Improving the Quality and Transparency of Building Life Cycle Assessment

by

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Abstract

Life cycle assessment, or LCA, is a powerful method for measuring and reducing a building's environmental impacts. Its widespread adoption among designers would allow the environmental component of sustainability to gain more traction in design philosophy and client goals. Currently, the stakeholders in building design—both design professionals and clients—have few resources for proper LCA education and use, and there are no common metrics agreed upon for reporting the results of LCAs for buildings.

This thesis assesses the strengths and weaknesses of resources available to design practitioners for performing LCA, including a pilot credit in the United States Green Building Council's Leadership in Energy and Environmental Design ratings system. A case study performs an LCA comparing two structural materials in an office building. The study aims to be as transparent and repeatable as possible, in order to set a good example on which to model future building LCAs. Based on the critical review of LCA resources and the lessons learned from the case study, eight key points are proposed for improving the quality and transparency of building life cycle assessment projects.

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1. Introduction

1.1 Sustainability in the Building Industry

Construction materials constitute a major percentage of the resources humans use today. By the end of the 20th century, approximately 75% of all material consumption in the United States consisted of construction materials, and this number does not even include industrial minerals, such as the cement in concrete (Figure 1). Despite the fact that material consumption has grown much faster in the rest of the world than in the United States, the U.S. still consumed approximately one-third of the world's materials in 1995, or 2.8 billion metric tons. That corresponds to at least 2.1 billion metric tons of construction materials in the US alone, and only 8% of these materials are considered renewable (Matos and Wagner 1998).

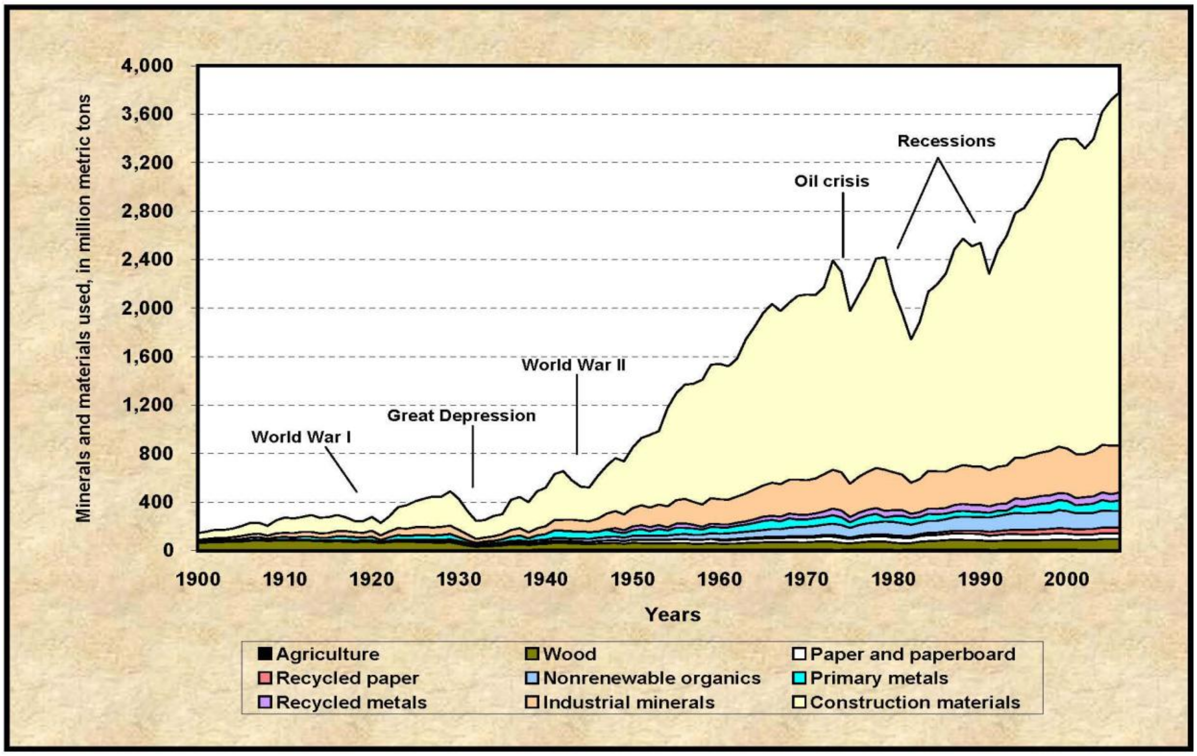


Figure 1: Material and mineral consumption in the United States, 1900-2006. Source: Matos 2009.

These materials produce greenhouse gas emissions that contribute to climate change (IPCC 2007). According to the US Environmental Information Agency (EIA), buildings and their use are responsible for 39% of the country’s carbon dioxide emissions and 72% of its electricity consumption (EIA CBECS 2003). These statistics do not account for the other environmental impacts that can be attributed to buildings, including pollution to water, ground, and air; toxicity to humans and animals; and urban heat island effects, among others. Reducing the environmental impact of buildings is crucial to combating global warming and other forms of environmental degradation.

The design community, composed of architects, engineers, the construction industry, government, and clients, is recognizing the need to reduce the greenhouse gas (GHG) emissions of the buildings it creates. Efforts to design “green” buildings take many forms, most notably the Leadership in Energy and Environmental Design (LEED) green buildings rating system, which is arguably the most prominent vehicle for building sustainability in the eyes of the public. Additionally, the Architecture 2030 Challenge calls for designers to drastically reduce the GHG emissions of buildings by the year 2030 (Architecture 2030 2011). Yet understanding of how to reduce the GHG emissions of buildings is still lacking among designers and clients.

Sustainability is commonly defined as developments that “meet present needs without compromising the ability of future generations to meet their needs” (United Nations 1987). The “triple bottom line” of sustainability specifies that for an object or process to be truly sustainable, it must consider three types of impacts: social, economic, and environmental (Hacking and Guthrie 2008). Industry, contractors, and owners are often most concerned with the economic impacts of a building’s construction and use: they want to construct the building cheaply and efficiently, and also pay low utility and maintenance bills during its use. Government and designers are often concerned with social impacts: the safety and aesthetics of the building. Theoretically, all groups in the design process should be concerned with environmental impacts as well, yet these impacts are poorly understood and tend to clash with economic and social interests. Short-term costs, and acceptance of the building by the owner or the public, take precedence over scientific evaluation and understanding of the building’s long-term environmental impact. The design and construction communities of most societies in the world today are primarily concerned with present-day building needs.

1.2 Life Cycle Assessment

One method to effectively quantify the environmental impact of buildings is an approach known as life cycle assessment (LCA). LCA tracks the materials and energy consumed by an object, system, or process over the course of its lifetime (Baumann and Tillman 2004). In the case of a building, this procedure encompasses the material extraction and production, through construction and use of the building, to its demolition and material reuse or landfill (Figure 2). In this way, the impacts of the building can be understood from a purely environmental, long-term perspective, free from the influence of short-term monetary or social concerns.

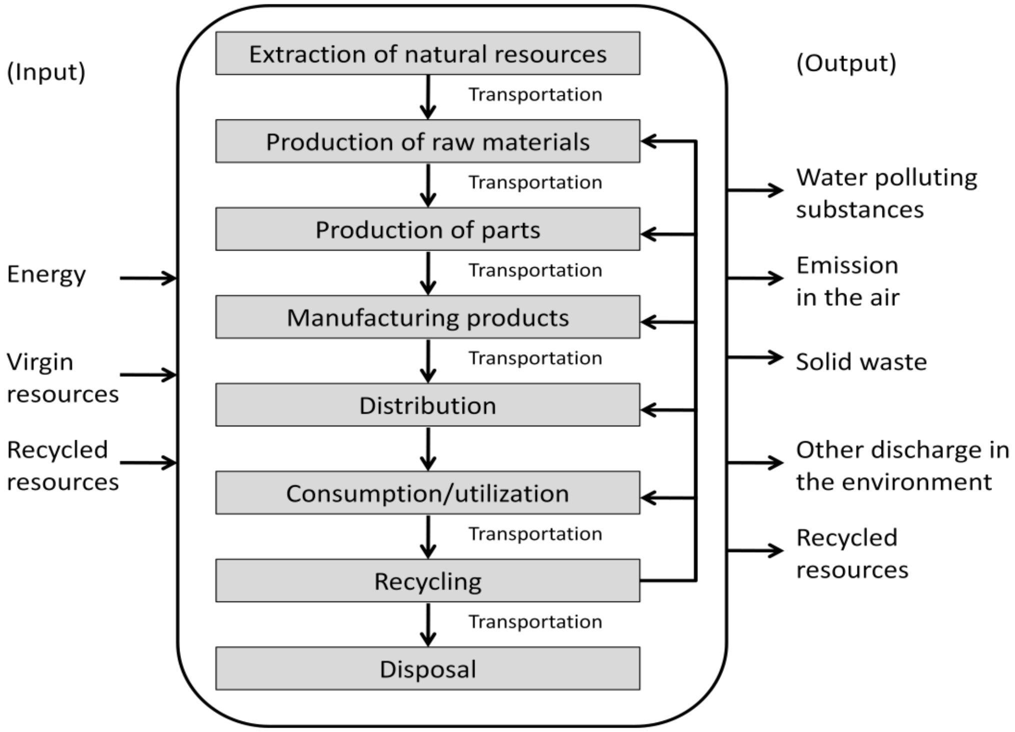


Figure 2: Steps in the life of a building that must be quantified and tracked in a life cycle assessment.

The International Organization for Standardization (ISO) specifies the procedures for carrying out an LCA in its 14040 series (2006a, 2006b). These procedures, shown in Figure 3, include:

- Goal and scope definition: a formal statement of the intended outcomes of an LCA, and a definition of what is and is not included in the project. LCAs can take days, months, or years depending on the scope and complexity sought. The boundaries must be defined according to what is feasible in the project's time frame. A functional unit is also defined to clarify how the material is collected and reported.
- Inventory analysis: data collection and organization. All inputs and outputs in the life cycle must be researched and quantified. Their environmental impacts are then determined. They can be tracked manually or organized in one of many software tools available for creating LCA inventories.
- Impact assessment: the results of the inventory are organized into "impact categories" according to the goal of the project. The categories could be any number of environmental impacts that the researchers wish to explore.
- Interpretation: iteration of the previous steps. Once initial results are obtained, it may be necessary to adjust the goal of the project or find better data sources to improve the results. Further conclusions are made using tools such as sensitivity analysis, which seeks to understand the impact of changing individual parameters in the inventory.

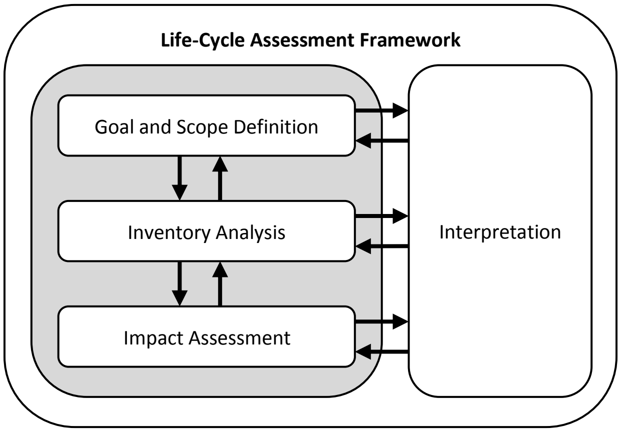


Figure 3: Steps in a formal life cycle assessment (ISO 2006a).

1.3 Problems with LCA

LCA could be a major tool for achieving better design, but it is still seen as a difficult method that requires extensive training to use properly. Understandably, many architects and engineers are hesitant to use a method they do not know very well. The ISO standards provide general guidelines for organizing an LCA, but do not provide information on the actual process of performing one, including the collection of accurate data and the calculations needed to complete an LCA by hand. The standards themselves are very flexible and allow for a wide range of projects that are too different to compare with one another (Kaethner and Yang 2011). Software is available to aid in LCA, but it is often a “black box” that conceals its calculations and assumptions, making it difficult for users to fully understand or trust. Kellenberger and Althaus (2009) provide useful information on simplifying building LCAs, but the paper is not a tutorial in itself. No one standard exists for educating design professionals on how to conduct an LCA. The U.S. Green Building Council (USGBC) has implemented an LCA pilot credit into its LEED ratings system, but it is too new for its effectiveness to be quantified. This pilot credit will be discussed further in chapter 2.

The body of work representing LCA is not transparent or accessible to designers wishing to adopt it in their sustainability plans. Academic LCA studies have been performed in a variety of contexts, but these studies are neither transparent nor reproducible. The variability seen in goal, scope, and boundary conditions makes it impossible to compare them to one another. Hsu (2010) summarized a set of studies representing a wide range of commercial buildings LCA models from around the world, which illustrate the lack of consistency in goals and results. Table 1 shows several key parameters of each study. The row titled “Real or Ideal?” refers to whether the buildings existed in real life or were created by the researchers for the sole purpose of performing an LCA on them.

Study	**Eaton & Amato**	**Junnila & Horvath**	**Guggemos & Horvath**	**Kofoworola & Gheewala**	**Jönsson et al**	**Cole & Kernan**	**Johnson**
Year	1998	2003	2005	2009	1998	1996	2006
No. of buildings studied	10	1	2	1	7	6	2
Real or ideal?	Ideal	Real	Ideal	Real	Ideal	Ideal	Ideal
Country	UK	Finland	USA (Midwest)	Thailand (Bangkok)	Sweden	Canada (2 cities)	USA (Boston)
Units reported	GJ/m^2 kg-CO_2/m^2	MW-h kg matls kg CO_2 kg SO_2 kg H_2C_4 kg PO_4 kg Pb	TJ Gg CO_2e Mg CO Mg NO_x Mg PM_{10} Mg SO_2	TJ GJ/m^2	kg matls MJ kg CO_2 kg NO_x kg SO_2 COD/unit kg waste	GJ GJ/m^2	kg CO_2 kg matls MJ kg CO_2/ft^2 kg matls/ft^2 MJ/ft^2
Full ISO LCA?	No	Yes	No	No; LCEA only	Yes	No	No; LCI only

Table 1: Summary of studies reviewed in Hsu (2010).

What is striking about these studies is the variety in their objectives and the units that were reported in the published papers. Kofoworola and Gheewala (2009) and Cole and Kernan (1996) consider only energy use. Just three studies report the weight of the materials used in the building, which is important information for readers to know if they wish to replicate or compare the study to others. Guggemos and Horvath (2005) report results in terms of carbon dioxide equivalents (CO_2e), which weights greenhouse gas emissions based on their global warming potential (GWP). The other studies which report greenhouse gas emissions do so by reporting each gas separately. While this is a thorough reporting method, it makes it harder for one to compare studies and buildings against one another, especially when each research team chooses different sets of gases to report. GWP is helpful because it combines the effects of many greenhouse gases into one unit that is easily communicated to the intended audience. While other environmental impacts certainly should not be ignored, GWP should be mandatory among all studies for easier comparison.

What makes it most difficult to compare these studies is the fact that some report their results in terms of the square footage of the building (with some considering usable area while others consider gross area of the building's footprint), while others report only the total quantity in the building, and still others report both. This problem reflects a lack of consistency in functional unit. Buildings come in many different configurations and sizes, and there must be a method of normalizing results among vastly different building types. When others read the reports and compare results to their own studies, normalizing them per unit area would help understand whether the results are comparable. The results of the previous studies have been normalized by unit area in Figure 4 to better understand their variability. Guggemos and Horvath's (2005) numbers are in GWP, while the other numbers are in units of CO_2 only.

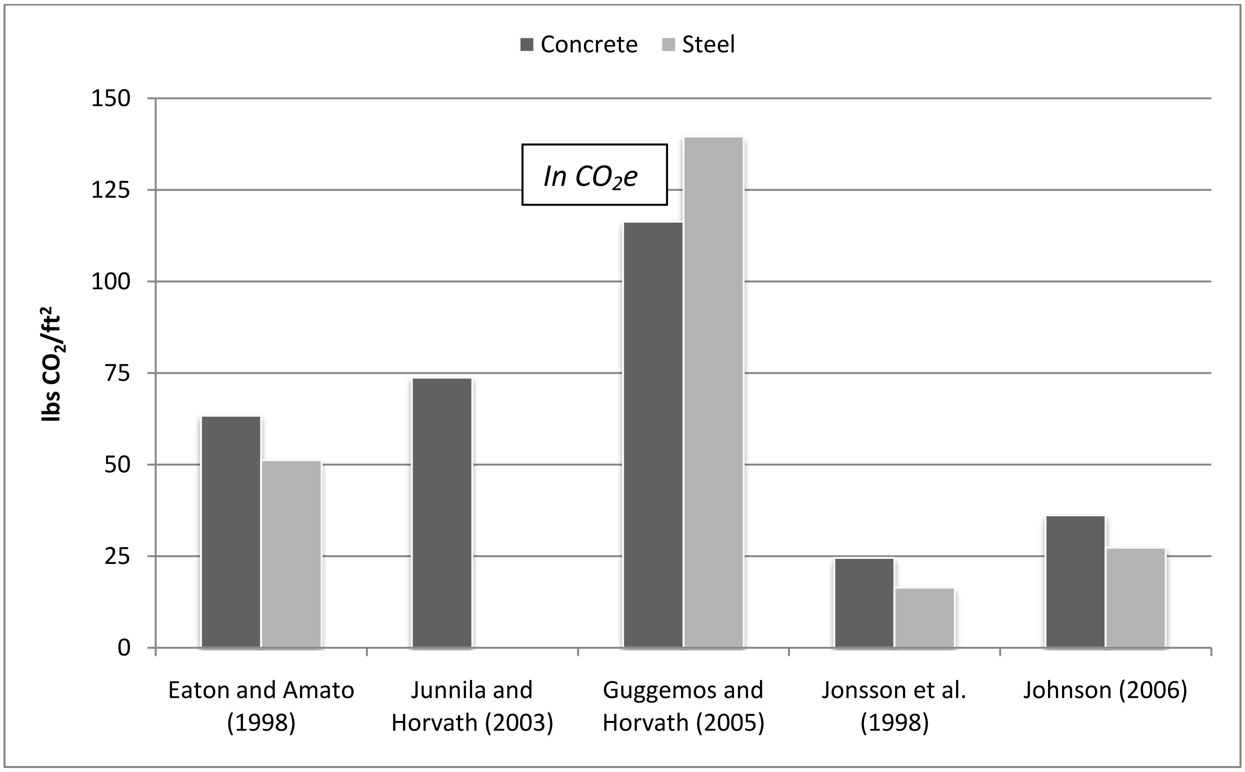


Figure 4: CO_2 emissions normalized by unit area for all studies.

1.4 Problem Statement

The LCA tools and standards available to design practitioners today need improvement, and professionals need better guidance and examples of how to perform a simple, transparent, and effective LCA. Applying LCA to new and existing building projects is crucial to understanding and reducing their environmental impact. Its widespread adoption among designers would allow the environmental component of sustainability to gain more traction in design philosophy and client goals. Currently, the stakeholders in building design—both design professionals and clients—have no standard resources for proper LCA education and use, and there are no common metrics agreed upon for reporting the results of LCAs for buildings.

1.5 Methodology

This study has two components. Chapter 2 contains a critical review of the most prominent LCA tools and standards available to design professionals today. Current shortcomings of LCA and difficulties encountered by designers are examined, and the need for further transparency and simplicity is emphasized throughout the review. The discussion focuses on how resources should be improved based on the needs of designers in the building industry and the need for a common, comprehensible unit for reporting results.

Chapter 3 presents a case study of a building LCA as the second component of this thesis. This study is a full LCA of a 12-story commercial office building set in two regions in the United States. The design process and energy models required to perform the LCA are summarized. It has been analyzed with the goal of providing as complete and transparent an LCA as possible, highlighting the positive aspects and weaknesses of the process along the way. Full documentation of the process is reproduced in appendices for the benefit of readers.

Discussion of the critical review and case study highlights a framework for how designers can create their own LCAs. Drawing on the results of chapters 2 and 3, chapter 4 presents eight key points for improving the quality of building LCAs among design practitioners.

2. Review of LCA Tools and Resources in the United States

This section reviews the major resources available to design professionals who wish to perform LCAs in the United States. Shortcomings of data and the LCA process are examined as they relate to buildings. The ultimate focus is on the USGBC's LEED standards, which have recently started to incorporate LCA (USGBC 2010). A discussion of the stakeholders in LEED standards specifies how the USGBC can best improve its new LCA standards for maximum benefit to design professionals and building occupants.

2.1 Data Sources

Data for LCAs is less organized and advanced in the United States than in Europe, where LCA originated. EcoInvent, which is a database from Switzerland, has detailed national data that is mandated by the Swiss government for use in all LCA projects (Wallbaum 2011). There is no equivalent data source of such repute in the United States, though reliable data can be collected from several sources for a project, such as those compiled by governments, industries, and private researchers. Kaethner and Yang (2011) perform a review of building material data from an engineer's viewpoint and find "gaps in information, data which [is] too general to be useful to the structural engineer or data inaccessible due to commercial interests." Van den Berg et al. (1999) have identified the need for better quality assessment of input data, and propose a methodology for validating data during and after an LCA is performed, but this is still a weak area of LCA, especially for an inexperienced user.

The Athena Institute produces the most comprehensive building material databases available in the United States today. The nonprofit institute claims to cover "95% of the structural and envelope systems typically used in residential and commercial buildings" in its Impact Estimator tool and associated publications of datasets (Athena Institute 2011c). It is an excellent example of free third-party data across a wide range of materials.

Industry associations can provide useful data as well, though some industries may keep data proprietary. The World Steel Association has produced datasets on steel materials that can be used in LCAs (though this data is based on global averages, not U.S.-specific numbers), and the Portland Cement Association provides cement data to LCA software tools (PE International 2011) and conducts its own LCA studies on cement and concrete structures (Marceau et al. 2007). Some industries have worked with LCA experts to perform their own LCAs and have made the results available to the public, such as Athena's study of wood as a building material for the Canadian Wood Council (Athena Institute 2011d). All of this data is available for users to implement in their own LCAs, though it should be treated with caution if it the research has been performed by industry affiliates who may be biased in favor of their own product.

To understand the electricity and natural gas mixes used in different parts of the country, users can turn to the North American Electric Reliability Corporation's (NERC) data available online (NERC 2011) and the EIA's Annual Energy Reviews (US EIA 2007, 2009, 2010). This allows users to know what energy sources might be used during the building's operational phase, though it is impossible to know how these sources will change over the building's lifetime. Electricity and gas use in the building can be estimated using building energy modeling or can be based on data from actual buildings. An example of the standards used in a case study is presented in chapter 3.

Often, it is unnecessary to obtain data for every last bit of material or every single process that goes into a building. Because of previous studies performed by LCA experts and database creators, shortcuts can be used to make assumptions about complex processes that may be beyond the capability of the LCA modeler. For example, Kellenberger and Althaus (2009) propose ways to simplify building LCAs in order to expedite the modeling process. According to their research, the equipment, labor, and transportation associated with the construction process on-site can be estimated as 8% of the total embodied impact of a building, given their approximate parameters and location. Using such an estimate could make it unnecessary to calculate the impact of individual machines and materials that may differ from site to site, though this shortcut represents just one research project's conclusion and has not been reinforced by general opinion.

2.2 Software Tools

To create a life cycle inventory and obtain results through the use of impact categories, an LCA user must calculate the total materials used in the building and the total environmental impacts associated with those materials. While these calculations can be performed manually, the process is streamlined by the use of a software tool with a convenient user interface. LCAs can become complicated because of the many different materials used in a building. The software is designed both to provide integrated databases for the user's convenience, and to help the user make fewer errors while constructing the inventory and calculating impacts.

Two software products dominate the market in Europe and have spread to the United States. One is GaBi, created by the German company PE International (2011). The other is SimaPro, which is made by a Dutch company named PRé Consultants (2011). These programs have many similarities: a highly visual interface that makes model creation easier, an extensive in-house database of materials, processes, and systems for users to take advantage of in their models, and a selection of hundreds of impact categories that have been created in different countries.

These are both European products, and each program has data that is most highly developed for its own country. Their data for North America and other parts of the world is lacking. Often, the information gathered from industry or government has not been validated by a third party (USGBC/Analytica 2008). During use of GaBi for the case study in section 3, it was discovered that the program's data for the GWP of Portland cement was off by 15% compared to the latest industry data from the Portland Cement Association (Marceau et al. 2006). In another instance, the process for creating structural steel was found to assume 60% recycled content, which is an international average taken from World Steel data. The actual recycled content of steel in the United States averages 93.3% according to the American Institute of Steel Construction (AISC 2011), but World Steel has not yet made this data available for use in the software.

Design professionals who do not have the time or expertise to check dataset and impact category sources will not be aware of errors in the software. Programs like GaBi and SimaPro can sometimes act as “black boxes” that can produce results without always making it clear where the numbers came from. It is important for users to take advantage of a program’s documentation and check sources to make sure they agree with the processes and calculations involved. It is possible for to make changes to data within the program if it is not specific enough or disagrees with the user’s own professional experience.

One major software tool has been developed specifically for the North American market. Called the Athena EcoCalculator, it is produced by the Athena Sustainable Materials Institute (2011a). This tool is not as complex as the European software, as it is designed only for building LCAs, and asks users to separate the elements of their building into broad groups such as “Exterior walls,” “Roofs,” “Windows,” etc. (Athena Institute 2011b). Users have a small range of construction types to choose from within these categories, and if they do not see the building element they need among the choices, they must substitute something close enough. Once the impact categories are determined, the program compares the project to “average performances” in each assembly category, though what these averages represent is unclear. The tool is simple enough to give users an approximate answer on the environmental impacts of their buildings, but it does not allow for more in-depth analysis if desired.

Kaethner and Yang (2011) propose a software tool specifically for structural engineers to estimate the environmental impact of structural components. The tool is designed to be part of an existing structural analysis program, and reports the embodied energy, embodied carbon dioxide emissions, and recycled content of a model. Though the idea is meant to make LCA easier to integrate in a project, it may be used too late in the project to affect the environmental impact of the building design. Structural engineers generally model a building frame after the initial design concept has been created by architects and approved by the client. Therefore, major changes or innovations to the building’s design may be impossible at the proposed stage of LCA use.

2.3 LEED

Leadership in Energy and Environmental Design (LEED) is a certification system created by the U.S. Green Building Council in 2000 (USGBC 2011). Hailed as a “focus for melding the U.S. environmental and architectural movements,” the purpose of LEED is to recognize green buildings and give design professionals a way to benchmark these buildings and receive certification through a credit system (Horst and Trusty 2002). Points are accrued through the implementation of building measures that promote environmental responsibility and health (USGBC 2011). Almost any building, including existing buildings which are renovated, can theoretically become LEED-certified. A major purpose of LEED is to promote sustainable buildings to clients and the general public.

Since 2007, a pilot credit has been available in the LEED rating system that allows users to obtain one certification credit, consisting of 1 to 7 points, for performing a USGBC-specified LCA on a new building design. This credit is still being evaluated by the USGBC as a replacement for three of the current Materials & Resources (MR) credits (Yang 2011). Its stated purpose is “[t]o encourage the use of environmentally preferable building materials and assemblies” (USGBC 2010). To obtain the credit, the designer must read materials on how to perform an LCA, then use the Athena EcoCalculator (Athena Institute 2011a) to create an LCA and compare various options in the design. The program produces Environmental Impact Estimates that are then reported in the USGBC LEED Credit Calculator, a simple online tool to aid the certification process (USGBC/Analytica 2011).

The LCA creation process to obtain this credit is currently very generic due to the limits of the EcoCalculator and the Credit Calculator. Projects qualifying for the credit must follow a standard assembly that fits neatly into the software, or else the designer must make assumptions to simplify the building design in the LCA process. If a material cannot fit into one of the EcoCalculator assembly groups, it is placed in an “Other/Unspecified” category, which will negatively affect the outcome of the LCA and subsequent points given. Once the basic size, geometry, and location of the building are also defined, the design is plugged into the

EcoCalculator to give a life cycle inventory, then the USGBC LEED Credit Calculator produces LCA results based on a predefined, weighted set of impact categories from the US EPA's TRACI methodology (USGBC 2008).

A major drawback of the LEED LCA pilot credit is that it considers only embodied impacts (USGBC 2010). That is, the materials and construction processes required to create a building are included in the assessment, as well as the demolition and disposal or recycling of the building at the end of an assumed 60-year lifespan (USGBC 2008), but the building's operational energy requirements during its use are not considered, nor are future emissions associated with maintenance and renovations. The USGBC has countered that the energy use impacts of a building are already accounted for in other LEED credits, mainly EA Credit 1 (Energy Performance) and thus are not necessary in the LCA credit. If this stance is maintained in future incarnations of the LCA credit, however, designers performing an LCA using this tool may not understand the importance of comparing a building's embodied impacts to its operating impacts.

As Horst and Trusty (2002) point out, LEED is an evolving system open to much interpretation. Designers are able to be innovative and arrive at the credits using many different paths. There are few strict requirements that all must follow in the same way to obtain certification. But the LCA pilot credit is currently too vague and contains too many assumptions to allow for innovation in building design. The wide variety of buildings that receive LEED certification every year are far too different from one another to fit neatly into the material categories specified by the current process, necessitating assumptions that do not represent most real buildings. By using the pilot credit's LCA method, designers may be fooled into thinking the LCA process is easy, and trust the results more than they should.

The LEED method might be doing LCA a disservice by making it appear too simple and misrepresenting the purpose and advantages of the method. For example, the program is not designed to give the user any incentive to use materials more efficiently. The ISO standards for performing an LCA are not a part of the pilot credit, so designers are not asked to create a goal and scope or define system boundaries. The impact categories are chosen by the USGBC, and the user is given a simple score at the end of the process instead of being given a chance to understand the building's environmental impacts and where they come from. Users are simply not given ways to explore options in a manner that will lower the environmental impacts of a building (Yang 2011).

The current baseline against which any building is compared is "shifted toward timber buildings" (Yang 2011), which makes the baseline worthless as a comparison for many building types that would never use timber. Yang suggests that the USGBC should collect a database of user-submitted buildings, which would comprise a more inclusive baseline for the LEED LCA tool. Lack of building data is a problem within the larger scope of LCA as well, because users have few existing studies they can compare with their own work.

2.4 Discussion

The tools and data available to design professionals require a range of competencies. To make use of the data sources, the user must have a strong knowledge of all materials that go into the building, as well as its projected energy use and lifespan. The software tools available for performing LCA are either very complex, requiring extensive training to use to their full extent, or overly simplified, allowing only a small range of sensitivity analysis and innovation. The LEED LCA credit is still in its pilot stage, and is far from perfected. To make it a useful tool for designers, the USGBC should make the credit a more interactive process and invite users to play a larger role in understanding a building's environmental impact. An effective tool must incorporate the use of ISO standards and the formal LCA process, without making it too hard for the user to gather reliable data.

Architecture and engineering firms currently do not have the resources to perform LCAs on most design projects. Not only does a typical firm lack employees trained in LCA, the project clients generally do not understand the importance of LCA and do not want it to be part of the budget (Elbaum 2011). Because the client is generally interested in the up-front construction cost, the long-term savings of energy-efficient construction are often ignored. Architecture firms that show a strong commitment to sustainability, such as Sasaki and Siegel & Strain, are companies that have managed to include sustainability professionals in their teams and are working on communicating the importance of LCA to clients. LCA will not become standard practice in building projects until clients know enough about it to demand its inclusion and are more concerned with long-term cost savings.

If the LEED LCA credit is to become more robust, it must first become more useful to the design practitioner. It must help the designer learn how to use LCA efficiently without oversimplifying the process. The user also has to realize that LCA does not have to be in the realm of a separate "expert," and that it is possible to perform an effective LCA given the proper tools and tutorials. Ideally, users need training to use more complex tools in ways that accomplish their goals in a short time frame. They should be taught to focus on a single impact category such as global warming potential (GWP) so that they are not overwhelmed by the many category choices available in the software. Design professionals need to start using LCA more often in order to build knowledge of appropriate assumptions and provide comparisons for one another. Tools such as the USGBC calculator will not become useful until understanding of the LCA process is heightened.

This chapter has assessed the benefits and shortcomings of the resources available to design professionals for performing building LCAs. The United States lacks a clear resource for obtaining inventory data, and the software available for LCA modeling is often difficult to understand or does not contain sufficient U.S. data. The LEED LCA credit is a work in progress that must be evaluated and improved before it becomes an accepted tool. Design professionals are not LCA experts, and need resources that help them perform LCA more easily. They also need examples of good building LCAs to work from. The next chapter will describe a case study that aims to be such a resource.

3. Case Study of a Commercial Building LCA

3.1 Introduction

This case study uses the ISO 14040 series to perform a full LCA of a commercial office building, with the goal of comparing two common structural materials: reinforced concrete and structural steel. The purpose of including the study is to show how an LCA of a building can be performed efficiently and transparently. Throughout the study, elements of the LCA process are highlighted with explanations of how they are being performed in the simplest manner possible, or how they might be improved by future LCA modelers. Assumptions are specified with justifications for their inclusion. The appendices contain supporting information and documentation that is meant to show the user the level of detail that should be performed in a building LCA. This study is also discussed in Ochsendorf et al. (2011).

3.1.1 Background

The building created in this example shows just one type of building out of many existing in the United States today, but its design is based on a standard benchmark established by the Department of Energy (DOE) in its Buildings Database. The database is a collection of building designs that provide typical energy-use characteristics and give the user a benchmark of existing building types (US DOE 2004). The “Large Office Building” benchmark has been chosen as a starting point in this case. It is a 12-story building of approximately 500,000 ft^2 that includes a basement.

Statistics from the DOE database have been combined with data from the EIA’s Commercial Buildings Energy Consumption Survey (CBECS) (US EIA 2003), produced every four years, to calculate the energy use that might occur in this building. Such practices are different from building to building, so the survey is used to create numbers that represent a meaningful average among typical office buildings. Data from both the Buildings Database and CBECS have been modified to suit the needs of the case study, but these modifications are specified in later sections. While the resulting LCA does not represent a specific existing building in the United

States, it is meant to mimic an average of the existing mid-rise office building stock, both in its construction and use.

Performing this LCA is important because there are approximately 5 million office buildings in the United States (US EIA 2003). Over $60 billion was spent annually on the construction of new office buildings in both 2009 and 2010 (US Census Bureau 2010). Most are constructed of reinforced concrete, structural steel, or a combination of both, and are clad with many different materials such as brick, glass, and aluminum. While the embodied impact (comprising construction, maintenance, and demolition) of these buildings has an environmental impact that should not be discounted, their operational energy is much greater, and accounts for approximately 35% of the total annual electricity consumption in the United States (US EIA 2007). Because these buildings contribute significantly to the country's impact on the environment, performing an LCA of a typical example from this set of building stock is a worthwhile task to illustrate typical new buildings today.

3.1.2 Goal and Scope

In this study, two equivalent structural systems, one of reinforced concrete and the other of structural steel, are chosen to compare their environmental impacts. All other aspects of the building, including the façade, wall and roof systems, stairs, and elevator cores, remain constant between building types to facilitate an accurate comparison of structural materials. The buildings are modeled in two different climate regions of the United States, Chicago and Phoenix. The effect of variation in concrete's fly ash content is explored in a sensitivity analysis at the conclusion of the study. The goal is to understand the effect of structural system and climate region on the global warming potential (GWP) of the buildings over a lifetime of 60 years, which is a typical lifespan for a commercial building (VanGeem 2010). Potential improvements to the concrete structure, which would reduce the embodied GWP over the building's lifetime, are examined in section 3.7 after the results of the initial LCA are reported.

The system boundary of the LCA is shown in Figure 5. The study seeks to understand all phases of the buildings' life cycles, omitting certain aspects of the life cycle for which data is poorly understood or assumed to be small, such as construction processes and HVAC equipment. The reasons for omitting these processes are explained in later sections. The study uses three computer programs to complete the LCA: Microsoft Excel for creating the life cycle inventory of materials and energy use, the DOE's EnergyPlus engine in the DesignBuilder interface for creating energy models (DesignBuilder Software 2010), and GaBi 4 for creating the full life cycle models and performing the impact assessment (PE International 2011). All energy modeling was performed by Andrea Love in tandem with this LCA study (2011).

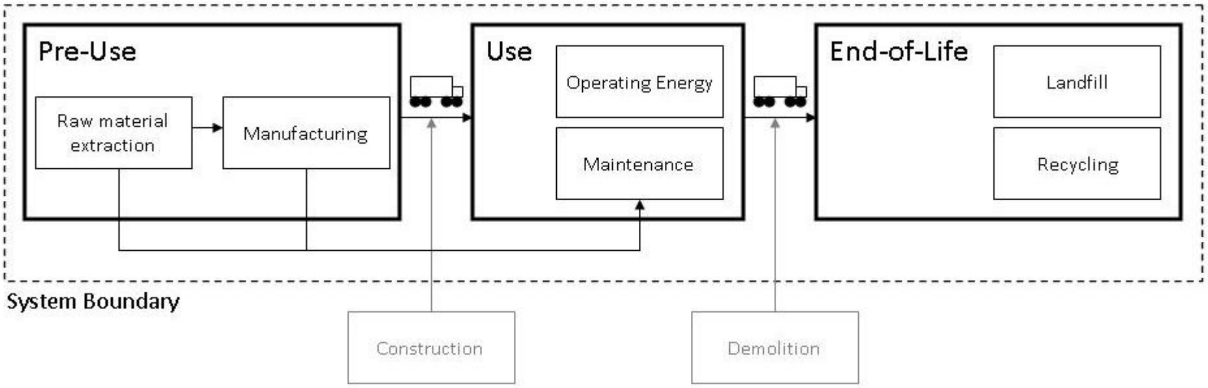


Figure 5: System boundary showing the life cycle processes which are included and excluded from the study. Drawing by Margaret Wildnauer.

The functional unit of the study is one building before occupation. This means that all the materials that go into the construction, use, maintenance, and demolition of the structure and shell are entered into the model, as well as the operational energy used in the building over its 60-year lifespan. Excluded from this model are interior partitions and furnishings, as well as the materials for the HVAC systems in the building. For convenience, results are reported both in terms of the functional unit *and* per square foot of total building area. Normalizing by square footage makes it easier to compare the environmental impacts of the building to other buildings that may be very different in size or construction.

3.2 Design and Construction

Though basic dimensions and features were taken from the Department of Energy Buildings Database (US DOE 2004), these buildings are designed from scratch and subjected to structural analysis as part of the case study. Each building has a width of 162 feet and length of 243 feet, and it is comprised of twelve 13-foot-high stories and a basement, giving a total square footage of 511,758 ft^2. The façade is 40% glazing and 60% aluminum rainscreen panels, as shown in Figure 6. The interior of the building, which has a usable square footage of 498,590 ft^2, is unfinished in the LCA model. Though interior furnishings are not considered in the LCA material quantities, they are included in the energy model to accurately represent the internal massing for HVAC purposes (Love 2011). Each floor is divided into five HVAC zones, as seen in Figure 7, which sums to 61 zones in the building, as the basement is considered a single zone.

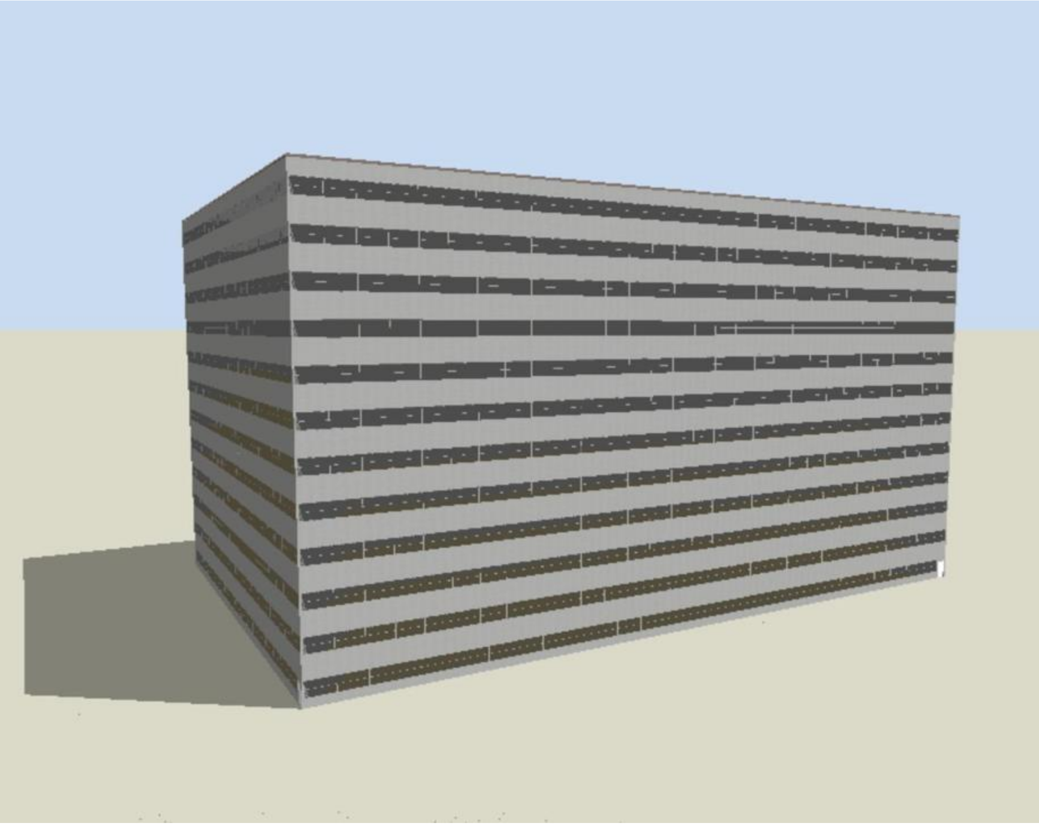


Figure 6: Rendering of the twelve-story commercial building exterior, with 40% glazing and 60% aluminum rainscreen panel cladding. Source: Love (2011).

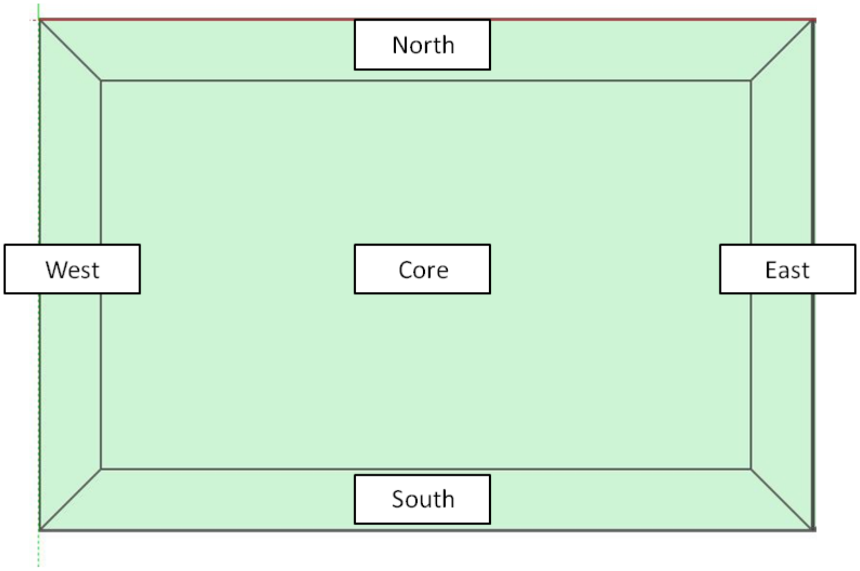


Figure 7: Energy model zoning within the commercial building on each floor. Source: Love (2011).

3.2.1 Structural Design

The structures are composed of moment frame systems with two cores to provide lateral stability. A section of each structural frame is shown in Figure 8. All bays are spaced 27 ft apart in both directions. Concrete mixes are derived from Nisbet et al. (2007) and have 10% fly ash by weight added. A description and documentation of the mix design is provided in Appendix B. Loads for all structural members are taken from ASCE 7 (2005). A 100 pound per square foot (psf) dead load and 50 psf live load are used on all floors except the first floor, which has a 100 psf live load. The roof is designed for a 20 psf live load, and the stairs for a 100 psf live load. The two stair and elevator cores are designed to resist a 50 psf wind load. The LRFD load combination equation 1.2D + 1.6L was used. Based on these numbers, a load takedown spreadsheet was created to determine the loads on the floor system required at each floor.

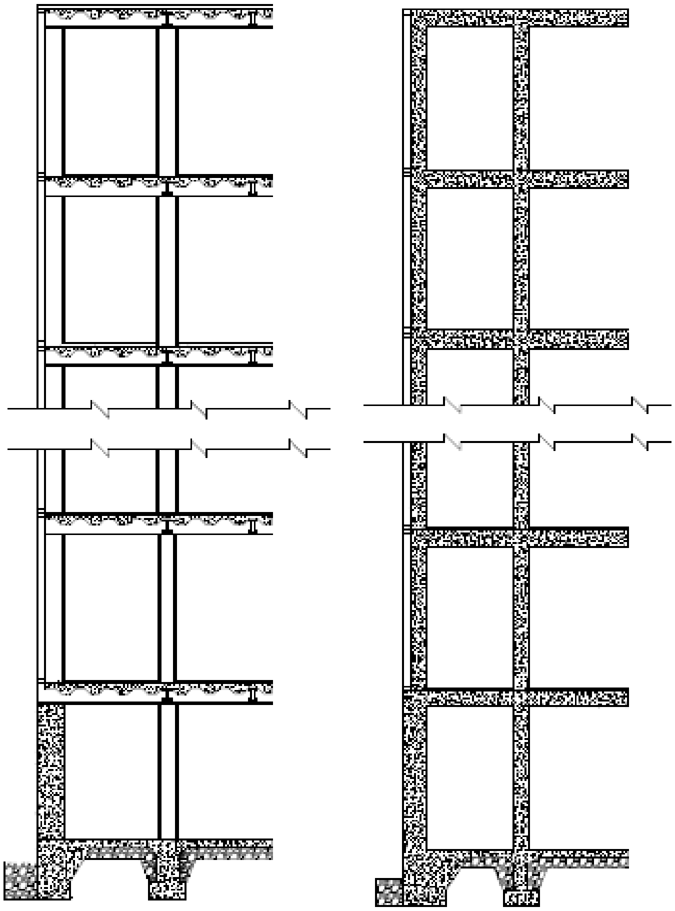


Figure 8: Section of steel (left) and concrete (right) frames. Drawings by Omar Swei.

The foundation is the same in each building: a concrete retaining wall comprising the basement, with a slab and footings under each column. Under each slab are layers of extruded polystyrene, sand, and gravel. Foundation schemes are created using Ching (2008) and ACI 318 (2005). Because these buildings do not exist on a real site, soil conditions could not be assessed to create a structurally accurate foundation. The foundations are therefore typical to what one might find under a building of this size, but have not been checked structurally.

The steel structural system is designed using the *AISC Steel Construction Manual, 13th Edition* and *Basic Steel Design with LRFD* (AISC 2005; Galambos, Lin & Johnston 1996). The load combination over a tributary area is used to choose steel W shapes for the columns based on their axial load capacity. The floor system consists of 5” reinforced concrete on top of corrugated metal deck. Girders are spaced 27 ft apart, and beams are spaced 9 ft apart, under the deck. The cores are composed of steel members based on the required area of steel to resist the given wind load, assuming that they carry 50% of the bending moment and 50% of the axial load (the other 50% of each is carried by the building's columns). The connections in the frame were assumed to weigh 5% of the total quantity of steel members, rather than being designed and counted. A summary of the W shapes chosen for these elements is shown in Table 2.

The concrete structural system is designed using ACI 318 (2005). The load requirements are satisfied by 12" square columns on the upper floors, and 16" square columns on the first floor and basement, spaced 27 ft apart in both directions. The floor system consists of a two-way 10" reinforced concrete slab. The cores are again composed of the amount of reinforced concrete required to resist 50% of the bending moment and axial load. The concrete design is summarized in Table 2.

	Steel	**Concrete**
Slab	2" decking w/ 5" slab	2-way, 10" slab
Columns	W14x283 (floors B-2) W14x211 (3-5) W14x145 (6-8) W14x90 (9-12)	16"x16" (floors B-1) 12"x12" (2-12)
Beams	W16x36, on column lines	n/a
Girders	W21x44, spaced 9' on center	n/a
Cores	28 W14x257 columns each	27'x27', 2' thick each

Table 2: Structural design details of steel and concrete buildings.

3.2.2 Shell and Interior Design

Façade and floor system details are obtained from standard practice references (Allen 2002; Ching 2008). Reinforced concrete staircases are designed according to standard practice. Interior and exterior doors are composed of hollow steel and are of standard dimensions. All steel members in the steel building are clad in 5/8" gypsum board to protect against fire.

The wall system is composed of aluminum rainscreen panels, a vapor barrier, 4.5” extruded polystyrene insulation, 3.5” by 1.5” aluminum studs with a thickness of 0.143”, and 5/8” gypsum board for an interior finish. Both the interior and exterior are painted. Windows are composed of double-paned 55” x 112” glass with aluminum frames.

The roof is composed of 4.7” extruded polystyrene, a layer of asphalt roofing, and 2” gravel ballast. Under this roofing material is the structural roof, which is composed of either 2” corrugated metal deck or 10” reinforced concrete, corresponding to the structural system.

Certain portions of the buildings need to be maintained and replaced over its lifespan. In this study, windows, roofing, and paint are assumed to need replacement. The building is repainted every 10 years, and the windows and roofing are replaced every 15 years. The materials associated with this maintenance are also accounted for in the embodied portion of the life cycle.

3.2.3 Construction

The equipment and materials associated with construction of each building has not been quantified in this study. Little research has been done on the life cycle impacts of construction, and practices also vary greatly within the country. The construction impacts are assumed to be equal across building types, but future research should consider these impacts more carefully. Work done on estimating the construction impacts of buildings can be found in Oka et al. (1993).

3.2.4 Transportation Distances

Most materials that go into the building must be transported from somewhere else. These transportation distances, shown in Appendix C, are found by visiting the websites of local suppliers and manufacturers in both Phoenix and Chicago. Research was done to determine where supplies come from in each city. The total distance from the supplier or manufacturer to

the city is calculated using Google Maps. If a supplier is based within the city itself, a flat distance of 10 miles is assumed, since the buildings have no specific site within each city.
An exception to this region-specific transportation distance calculation is that of the concrete mix components. Because regional data is too difficult to ascertain, a set of national averages is used from a commodity flow survey (BTS 2007). Cement and aggregates are assumed to be transported to local ready-mix plants using three transportation modes—truck, rail, and barge—based on the national percentage of material transported by each mode, and the average distance it travels. The ready-mix plant is assumed to be within city limits, and therefore the concrete travels an additional 10 miles to each site by a concrete mixer.

3.3 Material Quantity Calculation

Calculation of material quantities is done using Microsoft Excel. Spreadsheets are created where each structural and shell element has its own section and weight calculations. Material densities and conversion factors are linked to the same cell every time to ensure consistency (Reade 2006). Final numbers are accumulated for easy comparison and unit conversion, and they are shown in both metric and imperial units in Appendix D.

The total weight of materials per square foot in the building is shown in Figure 9. The mass of the concrete building is about 1.9 times higher than that of the steel building. The material quantities do not vary between climates, meaning that each structural frame has an identical weight in both Chicago and Phoenix in this graph.

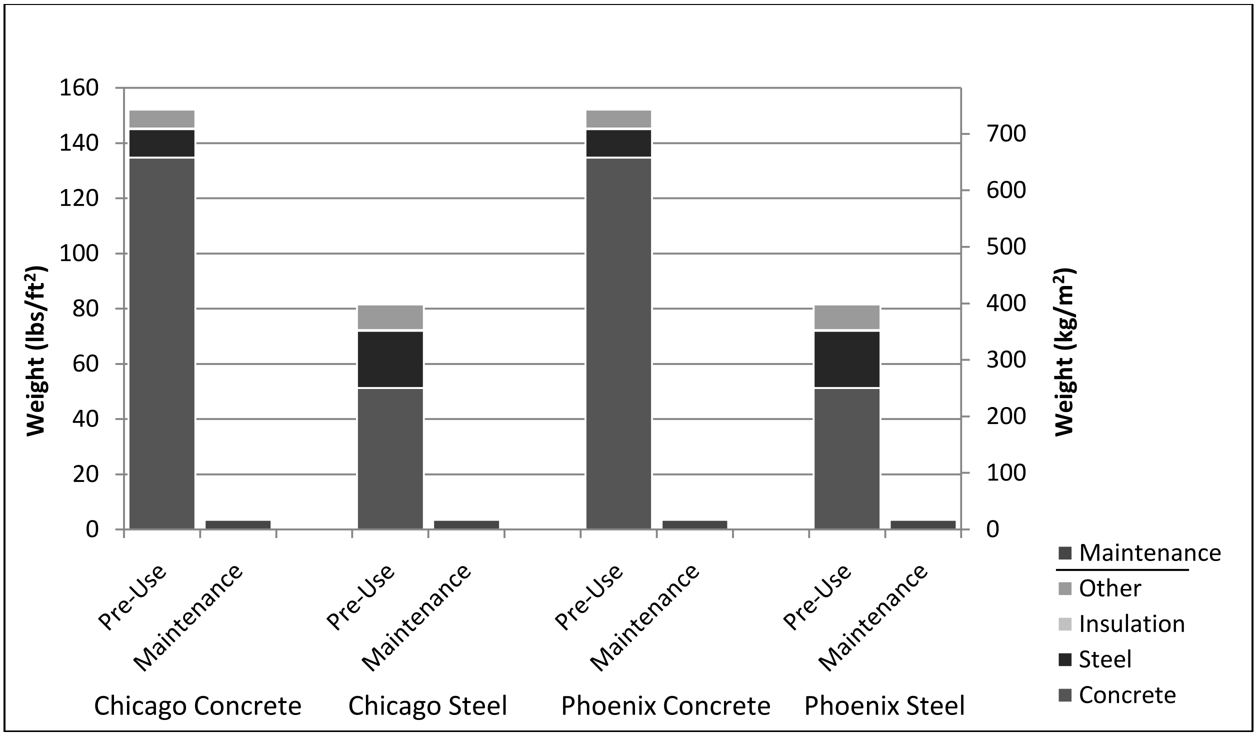


Figure 9: Weight per square foot of initial construction and maintenance materials in each building.

3.4 Energy Models

The buildings' structures and shells were modeled by Love (2011) in EnergyPlus to estimate their annual energy use. The basic design parameters are summarized in this section, with additional documentation on the energy models in Appendix E.

3.4.1 Building Envelope

The thermal resistance and thermal mass, two of the more important aspects of the commercial building for the purposes of this study, are presented in Table 3 below. Also included are the requirements for the R-value in the wall system and roof, based on the relevant energy code (ASHRAE 90.1-2007). Though the concrete building is modeled with and without finishes in EnergyPlus, only the concrete without finishes is considered in the LCA study.

		R-values (ft^2·°F·h/Btu)			Thermal mass (kJ/km^2)	
		Requirements	Steel	Concrete	Steel	Concrete
Exterior Wall	Chicago	13-cavity, 7.5-exterior	15.3	15.3	40.5	40.5
	Phoenix	13-cavity	6.8	6.8	38.3	38.3
Ground Floor	Chicago	Not required	0		363.5	
	Phoenix	Not required				
Roof		Both: 20 above deck	20.0	20.0	145.1	609.4

Table 3: R-value and thermal resistance requirements and values of the commercial buildings.

The windows are built to satisfy ASHRAE 90.1-2007 minimum standards, and assumed to be double-glazed with an aluminum frame. The glazing properties are given in Table 4.

	U-value (W/m^{2}K)	Solar Heat Gain Coefficient
Chicago	3.12	0.40
Phoenix	4.26	0.25

Table 4: Thermal and solar properties of window glazing in the commercial building. From Love (2011).

3.4.2 Building Energy Design

The energy systems in the building are designed using the following sources listed in Table 5.

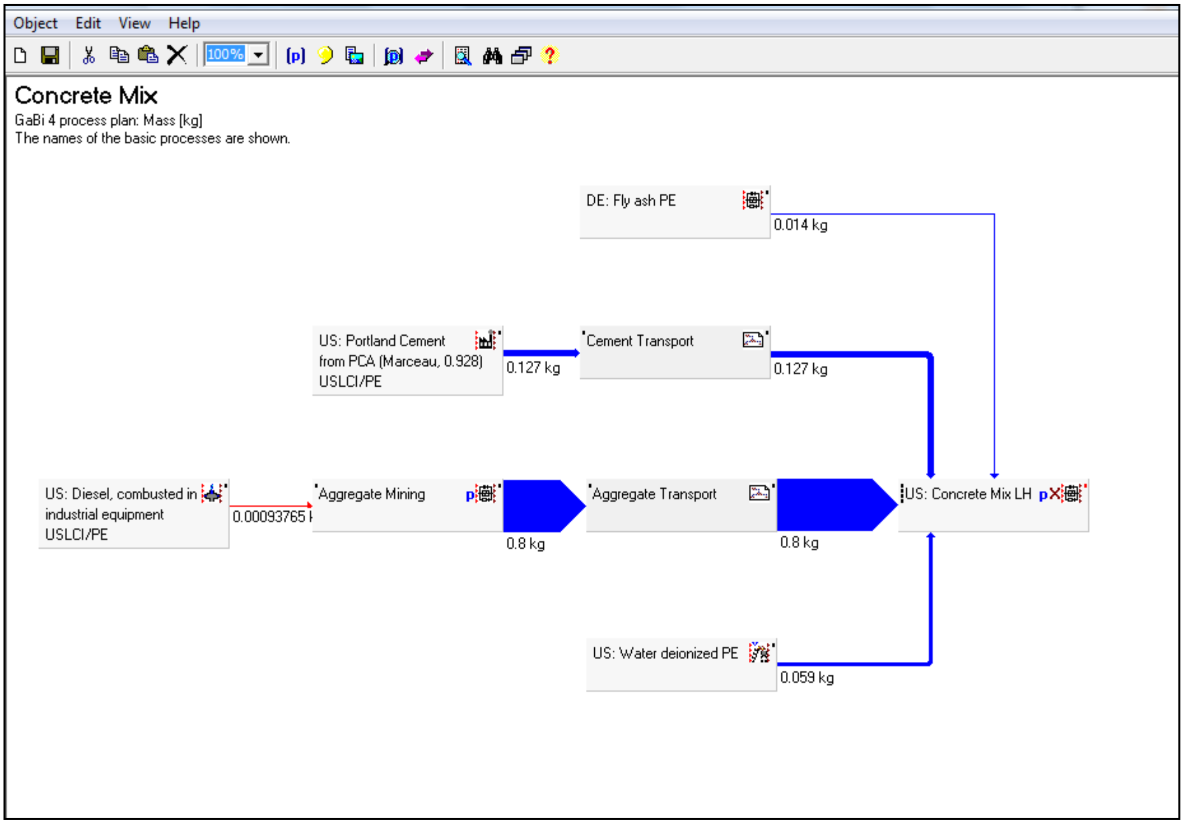
	Referenced Source
Building Form & Size	CBECS 2003
Occupancy	ASHRAE 62.1-2004
Ventilation Requirements	ASHRAE 62-1999
Plug & Process Loads	Engineering Judgment
Hot Water Demand	ASHRAE Advanced Energy Design Guide for Small Office Buildings
Schedules	ASHRAE 90.1-1989
Building Envelope	CBECS 2003 for assembly choice, ASHRAE 90.1-2004 for thermal performance
Percentage of Glazing	CBECS 2003
Infiltration	ASHRAE 90.1-2004, Addendum
Lighting	ASHRAE 90.1-2004
HVAC System	CBECS 2003 for system types, ASHRAE 90.1-2004 for efficiencies
Fan Efficiencies	ASHRAE 90.1-2004 & Energy Policy Act of 1992

Table 5: Reference sources for energy design. From Love (2011).

Appendix E contains a table summarizing the internal zone loads assumed for occupancy, equipment, lights, infiltration, ventilation, and domestic hot water. It is important to note that the equipment and lighting loads are not running continuously, but rather according to a specific schedule. The second table in Appendix E shows the HVAC equipment efficiencies used in the design.

3.5 Life Cycle Inventory Creation

The life cycle inventory model is created using GaBi 4 software (PE International 2011). This program has a convenient interface that allows users to visualize the life cycle model and help organize complex relationships between processes (Figure 10). PE has also incorporated many common impact category packages, such as the EPA's TRACI categories for United States users. Once the user has created a material inventory, the rest of the work may be done entirely within the program.



Concrete Mix

GaBi 4 process plan: Mass [kg]

The names of the basic processes are shown.

Figure 10: GaBi screenshot of a typical model plan.

Documentation exists within the program so that users can understand sources for the processes they choose, but much of the documentation is too vague, or the processes are too general to be used for a building in the United States. In many cases, more thoroughly researched European data had to be substituted, such as for gravel and windows. In other cases, industry spokespersons were contacted directly to obtain better data that was manually entered in the program. A list of sources for each process used in the program is shown in Appendix F.

The material inventory, transportation distances, and energy quantities are entered into the program to create four models: one for each building type in each climate. Diesel fuel is used for all transportation modes. The energy mixes correspond to the regions specified by the North America Electric Reliability Council (NERC). Regional electricity is difficult to quantify in an LCA because the US electricity grid is highly interconnected and the facilities being used change constantly; electrons do not respect state or municipal lines (Weber 2011). Thus, the NERC regions are arguably the best approximation available for the power mix being used in each city. Phoenix falls within the Western Electricity Coordinating Council (WECC) region and Chicago is in the Reliability*First* Corporation (RFC) region (NERC 2011). The corresponding average electricity mixes are shown in Appendix G.

The impact category used is global warming potential (GWP), which is the weight of carbon-dioxide equivalent (CO_2e) emitted per unit weight of material over 100 years, as defined by the Intergovernmental Panel on Climate Change (IPCC 1995). CO_2e is a weighted combination of greenhouse gases, the most abundant of which are carbon dioxide, nitrous oxide, and methane. The most recently updated conversion factors for these gases, which are also in GaBi, are shown in Table 6.

Greenhouse Gas	lbs CO_2e/lb material
Carbon Dioxide (CO_2)	1
Nitrous Oxide (N_2O)	298
Methane (CH_4)	25

Table 6: CO_2e conversion factors for greenhouse gases (IPCC 2007).

3.6 Results

The results of the life cycle assessment are divided into three sections that illustrate the most important aspects of the building's environmental impact. First, the embodied global warming potential is isolated and divided into pre-use materials, maintenance, and end-of-life processes. Next, the operating energy and its associated GWP are shown. Finally, the total life cycle GWP is calculated to compare the effects of embodied and operating contributions.

3.6.1 Embodied Emissions

The embodied GWP of the building materials per square foot is shown in Figure 11. The first bar shows the GWP associated with the pre-use phase, split up by material. The second bar shows the emissions from maintenance over the use phase, and the third bar shows the end-of-life emissions associated with landfilling and recycling. The last bar, outlined in black, shows the total embodied GWP for each building. The concrete buildings have pre-use emissions of 39.2 pounds of CO_2e/ft^2, and steel buildings have 48.5 pounds of CO_2e/ft^2. The concrete emissions are about 20% lower. Once maintenance and end-of-life are factored in, the total embodied emissions are approximately 42 pounds of CO_2e/ft^2 in all cases. Steel production dominates the GWP of the steel building; likewise, concrete production dominates concrete building. Transportation and diesel fuel are included in "Other." Interior finishes are not included.

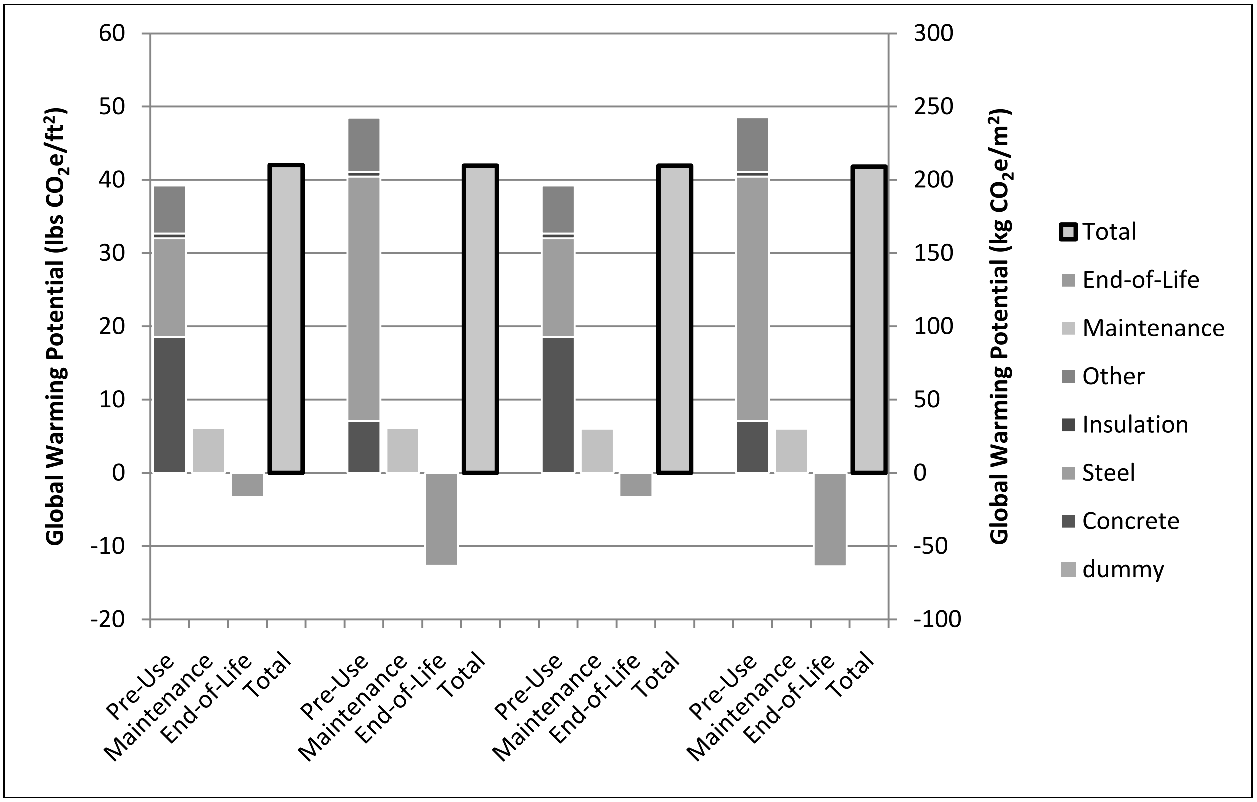


Figure 11: Embodied GWP of the four buildings, shown in terms of pre-use, maintenance, end-of-life, and total embodied GWP.

It is important to note that because the steel salvaged from the building is assumed to be partially recycled, that recycling adds a significant credit to the overall life cycle accounting. The large quantity of steel potentially recycled from a steel-framed building—70% of rebar and 98% of structural steel—means that the end-of-life GWP in the steel building is actually negative due to a recycling credit. Concrete is also recycled, but less readily and is downcycled to a low-grade aggregate. Assuming 50% of the concrete in these buildings is downcycled, and the rest landfilled, this causes the end-of-life GWP in the concrete building to be closer to zero than in the steel building, though still negative.

3.6.2 Operating Energy

Figure 12 displays the energy use of the commercial building in Chicago and Phoenix, split up into energy systems in the building. These results are adopted from energy modeling by Love (2011) and updated in Ochsendorf et al. (2011). The lighting, equipment, and water loads stay the same among all building and climate variations, but the HVAC, pumps, and fans change based on the climate and energy mix. 7-9% in HVAC energy savings can be seen in Chicago and Phoenix, respectively, when the concrete building is compared with the steel building. However, when the whole building energy results are viewed, the savings is diminished to about 3% in both climates. The energy use corresponds to a global warming potential of approximately 16 pounds per square foot (psf) per year for both building types in Chicago, and approximately 12 psf per year in Phoenix.

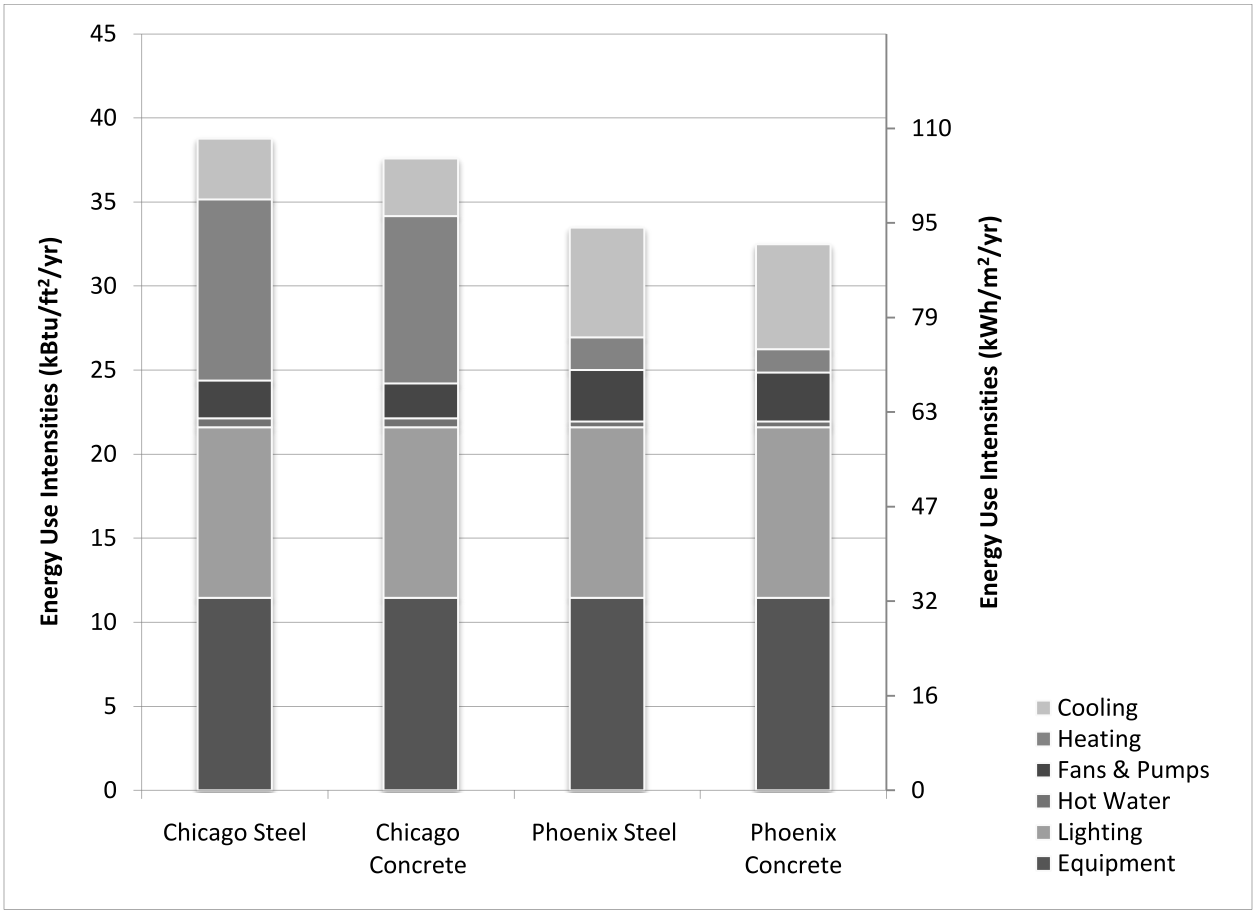


Figure 12: Annual energy use by system in each building type modeled. From Love (2011).

3.6.3 Total Life Cycle Emissions

When the GWP for the total life cycle is put together, it becomes clear that the embodied energy comprises only a small fraction of the life cycle GWP, as shown in Figure 13 for a typical building lifetime of 60 years. The two structural materials have a difference in GWP of 1.4% in Chicago and 0.3% in Phoenix, which is essentially negligible given the assumptions that were made as part of the LCA process. The total GWP of the buildings ranges from 768 to 1021 psf for this lifespan. Though the concrete building has initially higher emissions, the energy savings due to thermal mass compensate for this difference over 60 years. The steel and concrete buildings have very similar emissions over the full life cycle, showing that the choice of structural material does not dramatically influence the total emissions.

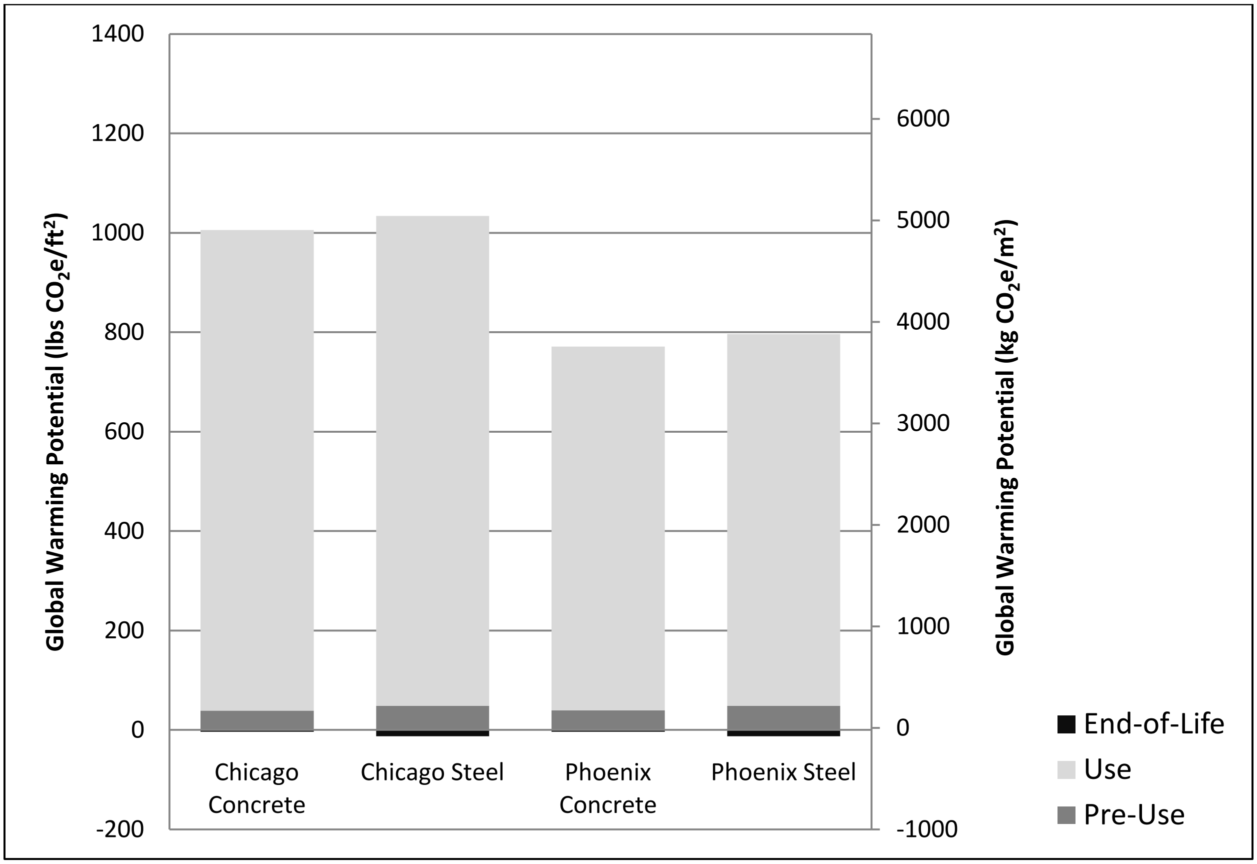


Figure 13: Total GWP over a 60-year building lifetime, split into pre-use, operation, and end-of-life contributions.

Regional variation has an impact on the life cycle of these commercial buildings. Assuming a 60-year lifetime, the difference in CO_2e between Chicago and Phoenix is approximately 20% due to the milder climate of Phoenix. This number decreases slightly as the lifetime of the building is increased, but it is still significant. Transportation distances, which may be very different from region to region, account for only a fraction of the embodied GWP, and are negligible over the total life cycle. Differences in HVAC needs are the primary reason for the regional variations.

3.7 Fly Ash Substitution as a Reduction Opportunity

As seen in Section 3.6.3, the embodied GWP of a concrete building is approximately 42 psf CO_2e, and the operating GWP is 12-16 psf CO_2e/ft^2 annually depending on climate region. Improvements to the structural design and concrete mix would reduce the embodied GWP and the overall life cycle impact of the building.

The GWP of either building type would change if different typical structural systems were implemented. For example, designing a one-way slab and beam system in the concrete building, instead of the two-way flat slab in this example, would increase the concrete building's global warming potential enough to make its embodied GWP higher than the steel building's embodied GWP.

The GWP of a concrete building can further be reduced by implementing future improvements in concrete mix design. One option is to increase the use of supplementary cementitious materials, such as fly ash, slag, or limestone, in concrete. Using a concrete mix with 25% or 50% fly ash content by volume (rather than the 10% assumed in the initial design) would lower the GWP of the concrete alone by 15% or 41% respectively. The pre-use GWP values for buildings using these revised concrete mixes are shown in Table 7. These mixture adjustments would correspond to an overall reduction of 0.2-0.7% in the total GWP of a concrete building in Chicago with a 60-year lifespan, and a 0.3-0.9% reduction in a similar building in Phoenix. The total amount of CO_2e averted would range from 435-742 tons as a result of these changes.

	Concrete Chicago	Concrete Phoenix	Steel Chicago	Steel Phoenix
Concrete – 10% fly ash (original design)	39.2	39.3	48.5	48.5
Concrete – 25% fly ash	37.5	37.5	47.4	47.4
Concrete – 50% fly ash	32.6	32.6	45.6	45.6

Table 7: Reduction in pre-use pounds of GWP/ft^2 due to fly ash substitution.

3.8 Data Validation

Material quantities vary across building designs based on the type of structural system used and the material elements chosen. One aspect of this study where material quantities could vary widely is in the steel design. The steel building currently has 18 pounds per square foot of structural steel (not including rebar). This steel frame, as well as the concrete building frame, has a conservative design that assumes loads with high safety factors. The design also represents an approximate calculation such as one that might be performed by an LCA expert at a design firm, who wishes to understand the approximate environmental impact of the building before its design is finalized.

Professional engineers were consulted to obtain typical pounds per square foot of structural steel in real buildings. The answers ranged from 8 psf (Kassabian 2011), to 11 psf (Hines 2010) and 15 psf (Ferriss 2011). Therefore, the design used in the study achieves its intended goal of being conservative, and could be lowered to more accurately reflect existing building stock.

The concrete mixes and reinforcement ratios are subject to variability based on the site conditions and the engineer in charge of concrete design. There are no national standards that apply to these variables in every case. Reinforcement ratios, in particular, are a matter of personal choice once the basic requirements are satisfied. The choices made for this case study were based on the designer's own experience, with assistance from the standard texts listed in section 3.2.1. A different engineer may have created a totally different design that increased or decreased the total amount of reinforcement in the building.

The material sources assumed in the building designs are estimated based on a search for suppliers and manufacturers in each region of the country analyzed. Usually, the material needed was verified through an Internet search or a phone call to a supplier. Because the LCA cannot account for networks and personal connections in the construction industry, the suppliers had to be chosen somewhat at random. In reality, certain materials could come from anywhere within a given radius of the site based on the contractor chosen. Other materials which are produced on a national scale were researched and sourced from the most likely manufacturing location. For example, all aluminum is assumed to come from Alcoa's plant in Texas, the country's largest aluminum producer by a significant margin (*Economist* 2007).

3.9 Conclusions

The buildings and their operation in this case study were modeled using the DOE Buildings Database and CBECS as a starting point. Together, these two resources provide the most comprehensive collection of average building designs and energy uses given the huge variety of buildings existing in the current stock.

The embodied GWP of the buildings is close enough to have no appreciable difference. When the total life cycle is considered, the concrete building has a slightly lower GWP than the steel building. Since the data is based on world averages, the recycled material content is actually rather low compared to current practice in the United States. Better country-specific data would present a more accurate picture of the GWP of steel used in buildings. This example illustrates how recycling methods chosen for the LCA can have a major impact on the outcome, and serves as a reminder of the inherent variability in any LCA. Since recycling practices vary so widely even among individual municipalities, the GWP of a building made of steel, concrete, or any other material will change with the site of the building.

The thermal mass of the concrete building provides HVAC savings of 7-9%, which account for 3% savings in annual operating GWP compared to the steel building. Thermal mass based on material choice will make a difference in utility costs and environmental impacts over the long run, which is an example of how LCA can illustrate long-term economic and environmental savings that may not be immediately apparent to a client during the design process.

Over a lifetime of 60 years, the only significant difference in emissions comes from regional effects on operational energy. Operating GWP dwarfs the differences in embodied GWP created by the material choices. At the same time, the massive environmental impact of the building's use means that even a seemingly small change, such as the HVAC savings of a concrete building over a steel building, can make a difference in the environmental impact of a building.

The results of the global warming potential study are summarized in Table 8. These numbers are calculated per square foot of gross building area. A further breakdown of the results by individual building elements is available in Appendix H. The results according to the functional unit, which is a whole building, are shown in Appendix I. Together, this combination of reporting methods gives the reader a comprehensive picture of the environmental impact of every aspect of the building.

City	Building Type	Materials/ ft^2	Pre-Use GWP/ft^2	Maintenance GWP/ft^2	Operational GWP/ft^2/yr	End-of-Life GWP/ft^2	Total GWP/ft^2 in 60 years
Chicago	Concrete	152.1	39.2	6.1	16.0	-3.3	1002
	Steel	81.5	48.5	6.1	16.3	-12.7	1021
Phoenix	Concrete	152.1	39.3	6.0	12.1	-3.3	768
	Steel	81.5	48.5	6.0	12.4	-12.7	783

Table 8: Summary of total pounds of GWP per square foot in all four buildings.

4. Discussion

4.1 The Current State of LCA Tools and Resources in the United States

The review of LCA practice today has shown that design professionals do not have adequate tools to perform simple and effective LCAs for their building designs. The sources that are available for LCA in the United States are not as comprehensive as those in Europe, where use of LCA is more prevalent, though U.S. government and industry data, along with datasets from the Athena Institute, are usually enough to perform an adequate LCA. The software available to users is often complex and requires extensive training to use effectively. Unfortunately, the documentation in the software is often difficult to access and understand, and users will not always know how the calculations are performed and where the data is coming from.

The LEED rating system is one of the most prominent sustainability tools available to designers in this country, but it has been slow to incorporate LCA. A pilot credit is currently available for users to experiment with, and is being explored as a substitute for existing credits. The tools provided to perform the LCA, however, are overly simplified and do not allow the user to explore a wide range of building materials and designs. The calculator tool is a black box for which users have no further information, and they are unable to explore the implications of the LCA and find ways to reduce the environmental impact of their building designs if they cannot understand the calculation parameters (Yang 2011). The LCA credit is not an effective way of helping designers learn how to perform LCAs, and may hinder the spread of LCA as a popular tool for design projects if it is not significantly improved. It is already difficult to persuade clients of LCA’s importance in a project, and the LEED credit may not be good enough to be worth a designer’s time and a client’s budget.

4.2 Case Study

The purpose of the case study was to show an LCA that is as transparent and simplified as possible, without eliminating crucial steps. Highlights of the study’s repeatability include:

- A stated goal, scope, and system boundary.

- A description of all design manuals, codes, and references used to create the life cycle inventory.
- A description of the specific processes used in the software.
- Global warming potential used as the primary impact category, so as not to confuse readers with a long discussion of multiple environmental impacts, and to avoid impact categories that were not properly validated during the study.
- Results presented in multiple ways for clear understanding.
- Results normalized by square footage for easier comparison to other buildings.

The chosen LCA software has some shortcomings which made the study more complicated. GaBi originates in Europe and thus has a focus on European data. Many of the North American datasets were not region-specific. Because the United States is such a large country with construction and manufacturing processes that vary from region to region, the level of detail in the North American processes is not good enough to create a robust LCA in one region of the country.

Another problem with the software is its “black box” nature that prevents the user from understanding the material sources well. GaBi does not provide clear, detailed documentation for many of its datasets. Validation was performed on much of the data used in the model, and in many cases, the data did not agree with other standard sources. Some datasets had to be manually changed or recreated to make the study more credible. This is not an easy process that can be implemented quickly by a design professional who is unfamiliar with the software, and it requires extra time that may not be within the scope of a project’s budget.

When the case study is compared to other typical studies performed in the past, its embodied GWP results are found to be lower than the other study reporting GWP (Figure 14). The studies reporting CO_2 emissions only are mostly lower than the case study’s GWP values, which makes sense. If total GWP had been reported in these studies, the case study would find itself somewhere in the middle of these values, not at the extreme upper or lower end of the range.

All other studies show steel as having a slightly lower GWP, while concrete and steel are equivalent in the case study. It should be noted that the other studies are all at least five years old. The case study has different characteristics than any of the other LCAs performed, and represents an average of the commercial mid-rise building stock in the United States today.

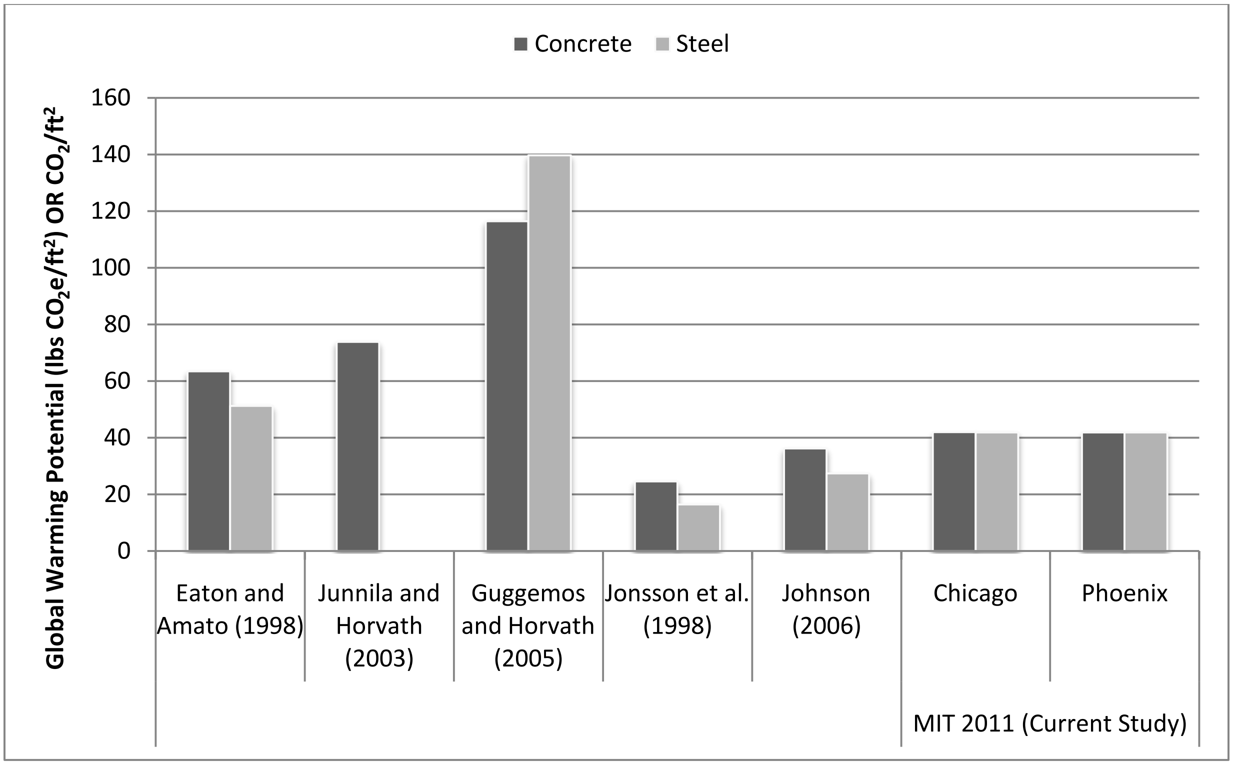


Figure 14: Comparison of embodied GWP (or CO_2 only) in this study and other studies discussed previously in Section 1.3.

4.3 Eight Key Points for Improving the Transparency and Quality of LCAs

Based on this research, eight key points are now presented for improving building LCAs. The recommendations are proposed based on what has been learned from examining the state of the tools and resources available to the design professional, the difficulties involved in performing an LCA simply and effectively, and a case study that has highlighted a transparent LCA.

1. Define a strict scope of work, including system boundary and functional unit.

Users cannot explore how to reduce the environmental impact of their buildings without first having a baseline and a stated goal for the LCA project. Defining a system boundary and functional unit encourages users to explore the implications of each step in the LCA process and decide what is and is not important to include. Many previous studies do not make these decisions clear. Knowing the boundaries of the project allows a user to effectively compare his or her study to previous studies that may have different goals and boundaries, which is especially important given that buildings are unique and difficult to compare to each other even when the goals and boundaries of an LCA are identical.

2. Evaluate the quality of software databases with respect to other published values.

Tools such as GaBi and SimaPro have been created by gathering data from a wide variety of sources. It is important not to take these sources entirely for granted. LCA users need to validate the most important data to their studies by checking other reliable sources, such as references from government and industry. The case study included extensive validation of steel, cement, and concrete data because these materials were the most crucial to the study's results. To make LCA easier, future software tools need to have more reliable and well-documented data.

3. Make use of accepted shortcuts and rules of thumb so the LCA is as complete as possible in a short time frame.

Complex LCAs can take years to perform accurately. Given the time frame of many projects, it is impossible to adhere to such detailed standards, especially if an LCA is a small part of a design project where professionals and clients want rougher estimates. Users should take advantage of shortcuts that have been tested and verified by the LCA and construction communities, as described in section 2. It is unnecessary to calculate every last screw in a timber-frame home if the user knows approximately how much metal would be used on a typical project. As LCA use continues to become more widespread, shortcuts such as this one will become more commonly understood.

4. Use CO_2e (GWP) as the main unit for communicating results.

GaBi gives the user a choice of over a hundred different impact categories to use in the LCA's impact assessment step. The LEED Credit Calculator uses a weighted set of predetermined impact categories that are invisible to the user. Neither of these systems helps make the LCA more transparent and easy to perform, nor does it make studies easy to compare. If the project time frame is short, the user should focus on carbon dioxide equivalents, or GWP, as a mandatory impact category that is easy for all to understand. This is not to say that other environmental impacts should not be studied if time permits. But if GWP becomes the main reporting unit of choice in every building LCA, a designer or a client can look at any LCA and understand the basic results quickly.

5. Normalize results in terms of unit area.

Buildings come in all shapes and sizes. Reporting the LCA results by area allows designers and clients to easily compare the building in question to other building designs that have also been modeled in an LCA, regardless of structural system or material choices.

6. Document every level of research and assumptions made.

Recording all data choices and resources used allows others to pick up the LCA, understand what has been done, and make modifications to it. Clients who would like to take a more active role in the process can explore the data sources themselves and understand the LCA more thoroughly.

7. Make results publicly available to create a database of buildings for all to use.

LCA cannot move forward as a standard inclusion in building design proposals until there is a larger body of work to which each new design can be compared. Clients will not understand the environmental impact of the building in question unless they understand the general range of impacts that a building type should generally have. The most important step toward improving the quality of building LCAs is creating a database of existing projects. The USGBC has a prime opportunity to lead the way in the creation of this database, by collecting projects that apply for LEED certification and creating a useful baseline for users of its own LCA credit tools (Yang 2011). But the goal could also be accomplished by the design community itself, if professionals were to work together to create a database of all projects modeled in LCA studies.

8. Highlight long-term cost savings to clients.

Clients do not currently appreciate the importance of LCA because it sometimes encourages higher up-front costs for long-term savings (such as energy efficiency and materials that last longer). Client opposition is a significant reason why LCAs have been slow to join the sustainability considerations of typical building projects. When an LCA is performed for a project, the potential long-term environmental savings need to be made explicit to the client to put short-term costs in perspective.

5. Conclusion

This thesis has focused on the problems and shortcomings inherent in LCA, with special attention paid to building LCAs and their use by the design community. It has found that the current body of work in building LCA has a great degree of variability because there are few agreed standards upon which to base the work. Design professionals and clients have an interest in making their buildings more sustainable, and LCA could be a valuable tool towards achieving lower-carbon buildings. Yet LCA is seen as a difficult method that cannot be employed efficiently by non-experts within the time frame of a building design project.

The strengths and weaknesses of the tools and resources available to practitioners today have been examined, highlighting the barriers that prevent building LCAs from being easier to perform and more transparent. An LCA pilot credit in the USGBC's LEED ratings system is still in its infancy, and has drawbacks that prevent it from being a useful calculator of a building's environmental impacts.

Eight key points, restated below, are proposed for improving the quality and transparency of building life cycle assessment projects:

1. Define a strict scope of work, including system boundary and functional unit.
2. Evaluate the quality of software databases with respect to other published values.
3. Make use of accepted shortcuts and rules of thumb so the LCA is as complete as possible in a short time frame.
4. Use CO_2e (GWP) as the main unit for communicating results.
5. Normalize results in terms of unit area.
6. Document every level of research and assumptions made.
7. Make results publicly available to create a database of buildings for all to use.
8. Highlight long-term cost savings to clients.

The points are based on the shortcomings seen among current practice, and backed up by the inclusion of a case study, which performs an LCA of a commercial building and compares the impact of two different structural materials. Data sources, assumptions, strengths, and weaknesses of the case study model are explained and documented throughout the report in order to make the study as transparent and repeatable as possible.

The study identifies the need for precedents to aid design professionals in performing robust LCAs, and suggests better dissemination of data and findings among the design community through the use of sustainability initiatives such as LEED. A baseline for design professionals to compare their own buildings LCAs is crucial to fostering better understanding of environmental impact reduction opportunities in buildings of the future.

6. Appendices

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B. Concrete Mixes and Documentation

Fly Ash Content	**%**	**10%**	**25%**	**50%**
Strength	*psi*	5000	--	--
Unit Weight	*lb/ft*^{3}	148	--	--
Cement	*lb/yd*^{3}	508	423	282
Fly Ash	*lb/yd*^{3}	56	131	282
Water	*lb/yd*^{3}	237	237	237
Coarse Aggregate	*lb/yd*^{3}	2000	2000	2000
Fine Aggregate	*lb/yd*^{3}	1200	1200	1200

Table 9: Concrete Mixes Based on Fly Ash Content

Standard concrete mixes vary by state specification. These mixes were taken from Marceau et al. (2007). Other sources that verify these approximate mix ratios are Low (2005) and USGS (2010). The decision to include fly ash was based on ACAA (2009) and USGS (2010), which suggest that the construction industry uses 8-10% fly ash in concrete mixes on average across the country.

The energy associated with crushing aggregate, which is assumed to come from diesel combustion, is an average of 53 MJ per ton of aggregate, with a 32% standard deviation (Zapata and Gambatese 2005). This corresponds to an emissions factor of 3.2E-3 lb CO_2e per pound of aggregate.

C. Transportation Distances

Material	Vendor	Distance in Miles
Aluminum	Alcoa Aluminum (Point Comfort, TX)	1202
Aluminum Window	Milgard (Aurora, IL)	48
Asphalt	IKO (Ashcroft, BC →Danville, IL → Kankakee, IL)	2379
Concrete	Ozinga (Chicago, IL)	10
Gravel	Joliet Sand & Gravel (Joliet, IL)	42
Gypsum	National Gypsum (Waukegan, IL)	43
Landfill	CID Landfill (Chicago, IL)	20
Paint	Benjamin Moore (Dallas, TX)	926
Sand	Joliet Sand & Gravel (Joliet, IL)	42
Steel, Doors	Goldy Locks (Tinley Park, IL)	27
Steel, Hot-rolled	Central Steel Fabrication (Chicago, IL)	10
Steel, Rebar	Central Steel Fabrication (Chicago, IL)	10
XPS	Owens Corning (Rockford, IL)	89

Table 10: Transportation Distances in Chicago

Material	Vendor	Distance in Miles
Aluminum	Alcoa Aluminum (Point Comfort, TX)	1136
Aluminum Window	Milgard (Phoenix, AZ)	10
Asphalt	Paramount Petroleum (Paramount, CA)	374
Concrete	Ready Mix, Inc (Tolleson, AZ)	12.5
Gravel	Pioneer Landscaping Materials (Gilbert, AZ)	22
Gypsum	National Gypsum (Phoenix, AZ)	10
Landfill	27th Avenue Solid Waste Management Facility	10
Paint	Benjamin Moore (Dallas, TX)	1068
Sand	Pioneer Landscaping Materials (Gilbert, AZ)	22
Steel, Doors	Steel Door (Tucson, AZ)	116
Steel, Hot-rolled	Schuff (Phoenix, AZ)	10
Steel, Rebar	Schuff (Phoenix, AZ)	10
XPS	Owens Corning (Rockford, IL)	1750

Table 11: Transportation Distances in Phoenix

D. Material Quantity Summaries

CONCRETE BUILDING				
Materials	*lbs*	*lbs/ft*^{2}	*kg*	*kg/m*^{2}
Metals				
Steel Rebar for Columns	253,929	0.5	115,180	2.4
Steel Rebar for Foundation	157,464	0.3	71,424	1.5
Steel Rebar for Deck Slabs	4,385,956	8.6	1,989,436	41.8
Steel Rebar for Retaining Wall	84,240	0.2	38,211	0.8
Steel Rebar for Elevator and Stair Cores	474,240	0.9	215,112	4.5
Steel Rebar for Foundation Footings	136,575	0.3	61,950	1.3
Steel Rebar for Stairs	32,893	0.1	14,920	0.3
Aluminum Window Frames	32,935	0.1	14,939	0.3
Aluminum Studs	15,941	0.0	7,231	0.2
Aluminum Cladding	174,654	0.3	79,222	1.7
Metal Doors	5,161	0.0	2,341	0.0
Cementitious Materials and Stone				
Concrete Columns	1,805,100	3.5	818,780	17.2
Concrete Deck Slabs	60,248,711	117.7	27,328,356	574.8
Concrete Foundation Slab	1,810,836	3.5	821,381	17.3
Concrete Retaining Wall	968,760	1.9	439,422	9.2
Concrete Footings	1,570,617	3.1	712,420	15.0
Concrete Elevator and Stair Cores	5,453,760	10.7	2,473,784	52.0
Concrete Stairs	378,268	0.7	171,579	3.6
Asphalt Roofing	58,119	0.1	26,362	0.6
Ballast Roofing	688,905	1.3	312,482	6.6
Gypsum Board	320,479	0.6	145,367	3.1
Insulations				
Extruded Polystyrene	132,822	0.3	60,247	1.3
Glazing				
Window Glass	320,918	0.6	145,566	3.1
Other				
Air/Vapor Barrier	7,032	0.0	3,190	0.1
Paint	21,153	0.0	9,595	0.2
Sand Foundation Layer	656,100	1.3	297,602	6.3
Gravel Foundation Layer	1,377,810	2.7	624,964	13.1

Table 12: Material Quantities for Concrete Building

STEEL BUILDING				
Materials	*lbs*	*lbs/ft*^{2}	*kg*	*kg/m*^{2}
Metals				
Steel Columns	1,727,022	3.4	783,364	16.5
Steel Beams and Girders	3,054,495	6.0	1,385,495	29.1
Steel Deck	1,796,369	3.5	814,819	17.1
Steel Rebar for Foundation	157,464	0.3	71,424	1.5
Steel Rebar for Deck Slabs	1,069,272	2.1	485,014	10.2
Steel Rebar for Retaining Wall	84,240	0.2	38,211	0.8
Steel Cores	2,737,140	5.3	1,241,546	26.1
Steel Rebar for Foundation Footings	136,575	0.3	61,950	1.3
Steel Rebar for Stairs	32,893	0.1	14,920	0.3
Steel Base Plates	345	0.0	156	0.0
Steel Connections	328,912	0.6	149,192	3.1
Aluminum Window Frames	32,935	0.1	14,939	0.3
Aluminum Studs	15,941	0.0	7,231	0.2
Aluminum Cladding	174,654	0.3	79,222	1.7
Metal Doors	5,161	0.0	2,341	0.0
Cementitious Materials and Stone				
Concrete Deck Slabs	22,774,730	44.5	10,330,444	217.3
Concrete Foundation Slab	1,810,836	3.5	821,381	17.3
Concrete Retaining Wall	968,760	1.9	439,422	9.2
Concrete Footings	1,570,617	3.1	712,420	15.0
Concrete Stairs	378,268	0.7	171,579	3.6
Asphalt Roofing	58,119	0.1	26,362	0.6
Gravel Ballast Roofing	688,905	1.3	312,482	6.6
Gypsum Board	320,479	0.6	145,367	3.1
Insulation				
Extruded Polystyrene	132,822	0.3	60,247	1.3
Glazing				
Window Glass	320,918	0.6	145,566	3.1
Other				
Fireproofing	1,274,136	2.5	577,938	12.2
Air/Vapor Barrier	7,032	0.0	3,190	0.1
Paint	21,153	0.0	9,595	0.2
Sand Foundation Layer	656,100	1.3	297,602	6.3

Table 13: Material Quantities in Steel Building

E. Additional Energy Model Design Details (based on Love 2011)

The DOE Large Office benchmark building was updated based on current codes and standards. The concrete building model created in EnergyPlus was slightly different than the LCA model designed for GaBi: the energy model includes 10”x10” reinforced concrete beams under the floor slabs, centered over the columns in both directions. The concrete system was modeled twice: one with “finishes”, meaning carpet and a drop ceiling, and once unfinished. This resulted in different roof systems: concrete decking with a drop ceiling, and an exposed concrete deck with no ceiling; but the insulation and roofing material are assumed to be the same for all cases. The steel building was also modeled with a drop ceiling. The reason these choices were made differently than in the building material inventory is because they can affect the energy use simulation.

Similarly, the internal floors are modeled in one of three ways: 1) as a composite metal deck and steel slab system with carpeting and a drop ceiling; 2) as a concrete deck with carpeting and a drop ceiling; and 3) as an exposed concrete deck with no floor or ceiling finish. Modeling all three buildings reveals the differences in energy use due to the structural material choice. All models used the conditioned area of the building, 498,584 square feet, which is smaller than the total area of 511,758 square feet.

Zone Name	People (m2/person)	Equipment (W/m2)	Lights (W/m2)	Infiltration (ACH)	Ventilation (L/s)	Domestic Hot Water (L/h)
Floor 12, Core	18.58	8.07	10.76	0	0.3/m2 + 2.5/person	80.6
Floor 12, Long	18.58	8.07	10.76	0.65	0.3/m2 + 2.5/person	0
Floor 12, Short	18.58	8.07	10.76	0.66	0.3/m2 + 2.5/person	0
Floors 1-11, Core	18.58	8.07	10.76	0	0.3/m2 + 2.5/person	80.6
Floors 1-11, Long	18.58	8.07	10.76	0.25	0.3/m2 + 2.5/person	0
Floors 1-11, Short	18.58	8.07	10.76	0.26	0.3/m2 + 2.5/person	0
Basement	37.16	4.84	10.76	0	0.3/m2 + 2.5/person	0

Table 14: Zone Load Summary in Energy Model. From Love (2011).

	Efficiency	**Source**
Cooling System Chiller (COP)	5.5	ASHRAE 90.1-2007
Heating System Boiler	0.8	ASHRAE 90.1-2007
Domestic Hot Water System Boiler	0.8	ASHRAE 90.1-2007
Floor 12 VAV Fan Efficiency	0.6045	DOE Reference Building
Floor 12 VAV Fan Pressure Rise (Pa)	1017.592	DOE Reference Building
Floors 2-11 VAV Fan Efficiency	0.6175	DOE Reference Building
Floors 2-11 VAV Fan Pressure Rise (Pa)	1017.592	DOE Reference Building
Floor 1 VAV Fan Efficiency	0.6045	DOE Reference Building
Floor 1 VAV Fan Pressure Rise (Pa)	1017.592	DOE Reference Building
Basement VAV Fan Efficiency	0.5915	DOE Reference Building
Basement VAV Fan Pressure Rise (Pa)	1109.648	DOE Reference Building

Table 15: HVAC Equipment Efficiencies and Reference Sources. From Love (2011).

A multi-zone variable-air-volume (VAV) system with a natural gas boiler and a water-cooled chiller is determined in the CBECS survey to be the most common HVAC system in large office buildings. The building is served by natural gas (for domestic hot water and the heating system boiler) and grid electricity (serving the chiller and other energy systems). As required by ASHRAE 90.1-2007, the cooling system has a differential dry-bulb economizer, which utilizes outside air for cooling when the outside air temperature is below the building's return air temperature. System sizes and flow rates are determined by EnergyPlus during simulation.

Because the thermal inertia of a building's structure affects the heat flow, and therefore temperature, of a space, the impact on energy usage will be seen in the HVAC system energy. Lighting and plug load equipment energy, however, charactericially constitute approximately half of an office building's energy usage. Because these loads remain unaffected by the thermal mass of a space, the influence the mass has on the energy usage is diminished by about half when the whole building results are examined. Because the heating system is served by natural gas, this further diminishes the significance of changes in the HVAC energy usage.

F. GaBi Process Data Sources

Process Name	Data Source	Year	Places Used in Model
Truck – flatbed, 34,000 lb payload	PE Int’l, US data	2008	Cement and aggregate transport
Diesel	PE Int’l, US data	2003	All land transport fuel
River freight ship	PE Int’l, global average	2005	Cement and aggregate transport
Aluminum ingot mix	European Aluminum Association (EAA)	2005	Studs; cladding
Aluminum extrusion profile	EAA	2005	Studs; cladding
General purpose polystyrene, at plant	National Renewable Energy Laboratory (NREL) US LCI database	2009	Extruded polystyrene;
Polyethylene film	PE Int’l, US data	2005	Vapor barrier
Gypsum board	PE Int’l, German data	2002	Interior walls; fireproofing
Fly ash	PE Int’l, German data	2007	Concrete mix
Portland cement	US Portland Cement Association	2007	Concrete mix
Water, deionized	PE Int’l, US data	2005	Concrete mix
Aggregate mining	PE Int’l, US data	2009	Aggregate production
Diesel, combusted in industrial equipment	NREL US LCI database	2009	Aggregate production
Steel rebar	Worldsteel, global average	2007	Rebar production
Steel section	Worldsteel, global average	2007	Steel structural member production
Emulsion paint, synthetic resin	PE Int’l, German data	2005	Paint
Cargo train	PE Int’l, global average	2005	Aggregate transport
Power grid mix	PE Int’l, US average	2002	Aggregate transport
Truck – tank, 50,000 lb payload	PE Int’l, US data	2008	Ready-mix concrete transport to site
Truck – trailer, 45,000 lb payload	PE Int’l, US data	2008	All land transport except concrete-related
Power grid mix – RFC region	PE Int’l, North American Electric Reliability Corporation data	2011	Power in Chicago buildings/mfg
Power grid mix – WECC region	PE Int’l, North American Electric Reliability Corporation data	2011	Power in Phoenix buildings/mfg
ECCS steel	Worldsteel, global average	2007	Steel doors
Gravel	PE Int’l, German data	2005	Roof; foundation
Bitumen, at refinery	NREL US LCI database	2009	Asphalt roofing
Silica sand	PE Int’l, US data	2005	Asphalt roofing; foundation
Lubricants at refinery	PE Int’l, US data	2003	Corrugated steel deck production
Compressed air, 7 bar	PE Int’l, global average	2002	Corrugated steel deck production

Steel sheet stamping and bending, 5% loss	PE Int’l, global average	2005	Corrugated steel deck production
Aluminum frame profile, thermically isolated, powder coated	PE Int’l, German data	2005	Window frames
Window glass	PE Int’l, German data	2010	Window panes
Thermal energy from natural gas	PE Int’l, US data	2002	Natural gas usage
Truck – dump, 52,000 lb payload	PE Int’l, US data	2008	Landfill transportation
Inert landfill – construction waste	PE Int’l, European average	2005	Landfilling of nonmetallic materials
Recycling credit	PE Int’l	2010	Credit for steel recycling
Global value of scrap	PE Int’l, global average	2010	Scrap value for steel recycling process
Aluminum recycling, including scrap preparation	EAA	2005	Aluminum recycling
Aluminum ingot mix	EAA	2005	Credit for aluminum recycling

Table 16: GaBi Processes Used and Their Sources.

G. NERC Electricity Mixes

	Chicago (RFC) (%)	Phoenix (WECC) (%)
Hard Coal	64.35	30.13
Natural Gas	6.54	31.38
Heavy Fuel Oil	0.54	0.42
Nuclear	26.45	9.61
Solid Biomass	0.70	1.18
Hydro	0.54	23.08
Other Renewable (wind, solar, geothermal)	0.14	3.77
Other Fossil	0.74	0.43

Table 17: NERC Electricity Mixes in Chicago and Phoenix. Source: US EIA 2000.

H. Embodied GWP Results Separated by Building Element

	STEEL lb CO$_2$e		**CONCRETE lb CO$_2$e**	
Material	**Chicago**	**Phoenix**	**Chicago**	**Phoenix**
Steel doors exterior	773	773	773	773
Steel doors interior	5027	5027	5027	5027
Rebar stairs	18560	18560	18560	18560
Deck roof	103534	103534		
Rebar roof			190370	190370
Rebar footing	77064	77064	77064	77064
Steel base plate	244	244	244	244
Rebar retaining wall	47534	47534	47534	47534
Steel beams	1472144	1472144		
Steel connections	228741	228741		
Steel columns	1224499	1224499		
Rebar columns			143281	143281
Steel girders	693561	693561		
Steel shear walls	1940693	1940693		
Rebar shear walls			267594	267594
Rebar sog	88851	88851	88851	88851
Rebar floors	603345	603345	2284439	2284439
Deck floors	1242399	1242399		
STEEL TOTAL	**7746968**	**7746968**	**3123737**	**3123737**
Concrete roof			276225	276225
Concrete columns			107587	107587
Concrete shear walls			325053	325053
Concrete stairs	22545	22545	22545	22545
Concrete footing	93611	93611	93611	93611
Concrete retaining wall	57740	57740	57740	57740
Concrete sog	107929	107929	107929	107929
Concrete floors	1357411	1357411	3314698	3314698
CONCRETE TOTAL	**1639236**	**1639236**	**4305387**	**4305387**
XPS cladding	73925	73925	73925	73925
XPS roof	41914	41914	41914	41914
XPS foundation	36880	36880	36880	36880
XPS TOTAL	**152719**	**152719**	**152719**	**152719**
OTHER TOTAL	**1718139**	**1722487**	**1523454**	**1536142**

Table 18: Embodied GWP Separated by Building Element.

I. GWP Results Summary

		Chicago Concrete		Chicago Steel		Phoenix Concrete		Phoenix Steel	
		lbs CO_2e	*lbs CO_2e/ft^2*	*lbs CO_2e*	*lbs CO_2e/ft^2*	*lbs CO_2e*	*lbs CO_2e/ft^2*	*lbs CO_2e*	*lbs CO_2e/ft^2*
Pre-Use	Concrete	9491754	18.6	3613898	7.1	9491754	18.6	3613898	7.1
	Steel	6886661	13.5	17079142	33.4	6886661	13.5	17079142	33.4
	XPS	336688	0.7	336688	0.7	336688	0.7	336688	0.7
	Other	3358641	6.6	3787849	7.4	3386613	6.6	3797434	7.4
Use	Maint.	3123910	6.1	3123910	6.1	3080263	6.0	3080263	6.0
	Op. Energy	491282073	960	501237267	979	371340902	726	379464848	741
End-of-Life	End-of-Life	-1689208	-3.3	-6478349	-12.7	-1700848	-3.3	-6522760	-12.7
	Total	512790519	1002	522700405	1021	392822033	768	400849513	783

Table 19: GWP Results Summary in IP Units.

		Chicago Concrete		Chicago Steel		Phoenix Concrete		Phoenix Steel	
		kg CO_2e	*kg CO_2e/m^2*	*kg CO_2e*	*kg CO_2e/m^2*	*kg CO_2e*	*kg CO_2e/m^2*	*kg CO_2e*	*kg CO_2e/m^2*
Pre-Use	Concrete	4305387	90.6	1639236	34.5	4305387	90.6	1639236	34.5
	Steel	3123737	65.7	7746968	162.9	3123737	65.7	7746968	162.9
	XPS	152719	3.2	152719	3.2	152719	3.2	152719	3.2
	Other	1523454	32.0	1718139	36.1	1536142	32.3	1722487	36.2
Use	Maint.	1416982	29.8	1416982	29.8	1397184	29.4	1,397,184	29.4
	Op. Energy	222841800	4687	227357400	4782	168437400	3543	172122360	3620
End-of-Life	End-of-Life	-766212	-16.1	-2938529	-61.8	-771492	-16.2	-2958674	-62.2
	Total	232597867	4892	237092915	4987	178181077	3748	181822280	3824

Table 20: GWP Results Summary in SI Units.