

Materials Choices Matter: An Eco-Balance Evaluation of a LEED Certified Building.

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ABSTRACT: Since environmental sustainability becomes a central concern in the design process in both architectural education and practice, research on quantifying buildings impact on the environment is growing worldwide. Although many designers seek LEED certification, some claim their buildings to be sustainable based only on certification. In fact, unless a Life Cycle Assessment (LCA) study is carried out, it is difficult to *quantify and evaluate* the environmental burden a particular building, or a construction material, has on its surrounding environment. The study method employs a quantitative LCA approach in calculating these impacts. The paper models an office building over a service life of 60 years and its implications on the environment from cradle to grave. It also quantifies and compares the total impacts this building has throughout this life span. The case building is located in Michigan in the U.S. where steel construction is the dominant method of construction for commercial type. The building is a 1-story LEED certified building that uses a geothermal HVAC system and has many sustainable materials used. The study calculates the environmental footprint of the building per unit area (impact to air, water, and land). The study discusses the importance of setting metrics beyond LEED to choose more sustainable materials based on their environmental impact. To narrow down to the critical materials, the study provides an assessment to which building component (structure, enclosure, floors, roofs) contribute *the most* to the total building impacts where the worst burden and critical materials could be identified and replaced. The outcome highlights where LEED rating system may fall short regarding the best materials alternatives to use and in which component of the building. This contributes to reduced total impact through selecting these alternatives based on the least damage to the environment.

KEYWORDS: Environmental Profiling, Impact Assessment, Life Cycle Assessment, LEED.

INTRODUCTION

Life Cycle Assessment (LCA), or Eco-Balance Analysis, represents a quantitative tool for calculating the environmental impacts of products at all stages in their life cycle from cradle to grave. Throughout the life cycle of a building, various natural resources are consumed, including energy resources, water, land, and several pollutants are released back to the global/regional environment. These environmental burdens result in global warming, acidification, air pollution, etc., which impose damage on human health, primarily natural resources, and biodiversity. For example, in the United States, the construction and building sector has been estimated to be responsible for roughly 40% of the overall environmental burden (U.S.DOE 2002). The building sector, constitutes 40% of the nation's total energy demand and approximately 44% of the total material use as well as roughly 39% of the total CO₂ emission, has been identified as one of the main factors of greenhouse gas emissions (U.S.DOE 2008). There is no doubt that reducing the environmental burden of the construction industry is crucial to a sustainable future.

Most research on the environmental impacts of buildings examine the issues at a relatively broad level though extensive description. For example, Finnveden and Palm (2002) stated that the use phase accounts for the majority of the environmental impacts of buildings. Klunder (2001) gave a description of environmental issues of dwellings, noting that assessments should focus primarily on components that involve large quantities of materials (e.g., foundation, floors, and walls), but there are also dangerous materials that should be avoided regardless of quantity (e.g., lead). Some of the building-related environmental studies present detailed quantitative data about the life cycle of a building (Scheuer et al., 2003). Junnila and Horvath (2003) quantify the most significant impacts of a high-end office in Europe. However, this study narrows down to the systems and materials that release most emissions for the studied case in order to test better retrofitting or fit out alternatives as building adapts to its future.

Building assembly systems (structural, envelope, floors, and roofs) are rarely studied on individual or as combined systems in LCA studies. Thus, such information and data indicating the significant impacts by building systems would be of great use in design and management of the building life cycle maintenance. Ragheb (2011a) concluded that that the walls system has the highest percentage of emissions among other components, mainly in global warming, acidification, smog, and respiratory effect impacts in comparative

study office buildings. The study acknowledges that LCA stands among new metrics to quantify how sustainable our buildings are. The study also supports that the design process, especially for office buildings, is never a finished process and the procurement and building adaptation should support this fact. Thus, LCA could be a beneficial tool in this ongoing process as the findings support these flexible changes of these systems with way less impacts.

1. METHOD, AND ASSUMPTIONS

A life-cycle assessment (LCA) framework is selected to analyze the environmental impacts of a new office building in Michigan. Sixty years of use was assumed to be the basic life cycle. LCA is the most appropriate framework for the quantification and evaluation of the inputs, outputs, and the potential environmental impacts of a product, process, or service throughout its life cycle, from cradle to grave i.e., from raw material acquisition through production and use to disposal [as defined in ISO 14040, 1997]. The LCA had three main phases; *inventory analysis* for quantifying emissions and wastes, *impact assessment* for evaluating the potential environmental impacts of the inventory of emissions and wastes, and *interpretation* for defining the most significant impacts.

LCA is defined as a systematic, holistic, objective process to evaluate the environmental burdens associated with a product or process. The process identifies and quantifies *energy* and *materials* usage and environmental releases of the studied system and evaluates the corresponding impacts on the environment. Identification and quantification of material and energy flows of the building's life cycle were primarily derived from the floor plans and specifications of the building.

Some emissions data related to different energy and material flows were collected mainly from the actual manufacturers in Michigan. The *quality of the data* used in the life-cycle inventory was evaluated with the help of data quality pedigree matrix recommended by (U.S. EPA, 2016). The quality target for the LCA data was set to be at score of 2 (on a 5 scale, 1 being the highest), which means reliability of most recent documented data measured from actual drawings and specs sheets. In life-cycle impact assessment, the magnitude and significance of the energy and material flows (inputs and outputs) were evaluated. The impact categories included were those identified by EPA (2006) as 'Commonly Used Life Cycle Impact Categories'. Among the 10 listed categories, the impact categories in this paper include:

- Primary Energy (Fossil Fuel Consumption) *FFC*,
- Resources Use *RU*,
- Global Warming Potential *GWP* (Climate Change),
- Acidification Potential *AP*,
- Eutrophication Potential *EP*,
- Human Health Respiratory Effect Potential *HHREP*,
- Photochemical Ozone Creation Potential *POCP*, or Summer Smog,
- Ozone Depletion Potential *ODP*.

The chosen impact categories are also on the short list of environmental themes that most environmental experts agree to be of high importance in all regions of the world and for all corporate functions (Schmidt and Sullivan, 2002). The classification, or assigning of inventory data to impact categories, and the characterization, or modeling of inventory data within the impact categories (ISO 1997), were performed using the ATHENA 4.1 Impact Estimator (2012) which is used to model the building. The program filters the LCI results through a set of characterization measures based on the *mid-point impact assessment* methodology developed by the U.S. Environmental Protection Agency (U.S. EPA); the *Tool for the Reduction and Assessment of Chemical and other environmental Impacts* (TRACI) version 2.2 built in the software. TRACI "mid-point-impact" method includes emissions, fate, and exposure, and is less uncertain than the "end-point" method used by other LCA software. In the life-cycle interpretation section, the results are also examined from the building assembly systems (foundation, walls, floors, etc.) so that the environmental impact of each system's life cycle can be quantified. Some limitation on impacts included biodiversity, and indoor air quality are not assessed due to the lack of data and limitation of the modeling software. Some other elements like office furniture, computers, construction of infrastructure, were excluded to focus the attention on modeling the building itself as simply as possible.

1.1 Case Study Building Description

The case study is a new office building located in Michigan (climate zone 5) in the U.S. Its construction ended in 2010. The targeted use of the building is mainly medical offices. The building has 21,290 sq ft (1978 m²) of gross floor area, and a volume of 351,285 cu ft (9947 m³). The building consists of 1 main floor

16.5 ft (5 m) high with no basement. The structural frame is Hollow Structural Steel (HSS) columns and open web steel joist for roof support. Floors are light reinforced concrete of one floor. The exterior walls are brick veneer with steel studs backing. Interior walls are galvanized steel studs with gypsum board facing to receive paints or wall paper. Foundations are cast-in-place concrete. The annual energy consumption is calculated using eQuest 3.64 (2012). The estimated natural gas consumption, mainly for water heating, of the building is 34.42 Mbtu (1616 Btu/sq ft/year) and this is equivalent to 0.47 kWh/sq ft/year. The estimated electricity consumption is 183,870 kWh/year (8.6 kWh/sq ft/year, or 30,000 Btu/sq ft/year of energy intensity), which is below U.S. average consumption for a small office bldg. One important factor for this office building is that it is a LEED certified and that might interpret its slightly lower use of electricity because it uses geothermal ground loops in HVAC heating and cooling.

In the study, the life cycle of the building was divided into 5 main phases: building materials manufacturing, construction processes, operation phase, maintenance, and demolition. Transportation of materials was included in each life-cycle phase through the software. The building materials phase included all of the transportation to the wholesaler warehouse. The construction phase included the transportation from the warehouse to the site.

1.2 Building Elements and Materials Phase

The following building systems categories were included in the study: foundation, structural frame (beams & columns), floors, external walls (envelope), roofs, and some internal elements e.g., doors, partition walls, and suspended ceilings. The amount of each material used in the building was derived from the bill of quantities generated by the software. However, building modeling was mainly based on input from architectural and engineering drawings, and the architect's specifications. Around 30 different building materials were identified and modeled.

1.3 Building Construction Phase

The construction phase of the building included all materials and energy used in on-site activities. Data were modeled for the use of electricity, construction equipment, and transportation of building materials to the site (average 100 mi). Some of the data were collected from the architect, contractor, and were further confirmed on-site.

1.4 Building Operation Phase

The use of the building was divided into mainly heating service (by natural gas) and electrical consumption. For the purpose of energy simulation, the building was estimated to be used 55 hr/week for 60 years. Energy calculations were performed using eQuest 3.64, a DOE 2 energy simulation program for electricity use and HVAC heating and cooling loads. All building parameters (dimensions, orientation, walls, windows, etc) were modeled.

1.5 Maintenance and Retrofit Phase

The maintenance phase included all of the life-cycle elements needed during the 60 years of maintenance; use of building materials, construction activities, and waste management of discarded building materials. An estimated 75% of building materials was assumed to go to landfill, and 25% was assumed recovered for other purposes such as recycling.

1.6 Demolition Phase

The demolition phase included demolition activities on-site, transportation of discarded building materials (75% of the total) to a landfill (100 mi), and shipping of recovered building materials to recycling site (100 mi, on average). The entire building was assumed to be demolished at end of its life.

2. RESULTS

Fig.1 shows the proportions of each life-cycle phase in every impact category with the associated numbers. Fuel consumption FFC in MJ has a notable 80% or more in 4 life cycle phases with exception in material manufacturing phase in which it constitutes 68% of the whole impact in that phase. This is consistent with most previous studies to show the significance of impacts due to fuel consumption. Global warming GWP seems to have a consistent ratio of 7% in all life phases. Resources use RU (kg) logically happens during manufacturing and represents 25% of impact in that phase and another 5% in the maintenance when some of building materials are replaced to adapt to future and new regulations. Acidification potential AP comes next to GWP at almost 3% in each phase. The study also found the summer smog impact POCP in the *manufacturing* and *operation* phases to be the largest contributor sharing the cause of smog formation at

40% and 50% respectively. This study along with very few others (Tekes 2000) discussed the potential of this important impact category.

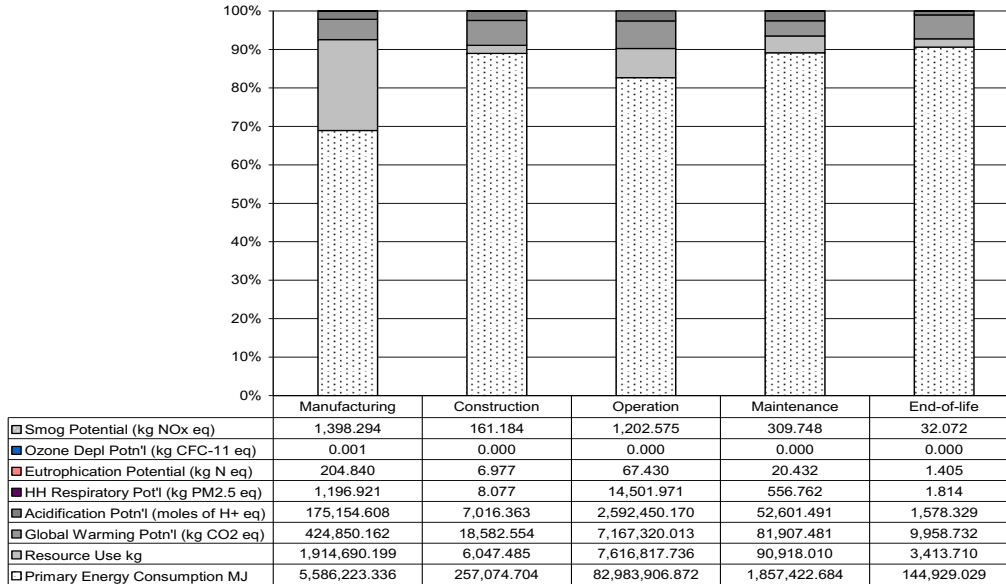


Fig. 1: Environmental Impacts by Life Cycle Stage

3. INTERPRETATION OF RESULTS

During materials *manufacturing* phase, the greatest contribution to overall impacts in the manufacturing phase comes from the extensive use of energy (68%) in the manufacturing process of the construction materials (steel, concrete, aluminum, glass, etc) that are required for construction. The resource depletion RU in this phase also represents 22% due to all virgin materials that are used and processed from the nature. GWP and AP represent the rest of the impacts at this phase at 10% mainly due to the releases from fossil fuel use in that phase.

In *construction* phase, the use of construction equipment is the only life-cycle element with significant impacts (88%). That is due to the fuel and electricity used during the erection of the bldg. The other 10% attributed to GWP and AP with small fraction attributed to EP and Smog impacts.

The *operations* phase dominates life cycle energy consumption. Numbers show the building operational demands over a 60 year life span, representing 83% (82×10^6 MJ) of the total life cycle energy. Almost 90% of life-cycle impacts in the use phase caused by electricity and natural gas used for heating in cold climate like Michigan.

The *maintenance* phase comes third to operation and manufacturing in terms of life cycle impacts. This is the adaptation and modification phase where several parts of the buildings are replaced or renovated to match future codes and needs. Ozone Depletion Potential ODP, albeit almost negligible in the study, most of its causes are concentrated in the manufacturing and maintenance due to the VOCs released by paint manufacturing and the re-painting processes (every 7-10 years). The *end-of-life* phase does not have significant impacts in the overall life cycle, except for the Eutrophication category (2%) and Smog (4%). Transportation of the waste material to the landfill produces most of the impacts in this phase.

4. LIFE CYCLE IMPACTS BY BUILDING SYSTEMS

In practice the building design process typically proceeds by choosing building systems, not by chronological life-cycle phases. To interpret the results for the purposes of design management, an analysis of the result from the building assembly perspective has been performed.

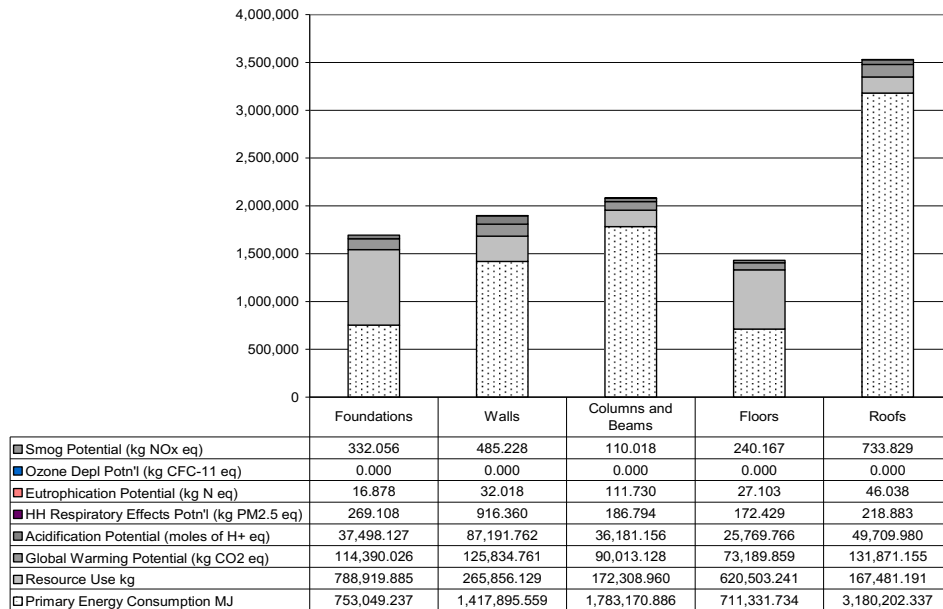


Fig. 2: Environmental Impacts by Building Assembly

The life-cycle phases are divided into life-cycle elements, the elements belonging to different building assembly systems are grouped together. The life-cycle impacts of each building system; foundations, walls, structure (columns and beams), roofs, floors, are also modeled and calculated. Fig. 2 shows that the environmental impacts of the office life cycle are divided into 5 building assembly systems. Three significant systems accounts for the highest environmental impacts of this building. These are roof, structure (columns/beams), and the wall systems respectively. These results show energy consumption (embodied + transportation energy) as the most dominant impact category in the whole assembly (Fig.2). Resource use is the highest in foundations and floors systems due to the massive concrete weight and wide area both systems cover. GWP has more impact in roof and walls (due to insulation manufacturing emissions) than structure. Acidification AP is the highest impact in walls assembly due to some materials such as gypsum boards, fiberglass insulation, and vapor barriers which release SO₂ and NO_x during manufacturing that increase the AP impact category.

When breaking down the air emissions constituents of the case study, the findings also support previous results of high impact incurred by walls and roof systems, which share insulation as major component. Fig. 3 shows that more than 30% of the major air emissions are released by wall system and at lesser degree the roof system throughout the life cycle of the building

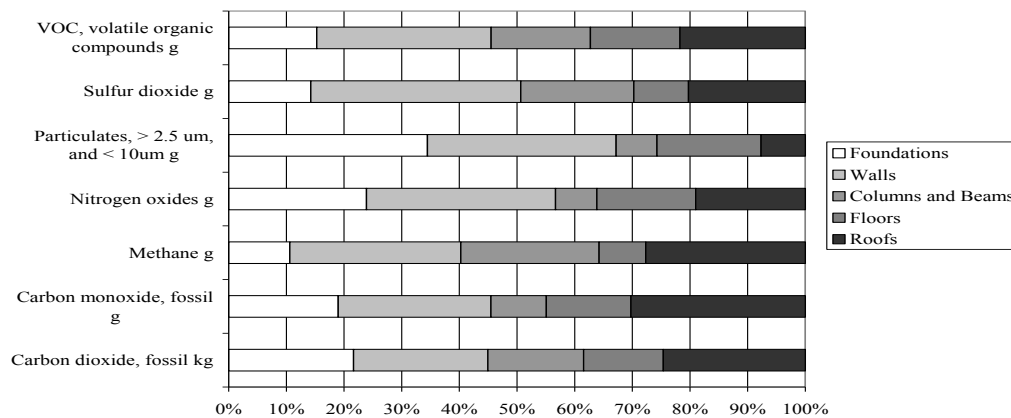


Fig. 3: Air Emissions by Building Assembly Systems

5. LEED VS. NON-LEED IMPACT COMPARISON

For a fair comparison between LEED vs. non-LEED buildings from previous studies, the results for all impacts in this study have been normalized per square meter of building area. Compared with a previous study (Ragheb, 2011b) using LCA to profile a non-LEED office building, the outcome showed that LEED building, in this study, performed environmentally better against non-LEED office building in the same climate zone 5 and with the same construction method (steel). The non-LEED building had more impact per sq. meter in all life cycle phases. For example, non-LEED scored 55% more in fossil fuel consumption FFC, 58% more in global warming GWP, 57% more in acidification AP, 22% more in Eutrophication EP, 5% more in smog POCP, 49% more in respiratory effect HHREP.

However, when comparing the environmental impacts of building assembly systems in this study to the previous study, it was surprising to find that the *roof system* in LEED building (Fig. 2) has almost double the impact of non-LEED building in most categories (FFC, GWP, AP, EP, POCP, HHREP). These results were primarily due to the increased roof insulation thickness to gain LEED points on energy reduction. The rigid insulation used (polyisocyanurate), albeit high R-value per inch, has high embodied energy and releases huge emissions during manufacturing phase. Insulation also covers huge surface area (the entire roof and walls) to form the building enclosure. This surface area with increased thickness significantly increased the environmental burden of roof and wall systems. The other material responsible for this huge roof impact, is steel (with its massive embodied and transportation energy) in building structure. A third material (roof membrane) is found to contribute to roof impact at a lesser degree.

It is worth noting that a “what if” scenario analysis (LCA sensitivity analysis) in this study has been performed using alternatives to the existing materials in the LCA model. It showed total impact reduction of 6-19% in many categories if an alternative *expanded polystyrene* insulation (to achieve same R-value) is used in lieu of the polyisocyanurate insulation. In addition, using a lighter color roof membrane (in lieu of the existing black EPDM rubber) also rendered 12% reduction in total impacts due to overall energy saving and lesser impact of such lighter membrane.

CONCLUSION

The purpose of the study was to show the relationship between LEED certification and LCA. It aimed to quantify and compare the potential environmental impact caused by an office building throughout life-cycle phases. The study examined the building assembly systems that most contribute to its life cycle impact. The study found that roof and wall systems to have significant environmental impacts due to the use of insulation and membrane materials. Using more environmental friendly materials can render a reduction 15% on average in different impact categories. Suggestions have shown the importance of LCA as tool to choose better alternatives during the design and maintenance (retrofit) phases of an office building.

LCA results demonstrated that the LEED certified building has significant lower energy consumption rate for an office building in the U.S. This is mainly due to using geo-thermal loop HVAC system during the operation phase in which most of the building impacts would occur. One shortcoming though was the use of tighter envelope and thicker insulation to gain LEED credits without considering the negative impact of using such insulation alternative (polyisocyanurate). This resulted in that the roof system of this LEED building had the highest impact in most categories even when compared to a non-LEED building from a previous study in the same climate. Using LCA method in this study opens the way for more testing of LEED certified buildings with high ratings e.g. gold or platinum using LCA impact analysis to verify their environmental performance. This helps to narrow down on the sensitive area of design and material choices (e.g. insulation, membrane) that LEED may fall short by awarding points for overall energy savings without looking at the significant environmental impact of material alternatives that achieve this saving.

One of the limitations of this study relates to the single-case study method used, because wider generalization based on a single case is not possible. However, the results of the study can be interpreted and compared with the results from previous LCA studies. The findings of this study support previous arguments that operation energy is a major environmental issue in the life-cycle of an office building. In addition, some building materials e.g. rigid insulation and roof membrane have significant impact. This is typical for an office building in the U.S. For other countries, it is more difficult to generalize findings based on the results of this study. There are many regional conditions used in the calculations that could affect considerably the results outside the U.S. Building design, intensity of materials, construction methods, and intensity of energy use in the operation phase differ. Most importantly, there are differences in electricity generation and energy use (grid mix); e.g. a higher proportion of coal is burned in the United States to generate electricity. Europe and Canada have a higher percentage of electricity from hydro power (almost

no emissions) and non-fossil fuels. These relatively clean sources affect the final emissions especially the release of CO₂, SO₂, and Nitrogen Oxides (NO_x) to air as major contributors to the impact categories previously measured. The study is also unique in modeling the building with the U.S. electricity grid which depends on coal as one major source at a relatively higher percentage of 31% (DOE, EIA 2016), which in turn render more air emissions than western Europe and Canada.

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