Environmental performance evaluation of enclosure systems alternatives in office buildings in the U.S.

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ABSTRACT: Low impact materials have become key player towards achieving environmental sustainability in the built environment. Such materials also contribute to carbon neutral buildings, responding to AIA 2030 challenge and many other initiatives by governmental and professional institutions. Building enclosure incorporates many construction materials that contribute to overall embodied energy and environmental impact. It also affects building operational energy as a barrier between indoor and outdoor environment. The study method employs a quantitative Life Cycle Assessment (LCA) approach in calculating environmental impacts of enclosure systems. 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 of the assembly systems of this building throughout this life span. The case building is located in the Midwest in zone 5, where steel construction is the common method of construction for commercial type in the region. The building is a 1-story high that incorporates few sustainable materials. The study calculates the environmental footprint of the building per unit area (impact to air, water, and land). To achieve its goal, the study provides an assessment to which building component (structure, walls, floors, roofs) contribute the most to the total building impacts where the worst burden, among its assembly systems, is identified. The outcome tests other materials alternatives to use in the roofing system to minimize its impact. The paper employs a "what if" scenario analysis to evaluate replacing high-impact materials with alternatives that have less impacts and briefly calculate the reduction in the total impacts against the original construction materials.

KEYWORDS: Environmental Impacts, Life Cycle Assessment, Sensitivity Analysis.

INTRODUCTION

The contribution of buildings to the overall environmental impacts of human activities has been significant and well-documented (EPA 2009, EIA 2015). According to the US Energy Information Administration (EIA 2015), 19% of the world's primary energy is consumed in the U.S. Buildings also contribute 40% to carbon dioxide emissions in the U.S. (EIA 2012) and near 66% of non-industrial solid waste generation (EPA 2009). The building sector in the U.S. constitutes approximately 44% of the total material use as well as roughly 1/3 of the total CO2 emission identified as one of the main factors of greenhouse gas emissions (U.S.DOE 2002). Life Cycle Assessment LCA represents a quantitative tool for calculating the environmental impacts of buildings 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, natural resources, and biodiversity. There is no doubt that reducing the environmental burden of the construction industry is crucial to a sustainable world.

Many studies use LCA in assessing the environmental impacts of buildings. For example. 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). Junnila and Horvath (2003) took the same path to 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. Ragheb (2011) 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 a comparative study of 3 office buildings. Tingley et al (2015) have used LCA at the level of construction materials to compare three different insulation materials when applied in a typical dwelling.

Building assembly systems (structural, envelope, floors, and roofs) on the commercial side 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. The literature also supports that the design process, especially for office buildings, is never a finished process and the retrofit and building adaptation support this fact. Thus, LCA is a beneficial tool in this ongoing adaptive process as the findings support these flexible retrofit of systems, and/or materials, with way less impacts alternatives.

1.0. RESEARCH METHOD AND ASSUMPTIONS

A life cycle assessment (LCA) framework is selected to analyze the environmental impacts of a new office building in the Midwest. Sixty years of use was assumed to be the basic life cycle. LCA is the most appropriate framework for the identification, 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 holistic and systematic process to calculate the environmental burdens associated with a product or process. The process identifies and quantifies energy and material usage and environmental releases of the studied system and evaluates the corresponding impacts on the environment. Identification and quantification of material and energy flows (inputs and outputs) of the case study office building were obtained from the construction drawings and specifications and modeled using series of software listed below.

The quality of the data used in the life-cycle inventory was evaluated with the help of a six-dimensional estimation framework recommended by (Heijungs, et al. 2002). The quality target for the LCA was set to be at the level of ‘‘good,’’ which means reliability of a most recent documented data from actual drawings, specs sheets. In life-cycle impact assessment LCIA, 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). Furthermore, the used impact categories are consistent with the air and water emissions that the World Bank (1998) has recommended to be targeted in environmental assessments of industrial enterprises. 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 4.2 Impact Estimator (2014) 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. In the life-cycle interpretation section, the results are also examined from the building assembly systems (foundations, structures, walls, floors, and roof) so that the environmental impact of each system's life cycle can be quantified.

1.1. Case study building description

The case study is a new office building located in zone 5 (per ASHRAE's classification) in the Midwest of the U.S. Its construction ended in 2014. The targeted use of the building is mainly offices. The building has 21,500 sq ft (1997 m^2) of gross floor area, and a volume of 354,750 cu ft (9985 m^3). 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 slab-on-grade floor. The exterior walls are brick veneer with steel studs backing. Interior walls are galvanized steel studs with gypsum board facing to receive paint or wall paper. Foundations are cast-in-place concrete. The annual energy consumption (operational energy) is modeled/calculated using eQuest 3.65 (2016). The estimated natural gas consumption, mainly for water heating, of the building is 35.44 Mbtu (1648 Btu/sq ft/year) and this is equivalent to 0.483 kWh/sq ft/year. The estimated electricity consumption is 184,650 kWh/year (8.58 kWh/sq ft/year, or approx. 29,300 Btu/sq ft/year of energy intensity), which is slightly below U.S. average consumption for a small office bldg.

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. Materials manufacturing

The following building element 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. 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).

1.4. 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 3.65, 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.

2.0. INTERPRETATION OF RESULTS

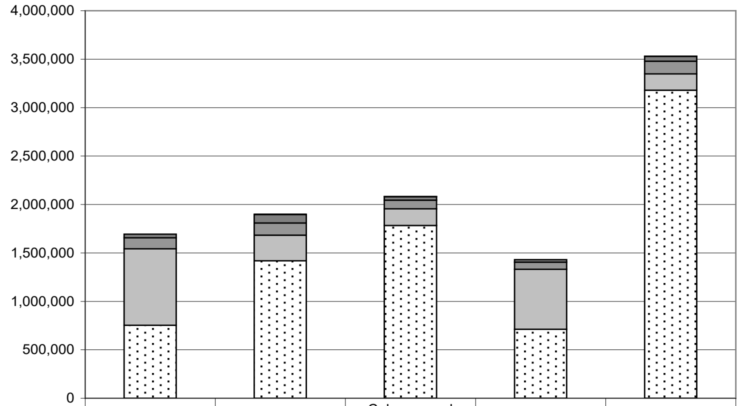
To interpret the results for the purposes of design management, an analysis of the result from the building assembly systems perspective is important. Hence, the life-cycle phases are divided into life-cycle elements, the elements belonging to different building assembly systems are grouped together, and the life-cycle impacts of each building system; foundations, walls, structure (columns and beams), roofs, floors, are calculated. Fig.1 shows that the environmental impacts of the office life cycle are divided into 5 building components systems. Three significant systems accounts for the highest environmental impacts of this building. These are roof, structure (columns/beams), and the wall systems respectively.

The results for all impacts have to be normalized per sq meter of building area for fair comparison. However, when comparing the life cycle impacts of assembly systems, it was surprising to find that the roof system has huge impact compared to building structures and walls which come second and third respectively. This happen in most impact categories (FFC, GWP, AP, EP, POCP, HHREP). In this study (Fig.1), the result was primarily due to increasing the roof insulation thickness to increase energy efficiency. The rigid insulation used (polyisocynurate), albeit high in R-value per inch (R 7.2), it has high embodied energy and has huge emissions during its manufacturing process. Insulation also covers wide area of the roof and walls systems forming the building enclosure. The other material, causes this huge roof impact, is steel (with its massive embodied and transportation energy) in building structure. These results made energy consumption (embodied + transportation energy) the most dominant impact category in the whole assembly (Fig.1). Resources use is the highest in foundations and floors systems due to the massive concrete weight and wide area both systems cover. GWP is more in roof and walls (due to insulation emissions) than structure. AP is the highest impact in walls assembly due to some materials such as gypsum boards, fiberglass insulation, and vapor barriers which release Sulphur dioxide (SO_2) and Nitrogen oxides (NOx) during manufacturing that contribute to acid rain formation when released to the environment.

3.0 RETROFIT SCENARIO ANALYSIS

Sensitivity analysis is typically used to check either the significance of changing key parameters contributing to the overall LCA or key assumptions governing the methodology of the LCA itself. The *what if* scenario is used for sensitivity analysis according to Pesonen et al. (2000). Sensitivity scenarios are used to compare the replacement of materials that have high impacts within the building with more environmentally friendly alternatives, and then quantify these changes in the environmental impacts again at the end of the 60 years. From the previous results, the study found that materials such as roof insulation and membrane have huge area, quantities, and potential high impact in many categories. Therefore, *roof* materials are replaced with more environmentally friendly altrnatives, then the total impacts are assessed again with the new alternatives to test how much reduction to the results was achieved. The other systems (foundations, structure, floors) are not changed in this analysis because they are fixed systems (cannot be changed) once building is erected. The roof is chosen because it represents the highest impacts share by building systems, besides structure

(Fig. 1). This is consistent with ISO 14043 (1998) to "asses the sensitivity of data elements that influence the results most greatly".



	Foundations	Walls	Columns and Beams	Floors	Roofs
Smog Potential (kg NOx eq)	332.056	485.228	110.018	240.167	733.829
Ozone Depl Potn'l (kg CFC-11 eq)	0.000	0.000	0.000	0.000	0.000
Eutrophication Potential (kg N eq)	16.878	32.018	111.730	27.103	46.038
HH Respiratory Effects Potn'l (kg PM2.5 eq)	269.108	916.360	186.794	172.429	218.883
Acidification Potential (moles of H+ eq)	37,498.127	87,191.762	36,181.156	25,769.766	49,709.980
Global Warming Potential (kg CO2 eq)	114,390.026	125,834.761	90,013.128	73,189.859	131,871.155
Resource Use kg	788,919.885	265,856.129	172,308.960	620,503.241	167,481.191
Primary Energy Consumption MJ	753,049.237	1,417,895.559	1,783,170.886	711,331.734	3,180,202.337

Fig. 1. Environmental Impacts by Building Assembly Systems

Table 1. Retrofit Scenario Analysis

	Roof Insulation	Roof Membrane
Existing	4.5" rigid poly-isocyanurate insulation w/ R-30	Mechanically fastened 60 mil black EPDM
Retrofit	6.5" rigid expanded polystyrene insulation w/ R-30	Mechanically fastened 60 mil white TPO

3.1. Retrofits assumptions scenarios

A list of changing variables included in the analysis is shown in (Table 1). The main assumptions for retrofitting was to try other alternatives for the roofing system since it showed the highest impact among assembly systems (Fig.1). Expanded polystyrene proved to be more environmentally friendly and gives comparable R-value over similar polyisocynurate insulation but with less environmental impact due to its recycling nature. Since polyisocynurate is more durable than expanded polystyrene, it is important to mention that although durability plays a factor in roof design, it was normalized here for the sake of testing and comparing the impact of these 2 alternatives. Roof replacement is suggested to take place 2 times during 60 years of life (every 30 years). This seems quite reasonable assumption since the life expectancy of an ordinary roof insulation is around 30 years. Suggested changes are to replace the 4.5" thick polyisocyanurate insulation and 60 mil black EPDM membrane with 6.5" thick expanded polystyrene insulation (to give the same R-value) and 60 mil white TPO membrane (Fig. 2). The materials that were chosen represent the most significant materials of the roof system due to quantity (coverage area) and their possible high emissions during manufacturing. Other materials such as steel decking, fasteners, roof board were similar in both comparative assemblies.

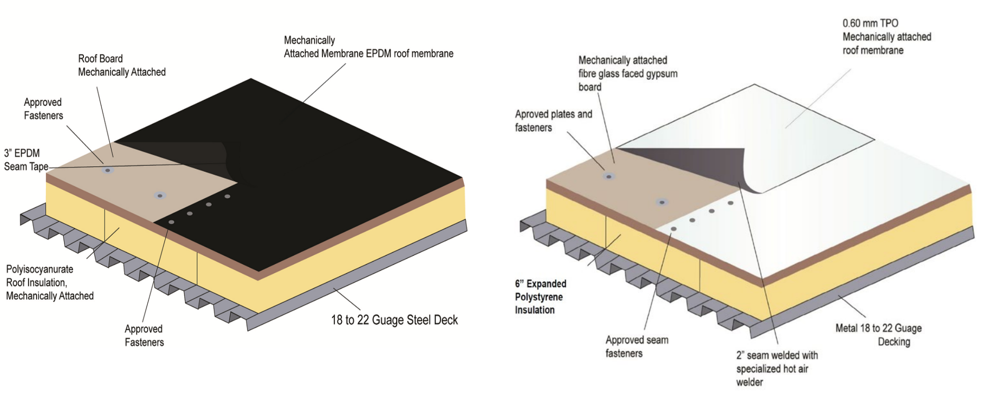
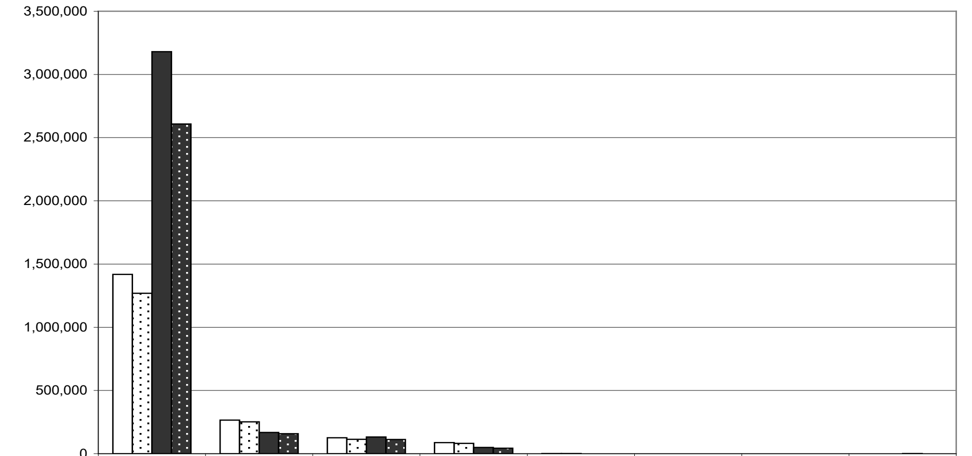


Fig. 2. Comparison between existing assembly (left) and proposed retrofit (right) (courtesy of Platinum Roofing, Inc.)

3.2. Retrofit sensitivity results

Figure 3 shows results of all impact categories by building assembly systems. The two scenarios are the *existing* calculations scenario and the *retrofit* scenario. Results show that sensitivity scenario with alternative materials has reduced values in all impact categories due to the change of insulation and membrane (Table 1). These reductions range between 6% and 19% in the 8 different impact categories this study has investigated. The retrofit sensitivity also highlights the importance of roof insulation and membrane as sensitive materials that have huge quantities within a building. They significantly reduce the whole impacts if chosen carefully by architects.



	Primary Energy Consumption MJ	Resource Use kg	Global Warming Potential (kg CO2 eq)	Acidification Potential (moles of H+ eq)	HH Respiratory Effects Potential (kg PM2.5 eq)	Eutrophication Potential (kg N eq)	Ozone Depletion Potential (kg CFC-11 eq)	Smog Potential (kg NOx eq)
Walls	1,417,895.559	265,856.129	125,834.761	87,191.762	916.360	32.018	0.000	485.228
Walls-retrofit	1,269,083.034	251,813.332	113,929.445	82,137.109	874.516	28.151	0.000	460.201
Roofs	3,180,202.337	167,481.191	131,871.155	49,709.980	218.883	46.038	0.000	733.829
Roofs-retrofit	2,608,569.761	157,969.073	112,643.815	43,395.097	198.901	47.620	0.000	440.144

Fig. 3. Environmental Impacts Reduction Due to Retrofitting

CONCLUSION

The purpose of the study is to quantify and compare the environmental impact caused by an office building's assembly systems. The study also determined the life-cycle phases that contribute the most to the whole building impact. The study examined the building assembly components 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 environmentally friendly materials (expanded polystyrene insulation + TPO membrane) in roof assembly rendered a reduction of 6% -19% in different impact categories throughout the entire life cycle. Using the TPO membrane reduced the annual energy consumption of the building by 10% over 60 years which in turn reduced the total impact. Suggestions have shown the importance of LCA as tool to choose better alternatives during the maintenance (retrofit) phase of an office building. Some limitation on impacts include office furniture, computers, construction of infrastructure are not assessed due to the limitation of the modeling software. These were excluded to focus on modeling the building assembly systems not the interior furniture.

LCA results demonstrated that the case study building has overall lower energy consumption rate for an office building in the U.S. This is mainly due to tighter enclosure. One shortcoming though was the use of polyisocyanurate insulation and EPDM rubber membrane without considering the high environmental impact of using such alternatives. This resulted in that the roof system had the highest impact in most categories. The LCA method helped to narrow down to this high-impact system and material choices used (e.g. insulation, membrane). Hence, even an energy efficient building may have a reverse huge impact due to selection of high-impact building materials within its assembly systems. It seems to have an overall annual energy savings but has significant high impact of materials that achieve this saving.

One of the limitations of the 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 together with the results from previous 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, and that some building materials e.g. insulation, membrane also have significant impact. This is typical for an office building in the U.S. For other countries, it is more difficult to generalize 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 are all different. Most importantly, there are differences in electricity generation and energy use (grid mix) especially if a higher proportion of coal is burned in the power plant like the case in the United States. Europe and Canada have a higher percentage of electricity from hydro power (almost no emissions) and non-fossil fuels which will affect the final emissions especially the release of CO_2, SO_2, and NO_x to air. The study is also unique in modeling the building with the U.S. electricity grid which depends on coal as a resource at 39% (DOE, EIA 2015).

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