From a Consumer Product to a Complex Building:
A Quantitative Approach to Sustainability Using Life Cycle Assessment (LCA)

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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 paper demonstrates how 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 paper also examines the significance of these impacts that occur during the life cycle through a case study of an office building in Michigan. It aims also to provide a comprehensive assessment to which building component (structure, walls, floors, etc.) contribute the most to the total impacts to inform architects' design decisions of buildings components that could reduce the total environmental burdens.

CONFERENCE THEME: Sustainability Measurements
KEYWORDS: Environmental research, Sustainability, Quantitative Methodology, Life Cycle Assessment, Environmental burden.

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 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 building 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 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 a six-dimensional estimation framework recommended by the Nordic guidelines on LCA (Lindfors et al. 1995). The quality target for the LCA was set to be at the level of "good," which means reliability of most recent documented 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 included:

- Fossil Fuel Use FFU,
- Resources Use RU,
- Global Warming Potential GWP (Climate Change),
- Ozone Depletion Potential ODP,
- Acidification Potential AP,
- Eutrophication Potential EP, and
- Photochemical Ozone Creation Potential POCP or Summer Smog

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.

2.1 CASE STUDY BUILDING DESCRIPTION

The building chosen for the study is a new office building in Michigan. 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(11,978 m^3) The building consists of 3 floors plus a partial basement. The structural frame is steel with cast-in-place concrete foundations. The annual energy consumption is c alculated using eQuest 3.64 (2010), a DOE interface for energy simulation. The estimated natural gas consumption (mainly for water heating) of the building is 1585 Btu/sq ft/year (eq. 0.46 kWh/sq ft/year). The estimated electricity consumption is 14.2 kWh/sq ft/year, which is close to the average in such cold weather in Michigan.

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 summary of energy and material flows used in the LCA is presented in Table 1.

2.2 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.

2.3 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, 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 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 building was 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.

2.5 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.

2.6 DEMOLITION

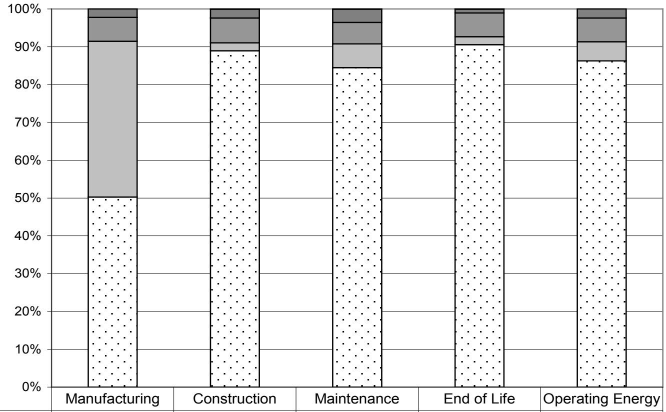
The demolition phase included demolition activities on-site, transportation of discarded building materials (75% of the total) to a landfill (50 mi), and shipping of recovered building materials to a recycling site (70 mi, on average). The entire building was assumed to be demolished. Energy needed for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

3. RESULTS

The results of the environmental impact assessment in each life cycle phase are presented in Table 1. 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

	Manufacturing			**Construction**			**Maintenance**			**End - Of - Life**			**Operating Energy**		**Total Effects**
	Matr'l	Transp	**Total**	Matr'l	Transp	**Total**	Matr'l	Transp	**Total**	Matr'l	Transp	**Total**	Annual	**Total**	
Fossil Fuel Consumption MJ	2E+07	885301	**2E+07**	262351	971062	**1E+06**	1080278	27868	**1E+06**	581526	378290	**959816**	8196594	**5E+08**	**5E+08**
Weighted Resource Use kg	1E+07	22086	**1E+07**	6171.7	22881	**29052**	81587.8	660.24	**82248**	13695	8913.4	**22608**	481718	**3E+07**	**4E+07**
Global Warming Potential (kg CO2 eq)	2E+06	65866	**2E+06**	18099	72689	**90788**	72099.3	2069.6	**74169**	37916	28318	**66234**	595552	**4E+07**	**4E+07**
Acidification Potential (moles of H+ eq)	777996	21723	**799718**	9730.4	22926	**32657**	45847.6	659.59	**46507**	2102.1	8931.3	**11033**	227304	**1E+07**	**1E+07**
Eutrophication Potential (kg N eq)	597.07	22.568	**619.64**	6.7945	23.749	**30.544**	17.669	0.6837	**18.35**	1.4434	8.4377	**9.8811**	11.4504	**687.02**	**1365.4**
Ozone Depletion Potential (kg CFC-11 eq)	0.0064	3E-06	**0.0064**	3E-11	3E-06	**3E-06**	4.6E-05	8E-08	**5E-05**	2E-06	1E-06	**3E-06**	1.9E-07	**1E-05**	**0.0064**
Smog Potential (kg NOx eq)	5738.5	487.64	**6226.1**	204.12	511.71	**715.83**	308.857	14.739	**323.6**	27.012	199.34	**226.35**	132.651	**7959.1**	**15451**

Table 1: Breakdown of Environmental Impacts by Life Cycle Stage



	Manufacturing	Construction	Maintenance	End of Life	Operating Energy
■ Smog Potential (kg NOx eq)	6,226.097	715.830	323.597	226.353	7,959.058
🟥 Ozone Depletion Pot'l (kg CFC-11 eq)	0.006	0.000	0.000	0.000	0.000
■ Eutrophication Potential (kg N eq)	619.641	30.544	18.353	9.881	687.021
■ Acidification Potential (moles of H+ eq)	799,718.355	32,656.796	46,507.142	11,033.421	13,638,231.948
■ Global Warming Potential (kg CO2 eq)	2,272,114.249	90,787.937	74,168.881	66,233.773	35,733,135.243
▨ Weighted Resource Use kg	14,859,791.697	29,052.279	82,248.016	22,608.223	28,903,092.395
□ Fossil Fuel Consumption MJ	18,116,845.189	1,233,413.568	1,108,146.302	959,816.152	491,795,611.942

Fig. 1: Environmental Impacts by Life Cycle Stage

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. Fig.1 shows the proportions of each life-cycle phase in every impact category with the associated numbers. Fuel consumption in MJ has a notable 80% or more in 4 life cycle phases with exception in material manufacturing phase in which it constitute 50% of the whole impact in that phase. This is consistent with most previous studies to show the significance of impacts due to fuel consumption. GWP seems to have a consistent ratio of 7% in all life phases. Resources use (kg) logically happens during manufacturing represents 40% of impact in that phase and another 10% in the maintenance where some of building materials are replaced. Acidification comes next to GWP at almost 3% in each phase. Looking at the same information in Fig. 1 from another perspective, Fig. 2 lays vertically the bldg phases to assess the contribution of the bldg phases to each impact category. It shows that bldg operation phase is responsible for 90%+ in 3 categories; fuel consumption, GWP, and acidification potential while this ratio decreases to

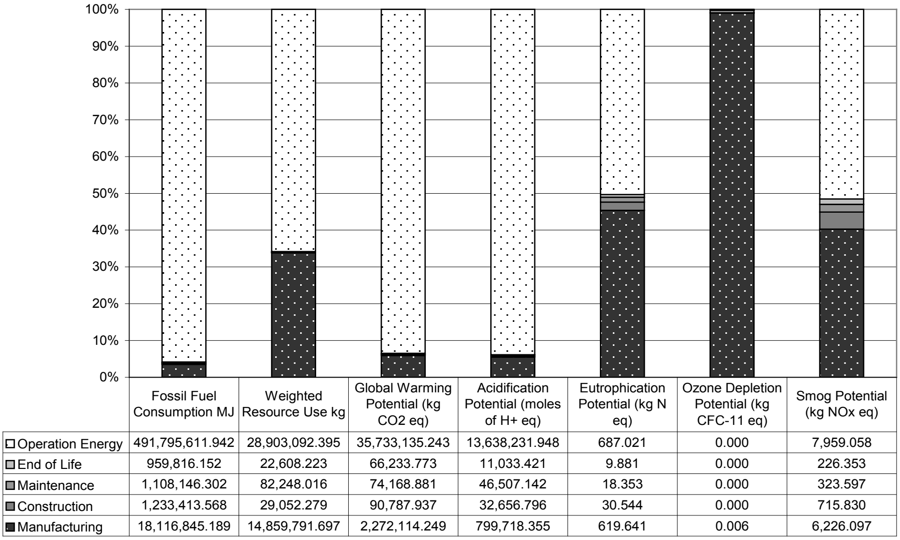
45% and 40% respectively in Eutrophication Potential EP and Smog formation impacts throughout the bldg life cycle. These two potential impacts tend to be released almost equally during manufacturing and operation phases. About 5% of smog is caused by construction phase.

The study found the summer smog impact of materials manufacturing and operation phases to be the largest contributor sharing the cause of smog formation at 40% and 50% respectively (fig.2). This study along with very few others (Tekes 2000) touched the potential of this important impact category.

4. INTERPRETATION OF RESULTS

4.1 BUILDING MATERIALS MANUFACTURING

Fig.1 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 represent 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.



	Fossil Fuel Consumption MJ	Weighted Resource Use kg	Global Warming Potential (kg CO2 eq)	Acidification Potential (moles of H+ eq)	Eutrophication Potential (kg N eq)	Ozone Depletion Potential (kg CFC-11 eq)	Smog Potential (kg NOx eq)
□ Operation Energy	491,795,611.942	28,903,092.395	35,733,135.243	13,638,231.948	687.021	0.000	7,959.058
▨ End of Life	959,816.152	22,608.223	66,233.773	11,033.421	9.881	0.000	226.353
▨ Maintenance	1,108,146.302	82,248.016	74,168.881	46,507.142	18.353	0.000	323.597
▨ Construction	1,233,413.568	29,052.279	90,787.937	32,656.796	30.544	0.000	715.830
■ Manufacturing	18,116,845.189	14,859,791.697	2,272,114.249	799,718.355	619.641	0.006	6,226.097

Fig. 2: Contribution of Bldg LC Phases to Each Impact Category

4.2 CONSTRUCTION

Fig.1 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

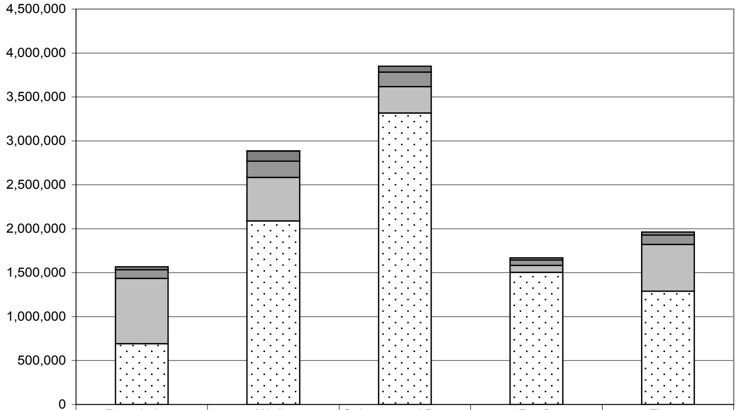
The operations phase dominates life cycle energy consumption. Table 1 shows the building operational demands over a 60 year life span, representing 96% (4.92×108 MJ) of the total life cycle energy. This ratio is off 2% of other studies in the same climate at 97.7% (Scheuer 2003). Almost 90% of life-cycle 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.



	Foundations	Walls	Columns and Beams	Roofs	Floors
■ Smog Potential (kg NOx eq)	304.290	676.367	209.974	347.943	195.299
🟥 Ozone Depl Potn'l (kg CFC-11 eq)	0.000	0.000	0.000	0.000	0.000
■ Eutrophication Potential (kg N eq)	15.927	46.559	221.159	21.719	48.381
▨ Acidification Potn'l (moles of H+ eq)	32,868.084	115,445.033	66,334.779	23,512.122	33,932.419
▨ Global Warming Potn'l (kg CO2 eq)	99,550.828	185,656.599	164,972.992	62,403.003	106,688.506
▨ Weighted Resource Use kg	743,235.260	494,534.755	301,093.389	79,218.629	532,867.889
☐ Fossil Fuel Consumption MJ	691,644.336	2,089,828.420	3,317,453.474	1,503,412.608	1,288,881.827

Fig. 3: Environmental Impacts by Building Assembly

4.6 LIFE-CYCLE IMPACTS BY BUILDING ASSEMBLY

In practice the building design process typically proceeds by building systems (design disciplines), 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 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, columns and beams, roofs, floors, are calculated.

Fig. 3 shows that the environmental impacts of the office life cycle are divided into 5 building components systems. The two systems that accounts for most of the environmental impacts are the columns/beams, and the walls systems.

This is due to the amount of steel (with its massive embodied and transportation energy) in columns and beams and the wide area walls system covers in the building facades. The most dominant impact category in the whole assembly is the fossil fuel used by each material (its embodied + transportation energy). Resource use is the highest in foundations and floors systems and then walls come third. That's due to the massive concrete weight and wide area both systems occupy. GWP is slightly more in walls (due to insulation emissions) than columns. 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 NOx during manufacturing.

5. CONCLUSION

The purpose of the study was to quantify and compare the potential environmental impact caused by an office building's 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 impact categories that others have not covered deeply such as summer smog, ozone depletion, and Resource 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.

One of the main 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. 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 charts 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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