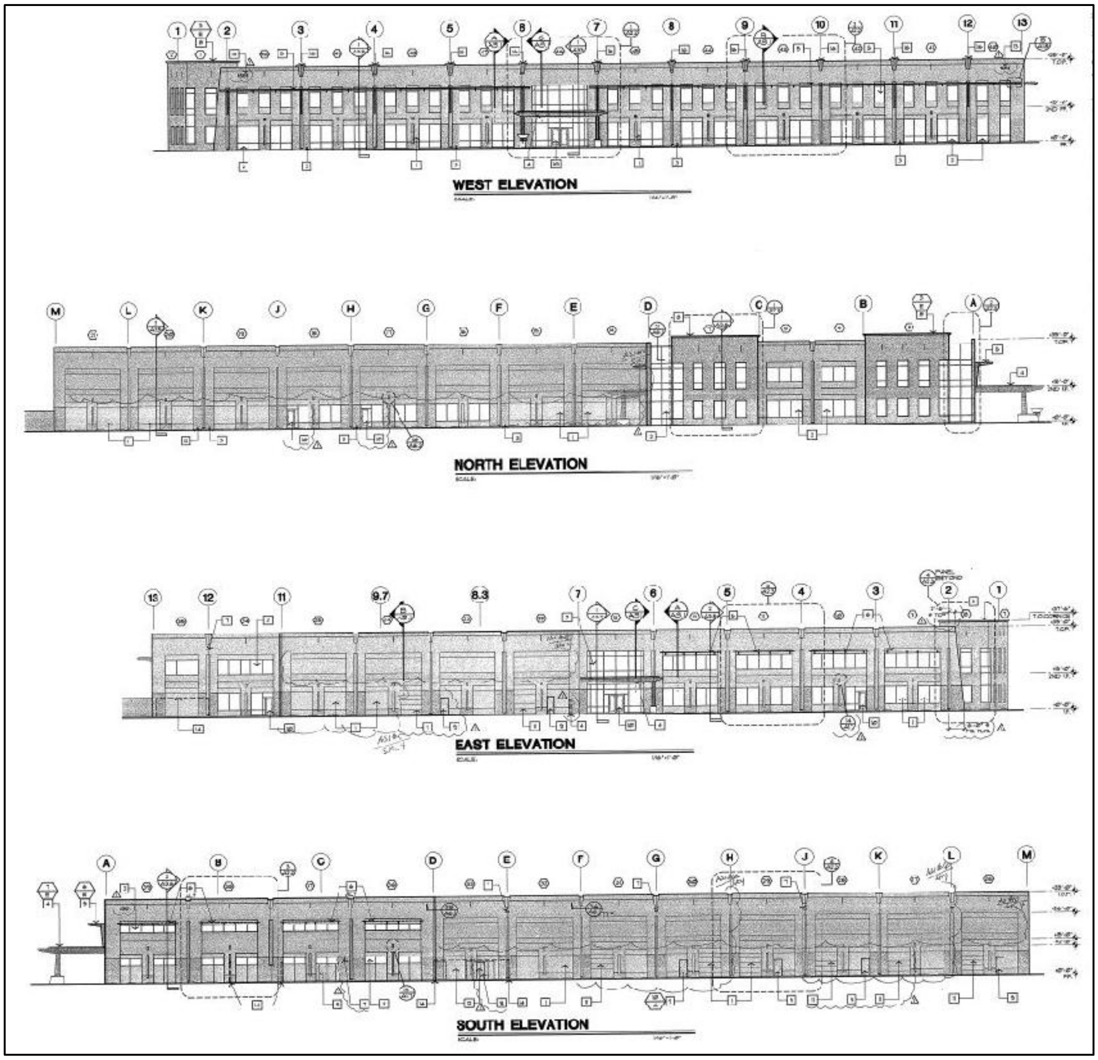
ARCHITECTURAL DRAWINGS FOR THE UNIVERSITY SERVICES BUILDING

Foundation Plan

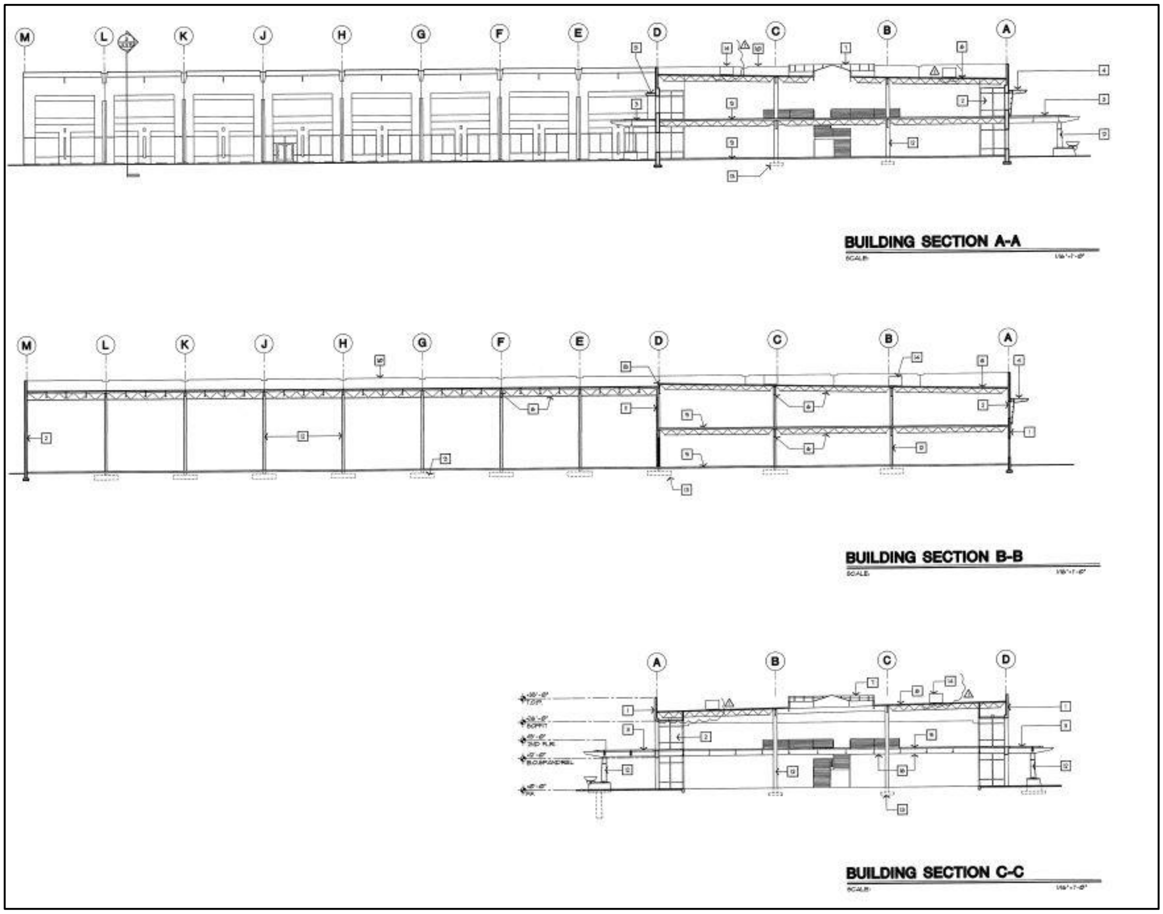
Floor Plan



Exterior Elevations



Sections


M
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BUILDING SECTION A-A
SCALE:
BUILDING SECTION B-B
SCALE:
BUILDING SECTION C-C
SCALE: