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Cradle to Grave: Case Studies of Buildings' Environmental Footprint

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ABSTRACT

As sustainability becomes a central figure in the design process in both architectural education and practice, conducting such environmental research is gaining high momentum in architectural education and practice worldwide. Although many architects claim their buildings to be sustainable, unless a comprehensive Life Cycle Assessment (LCA) study is conducted, it is difficult to *calculate* and *evaluate* the total burden that a particular building has on its surrounding and global environment. This study demonstrates how Cradle to Grave or Life Cycle Assessment (LCA) could be applied from a single bldg material or consumer product to a complex system such as an entire building throughout its life cycle. It highlights the difficulties in modeling the whole building over a long service life (60 years) and its implications on the construction process. Studying the whole life cycle of a building also shows to what extent each life cycle phase contributes to the total burdens, where some environmental strategies could be applied to reduce the total burden. The study also examines the significance of these impacts that occur during the life cycle through 3 cases study of office buildings in Michigan. Cases include one recent LEED certified vs. conventional construction to highlight the difference of choosing sustainable alternatives over others. The study aims also to provide a comprehensive assessment to which building assembly component (foundations, structure, walls, floors, roofs) contribute the most to the total impacts to inform architects' design decisions regarding the building components that could reduce the total environmental burdens.

1. INTRODUCTION

In recent years, building-related environmental issues have become increasingly important. The construction and building sector has been found to be responsible for a large part of the environmental impacts on human activities. 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). Building-related environmental issues are also important for companies. There are already more than 40,000 companies in the world that have been certified to the ISO 14001 Environmental Management System EMS (ISO 2002b). Many large companies such as IBM, General Motors, and Ford are now requiring or, at least, encouraging EMS registration from their suppliers (ISO 2002a). Management of building-related environmental issues requires tools and knowledge that enable the control of environmental aspects, thus minimize the environmental impacts (Roberts and Robinson 1998). An environmental aspect in this context is now an element of an organization's activity, product, or service that interacts with the environment (ISO 1996).

1.1 Background: Life Cycle Assessment Perspective

LCA represents a quantitative tool for calculating the environmental burdens (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. The building sector, constitutes 30-40% of the society's total energy demand and approximately 44% of the total material use as well as roughly 1/3 of the total CO2 emission, has been identified as one of the main factors of greenhouse gas emissions. There is no doubt that reducing the environmental burden of the construction industry is crucial to a sustainable world.

Most research on the environmental impacts of buildings examine the issues at a relatively broad level though extensive descriptions. 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). Energy consumption in space heating, hot water, lighting, and ventilation should be studied along with the energy carrier (electricity or gas). Some of the building-related environmental studies present detailed quantitative data about the life cycle of a building (Scheuer et al., 2003). However, most studies only utilize one or two indicators of environmental impacts. Treloar et al. (2001) have used a hybrid input-output model to estimate the primary energy consumption of building materials to study the relative importance of different life-cycle phases. Seo and Hwang (2001) evaluated the life-cycle primary energy usage and CO2 emissions of residential buildings in Korea. The results are presented by building materials and life-cycle phases, including materials manufacturing, operational energy, and demolition.

Other quantitative studies have used a wider set of environmental impact indicators in their analyses, but have only included certain life-cycle elements. Junnila and Saari (1998) have used life-cycle inventory analysis to estimate the primary energy consumption and environmental emissions of CO2 , CO, NOx , SO2 , volatile organic compounds (VOCs), and particulates from a residential building. The life-cycle phases studied included manufacturing of structural materials, construction, operational energy, maintenance, and demolition. Trusty and Meil (2000) have assessed the environmental impacts of an office building, including the structural and envelope elements, which were compared against the annual operational energy. Junnila and Horvath (2003) took the same path to quantify the most significant impact of a high-end office in Europe.

Despite the studies about the environmental impacts of buildings, it is still very difficult to find comprehensive information about the life-cycle impact of office buildings. Most of the previous studies have concentrated on either a limited set of life-cycle phases, or only one or two environmental impact indicators. Building assembly systems (structural, envelope, floors, and roofs) are rarely included, despite the fact that in practice most of the buildings are designed by such building systems or design disciplines. Thus, such information and data indicating the significant aspects by building systems would be of great use in design management.

2. APPROACH, METHOD, AND ASSUMPTIONS

A life-cycle assessment (LCA) framework is selected to analyze the environmental impacts of a new office building in Southeast Michigan. 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 aspects.

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 material usage and environmental releases of the studied system, and evaluates the corresponding impacts on the environment. Although LCA is widely used to assess environmental impacts of products and processes, it has its limitations, which are important to recognize while interpreting the results of an LCA study. For example, ISO 14040 (ISO 1997) has listed the following limitations. There are subjective choices (e.g., system boundaries, selection of data sources, and impact categories), the models used in inventory and impact assessment are limited (e.g., linear instead of nonlinear), the local conditions may not be adequately represented by regional or global conditions, the accuracy of the study may be limited by the accessibility or availability of relevant data, and the lack of spatial and temporal dimensions introduces uncertainty in impact assessment. Identification and quantification of material and energy flows (inputs and outputs) of the case study office buildings were conducted during the design and construction of the building in 2008. The material and energy flows of the building's life cycle were primarily obtained from the floor plans and specifications of the buildings.

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 a six-dimensional estimation framework recommended by the data quality guidelines from (Lindfors et al. 1995, Weidema, 1998). The quality target for the LCA was set to be at the level of ‘‘good,’’ which means reliability of most recent documented and measured data from drawings, specs sheets, and contractor rep on-site. 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:

- Fossil Fuel Consumption FFC,
- Resources Use RU,
- Global Warming Potential GWP (Climate Change),
- Acidification Potential AP,
- Eutrophication Potential EP,

- Photochemical Ozone Creation Potential POCP or Summer Smog,
- HH Respiratory Effect Potential REP, and
- 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 4.1 life-cycle calculation program (2010) which is used to model the building. The significance of different life-cycle aspects is evaluated by comparing the environmental impacts of different building elements in every impact category so that the significant environmental impact could be ranked in order of importance. In the life-cycle interpretation section, the results are also examined from the building assembly (foundation, walls, floors, etc.) so that the environmental impact of each system's life cycle can be quantified.

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. 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. The environmental profiles of impacts in each life cycle stage, and energy and material flows used in the LCA are presented in Tables 1-3 for the 3 cases.

2.1 Description of the Case Buildings

The method used in this research is multiple case studies consist of 3 office buildings located in South East Michigan, USA. Each floor plan represents a typical office building in the Midwestern area. Choosing a typical office also helps in generalizing the research findings to bigger sample of the same type. Description of cases is as follow:

2.1.1 Case 1: Brookside Office Building

Brookside is a newly built office building in Southeast Michigan in the U.S. Its construction ended in 2007. It is occupied by an insurance company with administrative employees. The building has 40,000 sq ft (3716 m^2) of gross floor area, and a volume of 600,000 cu ft (16990 m^3). The building consists of 2 floors (20,000 sq ft each, 15 ft floor height each) with no basement. The structural frame is Hollow Structural Steel HSS columns and broad flange (W sections) beams. Floors are metal decking with 2" concrete topping. 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 (2010), a DOE interface for energy simulation. The estimated natural gas consumption (mainly for water heating) of the building is 69.81 Million Btu/year

(1745 Btu/sq ft/year) and this is equivalent to 0.51 kWh/sq ft/year. The estimated electricity consumption is 425,000 kWh/year (10.6 kWh/sq ft/year).

2.1.2 Case 2: Southfield Office Building

Southfield is a new office building in Southeast Michigan in the U.S. Its construction ended in 2009. The targeted use of the building is mainly medical offices. The building has 29,000 sq ft (2690 m^2) of gross floor area, and a volume of 423,000 cu ft (11978 m^3). The building consists of 3 floors (9700 sq ft each, 14.6 ft average height) plus a partial basement. The structural frame is broad flange (W sections) columns and W sections beams. Floors are metal decking with 2” concrete topping. 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 (2010). The estimated natural gas consumption (mainly for water heating) of the building is 45.97 MBtu (1585 Btu/sq ft/year) and this is equivalent to 0.46 kWh/sq ft/year. The estimated electricity consumption is 412,860 kWh/year (14.2 kWh/sq ft/year).

2.1.3 Case 3: Huron Office Building

Huron is a new office building in Southeast Michigan in the U.S. Its construction ended in 2008. The targeted use of the building is mainly medical offices. The building has 21,290 sq ft (1978 m^2) of gross floor area, and a volume of 351,285 cu ft (9947 m^3). The building consists of 1 main floor (16.5 ft 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 1 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 (2010). 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). One important factor for Huron is that it is a LEED certified building and that might interprets its slightly lower use of electricity because it uses geothermal ground loops in heating and cooling.

2.2 Description of the Environmental Impacts Categories

2.2.1 Fossil Fuel Consumption FFC

FFC is referred to as *primary energy consumption* or *fuel depletion*. It is usually given in M and essentially characterizes the gain from the energy sources natural gas, crude oil, lignite, coal and uranium. Natural gas and crude oil will be used both for energy production and as material constituents e.g. in plastics. Coal will primarily be used for energy production. Uranium will only be used for electricity production in nuclear power stations. It is important that the end energy (e.g. 1 kWh of electricity) and the primary energy used are not miscalculated with each other; otherwise the efficiency for production or supply of the end energy will not be accounted for.

2.2.2 Global Warming Potential GWP

GWP is also called Greenhouse Effect or Carbon Footprint. This effect represents an average increase in earth temperature due to the burning of fossil fuels and other forms of energy resulting in higher atmospheric concentrations of gases such as carbon dioxide, methane, and nitrous oxide. The occurring short-wave radiation from the sun comes into contact with the earth's surface and is partly absorbed and partly reflected as infrared radiation. The reflected part is absorbed by greenhouse gases in the troposphere and is re-radiated in all directions, including back to earth. Hence, the quantity of heat the earth can give away to the space is accordingly reduced and the (mean) temperature of the layers of the atmospheric envelope (that are close to the ground) tends to increase accordingly. Greenhouse gases that are considered to be caused or increased are carbon dioxide, methane and CFCs. Figure ….shows the main processes of the greenhouse effect. An analysis of the greenhouse effect should consider the possible long term global effects. For other gases than CO2, GWP is calculated in carbon dioxide equivalents (kg CO2-eq.). This means that the greenhouse potential of an emission is given in relation to CO2. Since the residence time of the gases in the atmosphere is incorporated into the calculation; a time range for the assessment must also be specified. A period of 100 years is customary for GWP.

2.2.3 Acidification Potential AP

AP is also named as "Acid Rain". The acidification of soils and waters occurs through the transformation of air pollutants into acids. This leads to a decrease in the pH-value of rainwater and fog from 5.6 to 4 and even below forming "acid rain" that can pollute forests, lakes and rivers, as well as buildings. The most important substances contributing to AP is SO2 (sulfur dioxide) and NOx (nitrogen oxides) and their respective acids (H2SO4 und HNO3) produce relevant contributions. These are released into the atmosphere when fossil fuels such as oil and coal are combusted. This damages ecosystems, whereby forest dieback is the most well-known impact. Acid rain generally reduces the alkalinity of lakes. Acidification has direct and indirect damaging effects (such as nutrients being washed out of soils or an increased solubility of metals into soils). But even buildings and building materials can be damaged. Examples include metals and natural stones which are corroded or disintegrated at an increased rate. The acidification potential is described as the ability of certain substances to build and release H+ ions. It is measured in terms of the H^+ potential of Sulfur Dioxide (SO_2) as reference substance.

2.2.4 Eutrophication Potential EP

EP is also called "Over-fertilization". The term "eutrophic" means well-nourished, thus, "eutrophication" refers to natural or artificial addition of nutrients to bodies of water and to the effects of the added nutrients. When the effects are undesirable, eutrophication is considered a form of pollution." (National Academy of Sciences, 1969). The process happens when a body of water acquires a high concentration of nutrients, especially phosphates and nitrates. These typically promote excessive growth of algae. As the algae die and decompose, high levels of organic matter and the decomposing organisms deplete the water of available oxygen, causing the death of other organisms, such as fish. Eutrophication is a natural, slow-aging process for a water body, but human activity greatly speeds up the process. The calculated result of EP is expressed on an equivalent mass in kg of nitrogen (N) ion basis.

2.2.5 Photochemical Ozone Creation Potential POCP (Smog)

POCP always referred to as "Summer Smog" which is the production of ground level ozone. It is the result of reactions that take place between nitrogen oxides (NO_x) and volatile organic compounds (VOC) exposed to UV radiation. Under certain climatic conditions, air emissions from industry and transportation can be trapped at ground level where, in the presence of sunlight, they produce photochemical smog. While ozone is not emitted directly, it is a product of interactions of volatile organic compounds (VOCs) and nitrogen oxides (NO_x). The POCP or smog indicator is expressed on a mass of equivalent ethylene basis C_2H_4.

2.2.6 Human Health (HH) Respiratory Effect

Particulate Matter (PM) of various sizes PM_{10} and $PM_{2.5}$ (with aerodynamic diameters of 10 or 2.5 microns or less, respectively) have a considerable impact on human health. The US EPA (2002) has identified "particulates" (from diesel fuel combustion) as the number one cause of human health deterioration due to its impact on the human respiratory system – asthma, bronchitis, acute pulmonary disease, etc. These include PM_{10} (inhalable particles) and its fractions $PM_{2.5}$ (fine particles). It should be mentioned that particulates are an important environmental output of construction products production and need to be traced and addressed. The equivalent $PM_{2.5}$ basis is the final measure of this impact indicator.

2.2.7 Ozone Depletion Potential ODP

ODP is also called "Ozone Hole", which is the depletion of the stratospheric ozone layer. The ozone of the stratosphere absorbs a large portion of the hard UV sun rays. Depending on climatic conditions the catalytic action of CFC compounds degrades ozone down to oxygen. Some of these gases have a very long residence time in the stratosphere and may cause the ozone molecules to be destroyed even many years after their emission. Reduced concentration of the ozone (hole in the ozone layer) causes an increased transmission of UV sun rays with negative consequences for plants, animal and human beings (for instance increased skin cancer hazard, DNA damage, etc). The Ozone Depletion Potential (ODP) defined as the ozone depletion produced by a unit of the gas converted into ozone depletion values produced by the reference substance Trichlorofluoromethane (CCl_3F = CFC-11), is the measure which is used to assess the importance of the effect produced by the various gases.

2.3 Energy Sources

In order to estimate the environmental impact, the emissions from energy production must be known. During a 60-year life cycle, the energy source or the energy supply system will supposedly change several times. In the calculations, however, it is assumed that the energy supply system will be constant during the entire life cycle.

The average US average electricity mix is used to determine the environmental impact due to energy use (fig 4.3). The purpose of using the US electricity mix, e.g. during the operation phase (and not the local electricity net i.e. Midwest Grid) is primarily to compare the impact of the building and not the impact of the energy supply systems. Since every region in the US has its own source of electricity e.g. Hydro, wind, coal, nuclear, etc., the emissions for every kilowatt of electricity is different *by source* of energy. Therefore, the average US electricity mix will be used for future replication to other buildings in order to get same *emission set* from the source.

2.4 Methodological Consideration of Life Cycle Phases

2.4.1 Building Elements and Materials

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, suspended ceilings, and 2 stairs. The amount of each material used in the building was derived from the bill of quantities, architectural and engineering drawings, and the architect's specifications. Around 30 different building materials were identified and modeled.

2.4.2 Building Construction

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 contractor, and were further confirmed by interview with his representative on-site.

2.4.3 Building Operation and Use

The use of the building was divided into mainly heating service (by natural gas) and electrical consumption. For the purpose of energy simulation, the buildings were estimated to be used 55 hr/week for 60 years. Energy calculations were performed using eQUEST, 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.

2.4.4 Maintenance

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.

2.4.5 Demolition

The demolition phase included demolition activities on-site, transportation of discarded building materials (75% of the total) to a landfill (50 mi), and shipping of recovered building materials to a recycling site (70 mi, on average). The entire building was assumed to be demolished. Energy needed for demolition was estimated by the LCA software based on bldg parameters and another report from Athena (1997) for steel buildings demolition energy.

Table 1: Environmental Impacts by Life Cycle Stage – Brookside

	Manufacturing				**Construction**				**Maintenance**				**End - Of - Life**				**Oper Energy**			**Total**	**/ m2**
	Matr'l	Transp	**Total**	**/ m2**	Matr'l	Transp	**Total**	**/ m2**	Matr'l	Transp	**Total**	**/ m2**	Matr'l	Transp	**Total**	**/ m2**	Annual	**Total**	**/ m2**		
Fossil Fuel MJ	9E+06	2E+05	**9E+06**	**2493**	97938	2E+05	**3E+05**	**93.2**	2E+06	45598	**2E+06**	**585.3**	1E+05	69430	**2E+05**	**57.89**	3E+06	**2E+08**	**51434**	**2E+08**	**54664**
Resources kg	3E+06	4619	**3E+06**	**728.3**	2325	5853	**8177**	**2.201**	1E+05	1080	**1E+05**	**38.31**	3431	1636	**5067**	**1.364**	3E+05	**2E+07**	**4734**	**2E+07**	**5505**
GWP kg CO2 eq	7E+05	13084	**7E+05**	**185.2**	6500	18590	**25091**	**6.752**	1E+05	3382	**1E+05**	**34.9**	9499	5197	**14696**	**3.955**	3E+05	**2E+07**	**4448**	**2E+07**	**4679**
AP moles H+ eq	3E+05	4473	**3E+05**	**73.39**	3334	5864	**9198**	**2.475**	86676	1079	**87755**	**23.62**	526.6	1639	**2166**	**0.583**	99605	**6E+06**	**1608**	**6E+06**	**1708**
Resp kg PM2.5	1904	5.393	**1909**	**0.514**	3.706	7.048	**10.75**	**0.003**	1157	1.297	**1159**	**0.312**	0.501	1.97	**2.471**	**7E-04**	557.4	**33445**	**9**	**36526**	**9.829**
EP kg N eq	380.3	4.657	**384.9**	**0.104**	3.151	6.075	**9.226**	**0.002**	31.06	1.119	**32.18**	**0.009**	0.362	1.549	**1.91**	**5E-04**	2.574	**154.4**	**0.042**	**582.7**	**0.157**
ODP kg CFC-11	8E-04	5E-07	**8E-04**	**2E-07**	2E-11	8E-07	**8E-07**	**2E-10**	1E-04	1E-07	**1E-04**	**3E-08**	4E-07	2E-07	**6E-07**	**2E-10**	7E-08	**4E-06**	**1E-09**	**9E-04**	**2E-07**
Smog kg NOx eq	1729	100.9	**1830**	**0.492**	79	130.9	**209.9**	**0.056**	546.1	24.11	**570.2**	**0.153**	6.767	36.59	**43.35**	**0.012**	46.12	**2767**	**0.745**	**5420**	**1.459**

Table 2: Environmental Impacts by Life Cycle Stage – Southfield

	Manufacturing				**Construction**				**Maintenance**				**End - Of - Life**				**Oper Energy**			**Total**	**/ m2**
	Matr'l	Transp	**Total**	**/ m2**	Matr'l	Transp	**Total**	**/ m2**	Matr'l	Transp	**Total**	**/ m2**	Matr'l	Transp	**Total**	**/ m2**	Annual	**Total**	**/ m2**		
Fossil Fuel MJ	7E+06	1E+05	**7E+06**	**2683.6**	59331	2E+05	**3E+05**	**99.2**	1E+06	27149	**1E+06**	**456.7**	1E+05	57096	**2E+05**	**65.85**	3E+06	**2E+08**	**68456**	**2E+08**	**71922**
Resources kg	2E+06	3514	**2E+06**	**763.48**	1458	4889	**6347**	**2.36**	86025	643.2	**86668**	**32.22**	2827	1345	**4172**	**1.551**	3E+05	**2E+07**	**6343**	**2E+07**	**7158**
GWP kg CO2 eq	5E+05	9922	**5E+05**	**189.26**	3991	15524	**19514**	**7.254**	76526	2012	**78538**	**29.2**	7826	4274	**12100**	**4.498**	3E+05	**2E+07**	**5937**	**2E+07**	**6181**
AP moles H+ eq	2E+05	3400	**2E+05**	**76.35**	2109	4899	**7008**	**2.605**	57280	642.4	**57922**	**21.53**	433.9	1348	**1782**	**0.662**	96163	**6E+06**	**2145**	**6E+06**	**2251**
Resp kg PM2.5eq	1407	4.1	**1411**	**0.5247**	2.431	5.887	**8.318**	**0.003**	746.5	0.772	**747.3**	**0.278**	0.413	1.62	**2.033**	**8E-04**	538.7	**32320**	**12.01**	**34489**	**12.85**
EP kg N eq	321.7	3.541	**325.2**	**0.1209**	1.964	5.075	**7.039**	**0.003**	19.1	0.666	**19.77**	**0.007**	0.298	1.274	**1.571**	**6E-04**	2.447	**146.8**	**0.055**	**500.4**	**0.186**
ODP kg CFC-11	5E-04	4E-07	**5E-04**	**2E-07**	3E-11	6E-07	**6E-07**	**2E-10**	7E-05	8E-08	**7E-05**	**3E-08**	4E-07	2E-07	**5E-07**	**2E-10**	7E-08	**4E-06**	**2E-09**	**6E-04**	**2E-07**
Smog kg NOx eq	1097	76.69	**1174**	**0.4362**	49.21	109.3	**158.6**	**0.059**	351.8	14.36	**366.15**	**0.136**	5.575	30.09	**35.66**	**0.013**	44.34	**2660**	**0.989**	**4394**	**1.637**

Table 3: Environmental Impacts by Life Cycle Stage - Huron

	Manufacturing				**Construction**				**Maintenance**				**End - Of - Life**				**Oper Energy**			**Total**	**/ m2**
	Matr'l	Transp	**Total**	**/ m2**	Matr'l	Transp	**Total**	**/ m2**	Matr'l	Transp	**Total**	**/ m2**	Matr'l	Transp	**Total**	**/ m2**	Annual	**Total**	**/ m2**		
Fossil Fuel MJ	5E+06	1E+05	**6E+06**	**2824**	86521	2E+05	**3E+05**	**130**	2E+06	23120	**2E+06**	**939**	92194	52735	**1E+05**	**73.27**	1E+06	**8E+07**	**41953**	**9E+07**	**45920**
Resources kg	2E+06	2962	**2E+06**	**968**	2029	4019	**6047**	**3.057**	90369	549.4	**90918**	**45.96**	2171	1243	**3414**	**1.726**	1E+05	**8E+06**	**3851**	**1E+07**	**4870**
GWP kg CO2 eq	4E+05	8482	**4E+05**	**214.8**	5818	12765	**18583**	**9.395**	80199	1709	**81907**	**41.41**	6011	3948	**9959**	**5.035**	1E+05	**7E+06**	**3624**	**8E+06**	**3894**
AP moles H+ eq	2E+05	2878	**2E+05**	**88.55**	2990	4027	**7016**	**3.547**	52054	547.9	**52601**	**26.59**	333.3	1245	**1578**	**0.798**	43208	**3E+06**	**1311**	**3E+06**	**1430**
Resp kg PM2.5	1193	3.469	**1197**	**0.605**	3.238	4.839	**8.077**	**0.004**	556.1	0.659	**556.8**	**0.281**	0.317	1.496	**1.814**	**9E-04**	241.7	**14502**	**7.332**	**16266**	**8.223**
EP kg N eq	201.8	2.995	**204.8**	**0.104**	2.806	4.171	**6.977**	**0.004**	19.86	0.568	**20.43**	**0.01**	0.229	1.176	**1.405**	**7E-04**	1.124	**67.43**	**0.034**	**301.1**	**0.152**
ODP kg CFC-11	6E-04	3E-07	**6E-04**	**3E-07**	8E-12	5E-07	**5E-07**	**3E-10**	9E-05	7E-08	**9E-05**	**4E-08**	3E-07	2E-07	**4E-07**	**2E-10**	3E-08	**2E-06**	**1E-09**	**7E-04**	**3E-07**
Smog kg NOx eq	1333	64.84	**1398**	**0.707**	71.31	89.87	**161.2**	**0.081**	297.5	12.25	**309.7**	**0.157**	4.282	27.79	**32.07**	**0.016**	20.04	**1203**	**0.608**	**3104**	**1.569**

3. RESEARCH RESULTS

3.1 Normalization of Results

Since the 3 case studies are of different floor areas, the normalization of results is a must to ensure the validity of the comparison among cases. Before discussing in details why a specific normalization factor was selected, it should be mentioned that, although the selection of a normalization factor (m^2 vs. m^3) *does* affect the results in *absolute values* (the environmental impacts of each building), it *does not* affect the results in *relative values* (the environmental impact contribution to the building life cycle phases) which is the main focus of this study.

For comparison purposes, the results have been normalized per square meter (m^2) of floor area of the 3 buildings. Although the data base used in the study (ATHENA) allows some inputs in imperial units, the results of impact assessment, which is more important to the study findings, are presented in metric units. For this reason and for consistency purposes the square meter (m^2) is used as normalization factor instead of the square foot (ft^2). Another normalization factor could have been used is the volume unit of the building in cubic meter (m^3). The specific factor between the two measures is the height of the office spaces which will influence the quantities of materials in columns and walls. Since the height in Huron case is 16.5 ft which is the highest among others (15 ft for Brookside and 14.6 average for Southfield), the results of this case per m^2 would render between 5-10% higher than they would be in m^3.

3.2 Environmental Impact Absolute Values of the Cases

The results of impact assessment of the 3 office buildings are shown in Fig.1. The results show that there are differences between the buildings impacts. Southfield (case 2) has the highest impacts in almost all categories per unit area (m^2) although its floor area (2690 m^2) falls between Brookside (3716 m2) and Huron (1978 m2). Huron (case 3) has the lowest impact values in all categories. The values of the impacts of Huron are around 15% less in values than Brookside (case 1) with some exception of Brookside being less than Huron only in the smog potential (or POCP) by 7% (Fig.1).

It's important to mention that Huron is a LEED certified building. By looking at the nature of the life cycle phases where operation phase has the most impacts on the whole life cycle, Huron case saves significant energy during that phase due to the use of geothermal (earth energy) loop system in its HVAC systems both for heating and cooling (eQuest results, Appendix C-3). Impact absolute values would have been close if not more than Brookside if Huron uses the traditional HVAC system which includes boilers and chillers.

One conclusion on why Southfield case has the highest impacts absolute values could be the extensive use of steel W-sections (wide-flange beams and columns) as the structure system vs. HSS sections (Hollow Structural Steel) in columns for the other two cases. W-sections have significant embodied energy than the HSS sections.

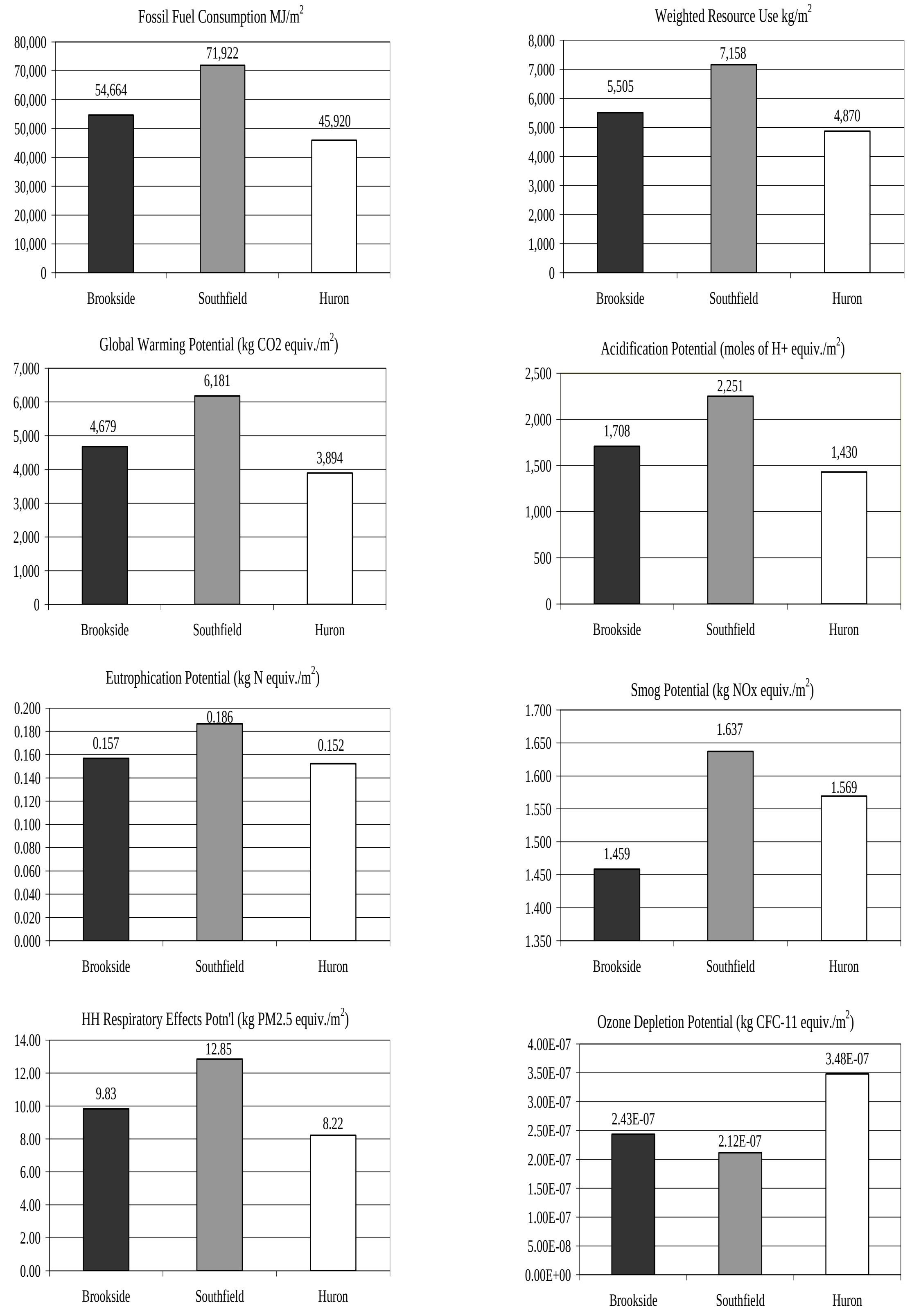


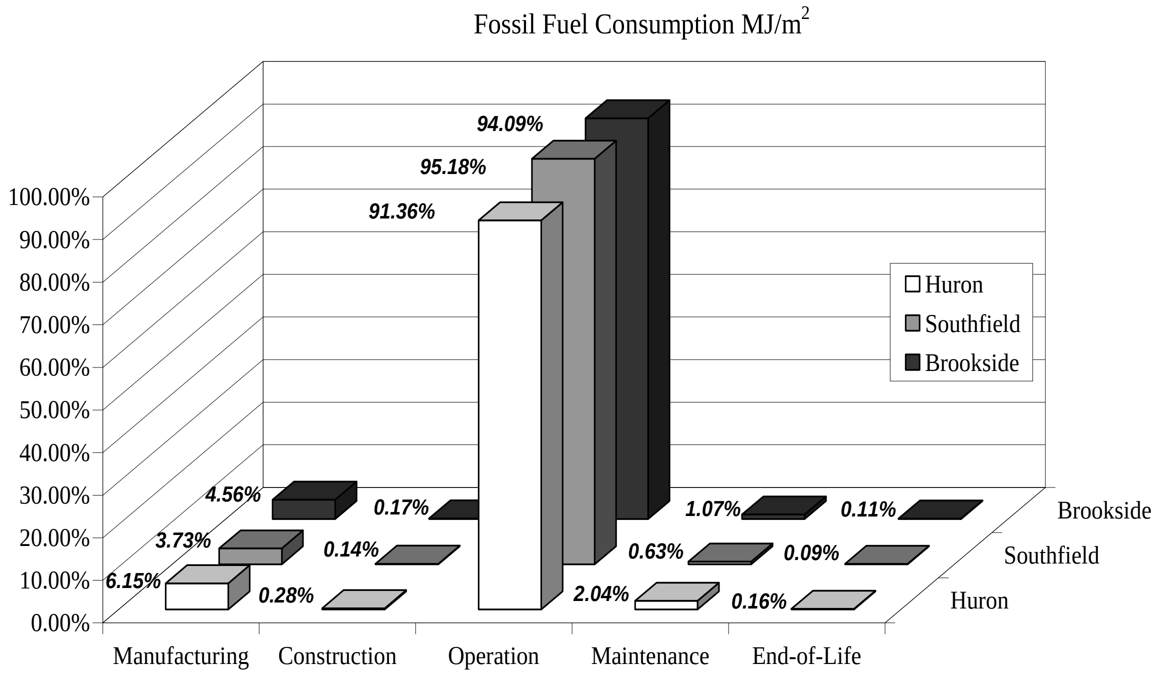
Figure 1: Environmental Impacts for 3 Buildings

3.3 Environmental Impacts Contribution to Life Cycle Phases

The overall environmental impact contribution to the life cycle phases of the 3 cases is shown in figure 2. Transportation impact in every phase is included as an asset to this study. Interestingly, results show that the transportation contributes 80% and 70% of the GWP and Acidification Potential (AP) respectively to the total life cycle impact during construction phase. At the end-of-life phase, this ratio represents 43% of GWP and 80% of the AP. In fact, the highest impact of transportation with higher ratios to the total phase impact is concentrated during these two phases; *construction* and *end-of-life*. This supports the argument of using local materials in building construction.

In all 3 cases, the contribution to each life cycle to the total impacts seems to follow a similar pattern:

- The operation (use) phase in all buildings dominates the environmental impacts in all impact categories except in Eutrophication Potential (EP) and Ozone Depletion Potential (ODP) which are dominated the manufacturing phase.
- Operation phase's share of impacts ranges between 79% - 96% in fuel consumption (FFC), resources use (RU), GWP, AP, and HH respiratory potential (fig. 2).
- Manufacturing phase has the highest impact in the ozone depletion (ODP) at 87%, and in Eutrophication (EP) at 65%
- The operation and manufacturing phases are somewhat balanced in the smog potential (or POCP) impact category with a share of 49% (av. 3 bldgs) and 35% (av. 3 bldgs) respectively.
- It is also noteworthy to mention that besides these 2 impact-dominant phases, *maintenance* phase comes third to dominate the whole impacts especially in ODP, smog (POCP), and Eutrophication (EP) with ranges between 12 % (av. 3 bldgs), 9.6% (av. 3 bldgs), and 5.4% (av. 3 bldgs) respectively.



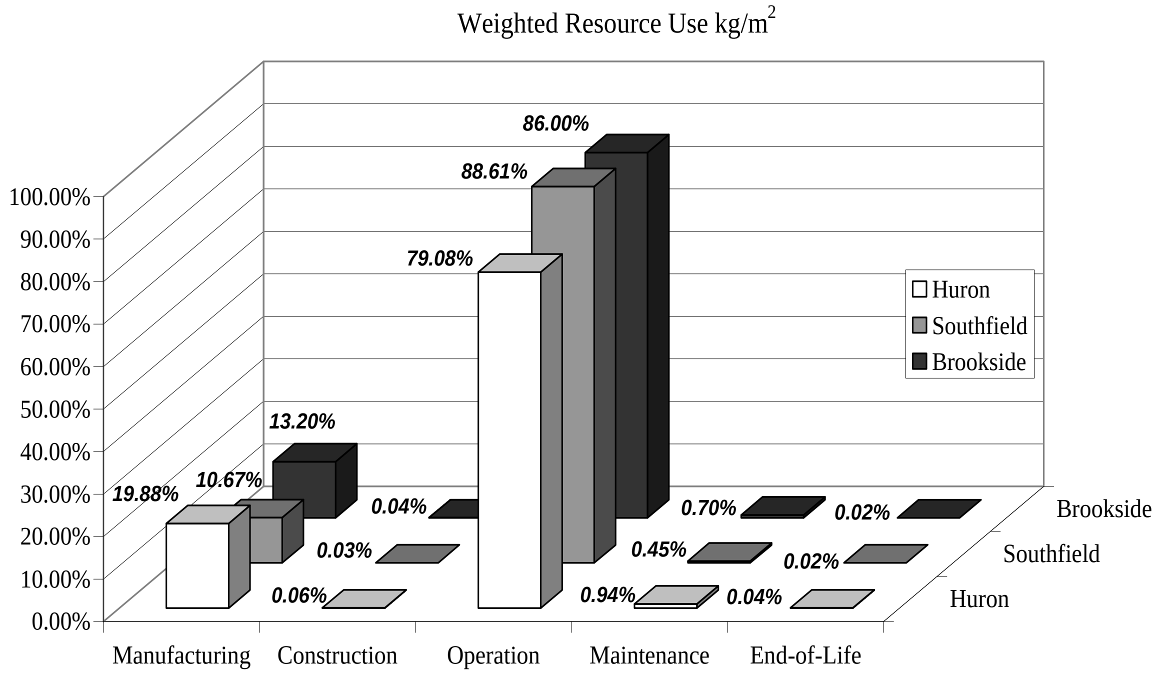
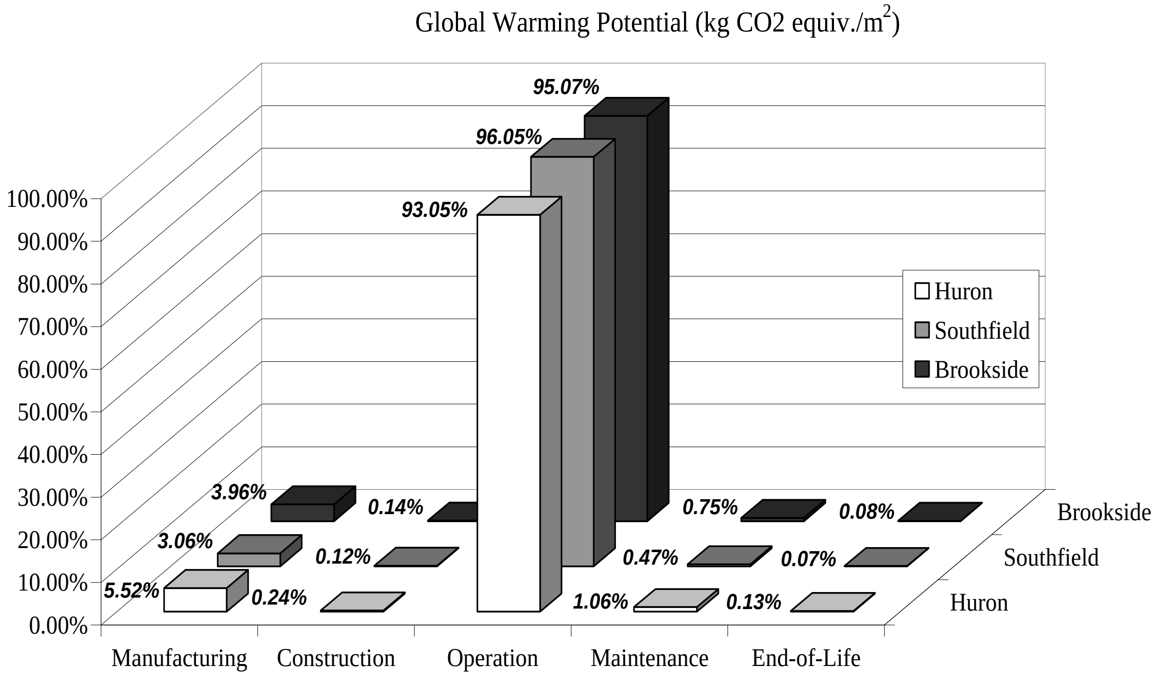


Figure 2: Contribution of Each Environmental Impact by Life Cycle Stage



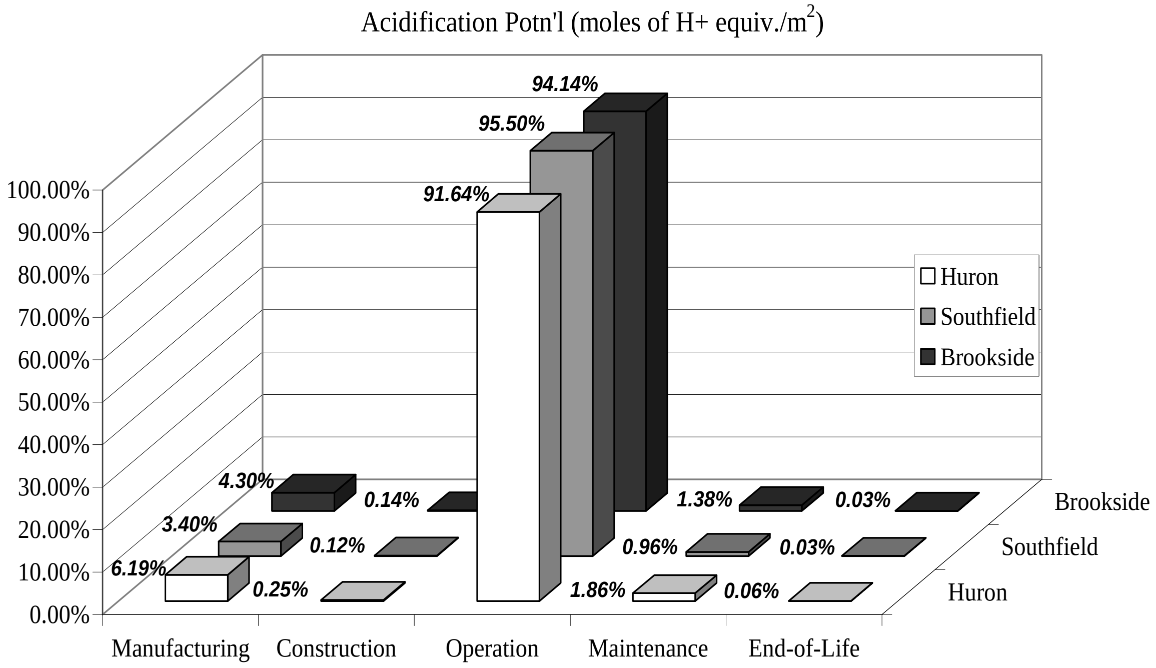
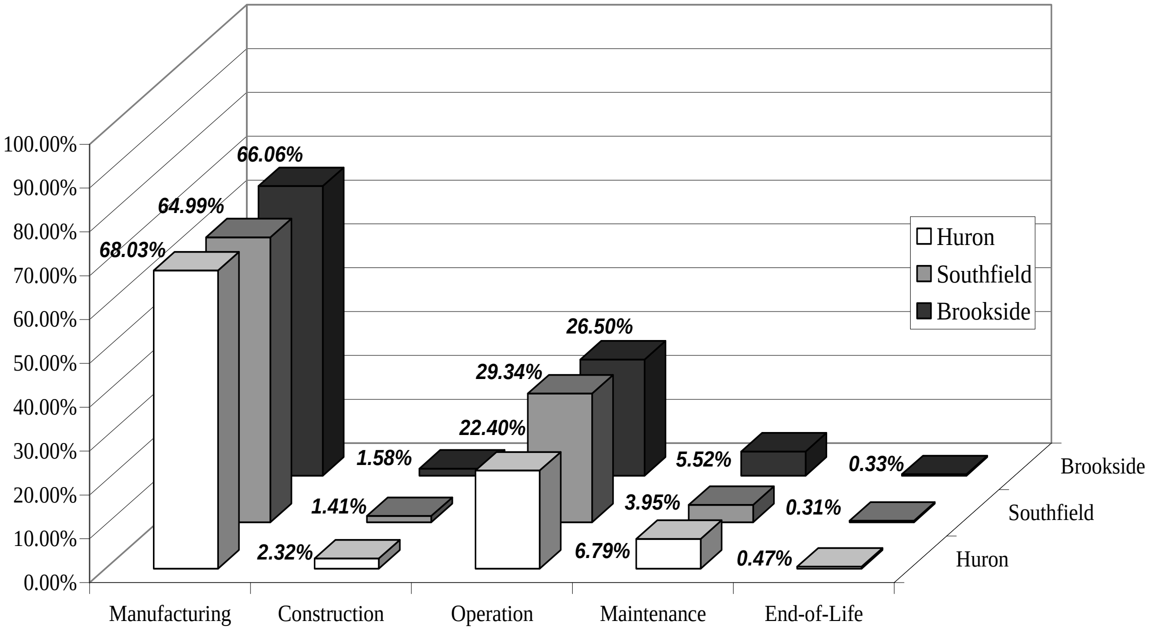


Figure 2: Contribution of Each Environmental Impact by Life Cycle Stage- Continued

Eutrophication Potential (kg N equiv./m^2)



Smog Potential (kg NOx equiv./m^2)

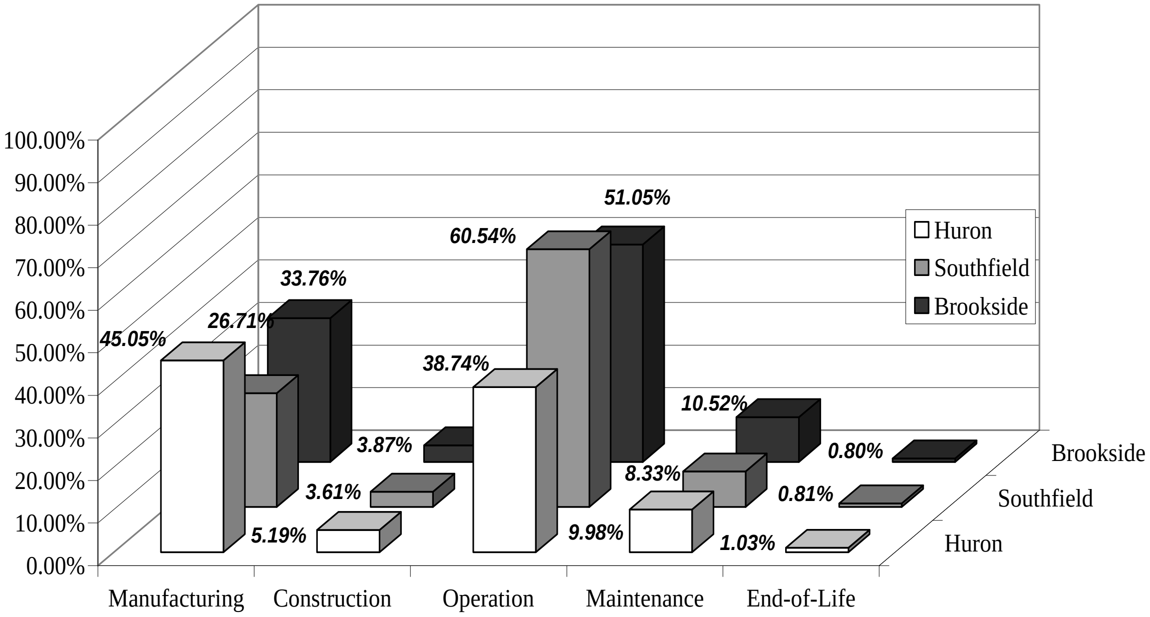
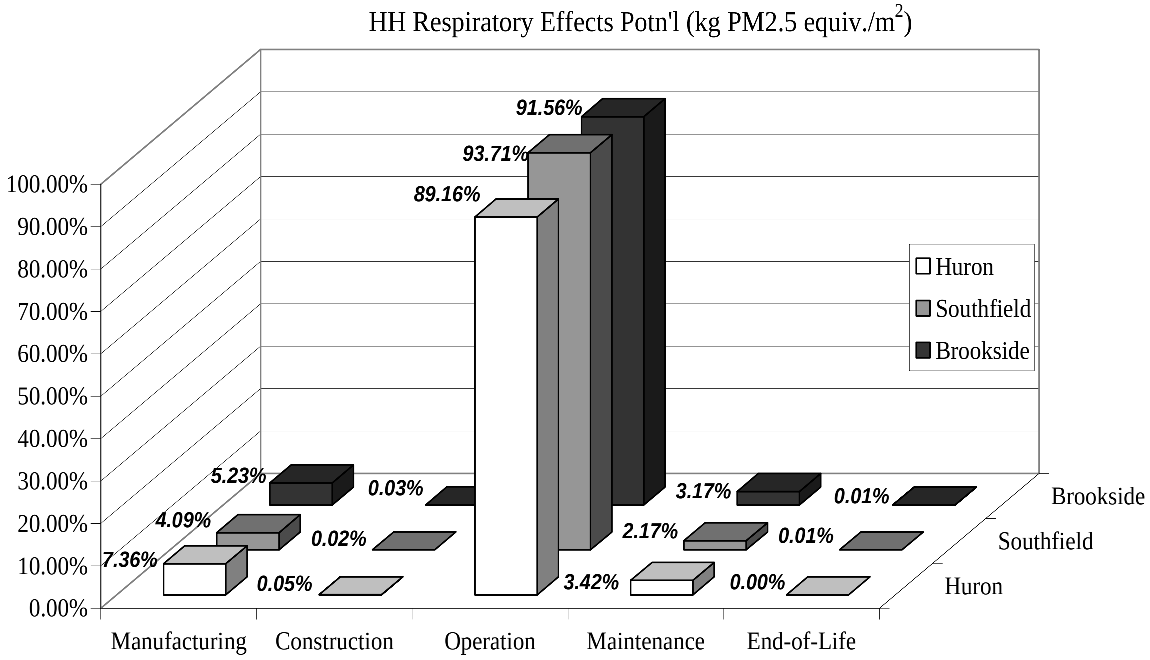


Figure 2: Contribution of Each Environmental Impact by Life Cycle Stage- Continued



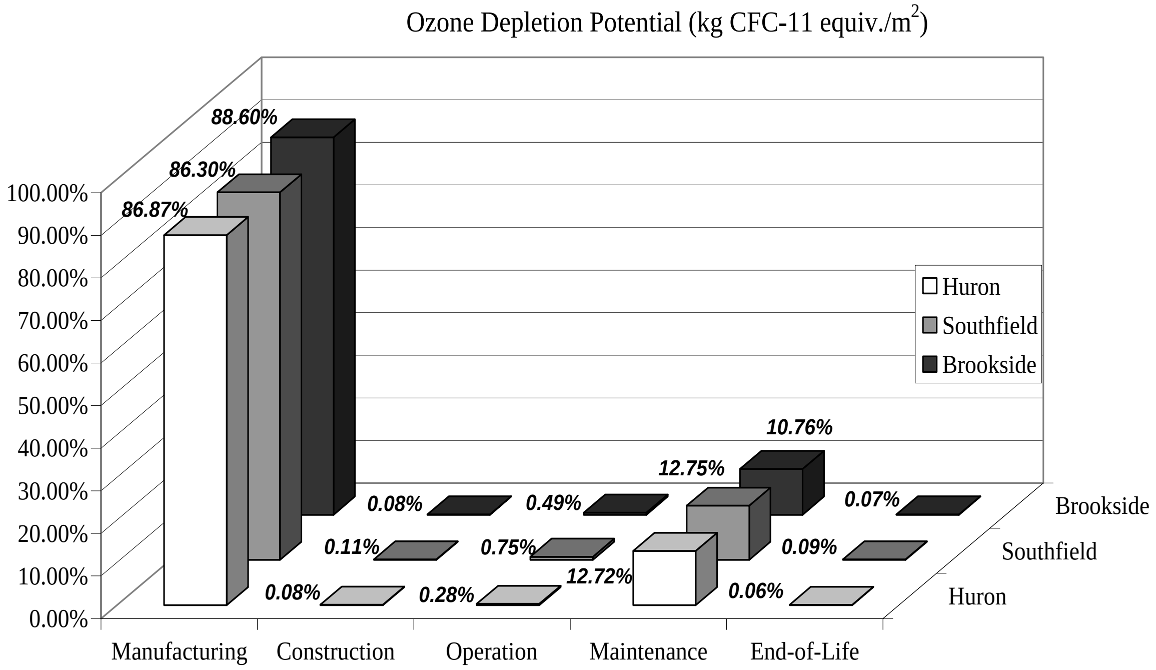


Figure 2: Contribution of Each Environmental Impact by Life Cycle Stage- Continued

3.4 Environmental Impacts Contribution to Assembly Systems

It is important to mention here that in architectural practice, the design of the building has different order than the chronological order of its life cycle in this study. The design of the building assembly systems (foundation type, structure, walls, floors, and roofs) usually takes place during the design process where determination of these systems is identified.

The overall environmental impact contribution to building assembly systems (foundations, structure, walls, floors, roof) of the 3 case studies are presented in (Figure 3). In all 3 cases, the contribution of each assembly system to the total impacts seems to follow a similar pattern:

- *Walls* system in all buildings dominates the environmental impacts in global warming GWP (av. 26%), acidification AP (av. 40%), smog potential POCP (av. 35%), and respiratory effect potential (av. 57%) categories.
- *Structure (beams and columns)* system of the buildings dominates the impacts in fossil fuel consumption FFC (av. 31%), Eutrophication (av. 56%) categories.
- *Roofs* system in all cases has also significant impacts (second to beams and columns) in fossil fuel consumption FFC (av. 27%), in global warming GWP (av. 17%), and comes second to walls in smog potential POCP (av. 29%).
- *Foundations* system dominates the ozone depletion potential ODP (av. 58%). Since foundation is the heaviest system among others, in also dominates the weighted resources use WRU (av. 40%) (Fig. 3).

It is also important to mention that the *roof* system of Huron case has highest potential impacts among other roof systems, while Southfield has the lowest roof impacts. Albeit a LEED certified, the impact of Huron roof is probably due to the one-floor plan the case has where the ratio of *roof area/floor area* in m^2 is 1. On the other hand, Southfield case has 3 floors where the ratio of *roof area/floor area* in m^2 is 1/3rd. In conclusion to this important point, roofs have significant impacts as an assembly systems and a minor change in its material flow with more environmental friendly alternatives (especially insulation as the case in sensitivity analysis) would render significant reduction of those impacts.

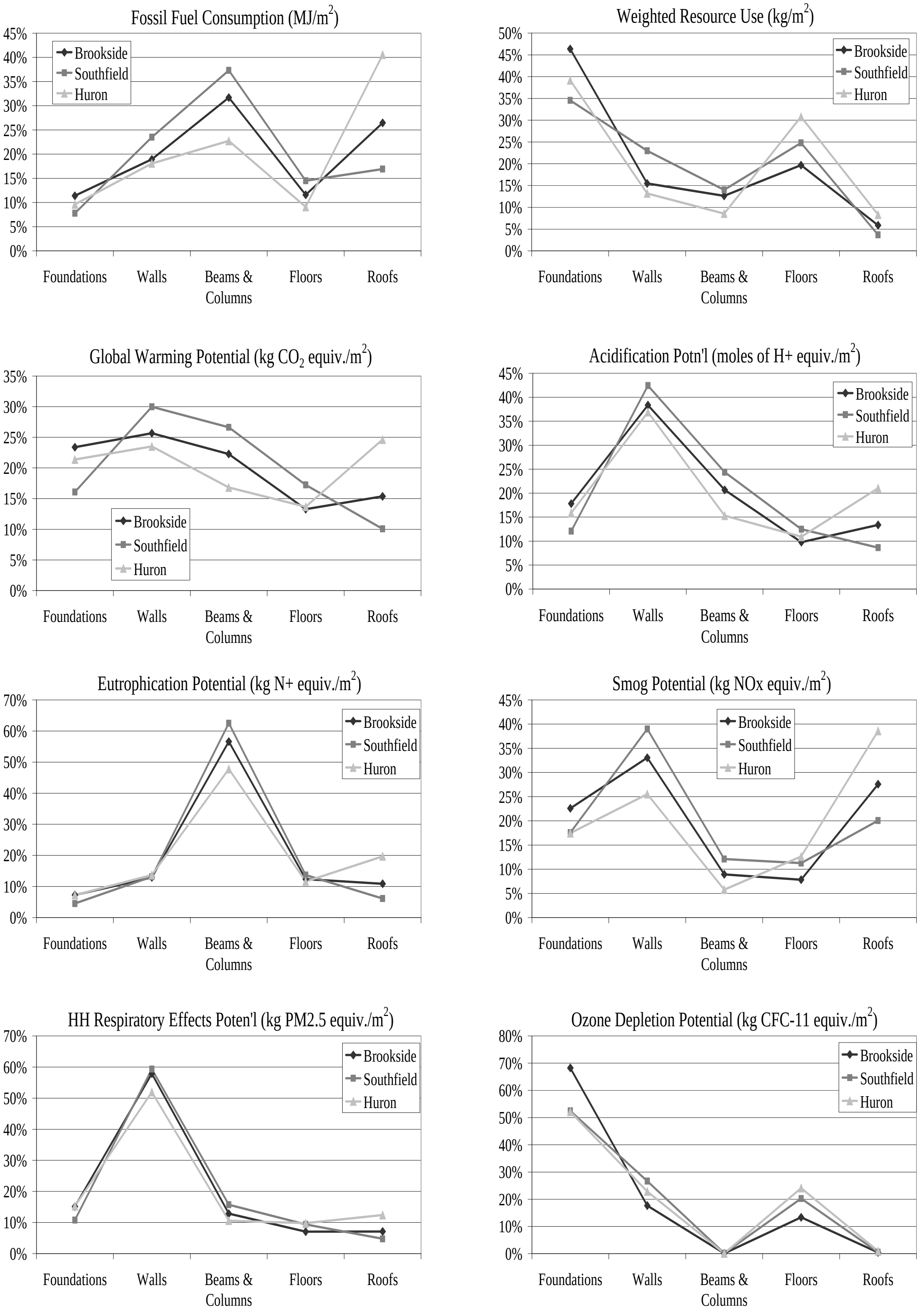


Fig. 3: Environmental Impact Contribution to Bldg Assembly Systems

4. INTERPRETATION OF RESULTS

4.1 Building Materials Manufacturing

Tables1-3 shows that the greatest contribution to overall impacts in the manufacturing phase comes from the extensive use of fossil fuel impact (45%) in the manufacturing possesses of the construction materials (steel, concrete, aluminum, glass, etc) that are required for construction. The resource depletion in this phase also represents 45% 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.

4.2 Construction

The study shows that in the construction phase, the use of construction equipment is the only life-cycle element with significant impacts (90%). 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.

4.3 Operation /Use

The operations phase dominates life cycle energy consumption. Tables 1-3 show the buildings operational demands over a 60 year life span, representing 96% (4.92×10^8 MJ) of the total life cycle energy. This ratio is off 2% of other studies in the same climate at 97.7% (Scheuer 2003). Almost 90% of life-cycle impacts in the use phase caused by electricity and natural gas used for heating in cold climate like Michigan.

4.4 Maintenance

This phase comes second to manufacturing in terms of resources use where several parts of the buildings are replaced or renovated. 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. The significance of the paint products has increased considerably from the original construction phase due to the frequency of repainting (every 10 years).

4.5 End of Life

Table 1 and Fig.1 show that the demolition 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.

5. CONCLUSION

The purpose of the study was to quantify and compare the potential environmental impact caused by 3 office buildings’ life-cycle phases. The study also determined the life-cycle phases contributing most to the impact and defines the significant environmental impacts of the building. The study also examines the building assembly components that most contribute to its life cycle impact. All life cycle phases were found to have significant environmental impacts. However, most of the significant impacts were in the operation phase and the building materials manufacturing phase.

The results of the current study on the contribution of different life-cycle phases are consistent with results from previous studies. Most of the previous studies have emphasized the significance of operational energy impact (Sheuer *et al.* 2003; Seo and Hwang 2001; Treloar *et al.* 2001; Thormark 2000), and some have also reported the possible significance of some building materials (Ochoa *et al.* 2002; Junnila and Saari 1998).

The study aimed at comprehensiveness; however, it included 8 impact categories of which others have not covered deeply such as Human Health Respiratory Potential, Summer Smog, Ozone Depletion, and Resources Use (consumption). Some limitation on impacts included biodiversity, and indoor air quality are not assessed due to the lack of data. 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.

The results of the study can be interpreted together with the results from previous studies. Another limitation of the study is the lack of other important environmental impact categories such as the construction wastes due to lack of data and modeling difficulty. 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 are also significant. 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 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, while Europe and Canada have a higher percentage of electricity from hydro (almost no emissions) and non-fossil fuels which will affect the final emissions especially the release of CO2, SO2, and NOx to air. The study is also unique in modeling the building with the U.S. electricity grid which depends on coal as resource at 45% (DOE, EIA 2009).

Practical applications of the study's results could be directed to more environmentally conscious design and more facilities management of office buildings. Companies, owners, project and facility managers, and designers who are not yet familiar with environmental impacts could use the profiles of the significant impacts and phases of the bldg where this happen to help them focus their attention on environmentally sensitive areas of design, construction, use, maintenance, and even demolition.

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