Life Cycle Assessment of Materials and Construction in Commercial Structures: Variability and Limitations

by

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Submitted to the Department of Civil and Environmental Engineering on May 7, 2010 in partial fulfillment of the requirements for the Degree of Master of Engineering in Civil and Environmental Engineering

Abstract

Life cycle assessment has become an important tool for determining the environmental impact of materials and products. It is also useful in analyzing the impact a structure has over the course of its life cycle. The International Organization of Standardization’s 14040 series specifies how to perform a formal life cycle assessment in which the materials, construction, use, and demolition of a building are quantified into embodied energy and carbon dioxide equivalents, along with representation of resource consumption and released emissions. These results are useful to architects, structural engineers, contractors, and owners interested in predicting environmental impacts throughout a structure’s life.

Although many life cycle assessments have already been performed on various types of structures, most have occurred outside the United States. The life cycles of American buildings must be better understood before their environmental impact can be reduced. Regional variations also must be taken into account. Most existing studies have a variety of focuses, which makes them difficult to compare to one another, and they do not examine a wide enough range of buildings.

This thesis quantifies the variability of building life cycle assessments by examining existing studies’ differences and comparing them to a new study conducted using GaBi software. The new model assesses the carbon dioxide equivalents of one ton of structural steel, in three different forms, and one ton of reinforced concrete, in three different mixes. Impact assessment is performed using two widely accepted methods. The results from this thesis can be used to standardize and improve the study of typical commercial structures across different regions of the United States.

Thesis Supervisor: John Ochsendorf
Title: Associate Professor, Civil and Environmental Engineering and Architecture
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Love to Michael, for proofreading and everything else.
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1. Introduction

1.1 The Concept of Life Cycle Assessment

In a world where resources are becoming scarce and societies are realizing that the
conveniences of modern life have a serious impact on the environment, it is becoming more important
to analyze engineering designs and find ways to reduce humankind’s environmental burden. Life cycle
assessment, or LCA, has become an accepted tool for performing these analyses and answering
important questions about current topics of concern to the public, such as greenhouse gas emissions.

Given its official name in 1991, life cycle assessment examines the full spectrum of processes
associated with a product from the beginning to the end of its life (Baumann and Tillman 43). The
International Organization for Standardization (ISO) defines the life cycle of a product as including “raw
material extraction and acquisition, through energy and material production and manufacturing, to use
and end of life treatment and final disposal” (ISO 14040:2006 6). The assessment includes examination
of the inflows and outflows associated with a product throughout these steps (13). Inflows include the
resources needed to make and transport the product, while outflows include the emissions and waste
the product creates throughout its life (Baumann and Tillman 19). These flows are organized into the
aforementioned series of phases in a product’s life cycle (Figure 1).

LCA grew out of separate studies and movements in many parts of the world, including the methods of “ecobalances” and “environmental profiles” (Baumann and Tillman 43). Although it was not called an LCA at the time, one of the first such projects involved a study of life cycle impacts for Coca-Cola products in 1969 (44). Other methodologies for measuring environmental impacts still exist, which often have different goals than LCA. These include the “ecological rucksack” method popular in Germany, which measures the environmental impact of a product according to the mass of all the material inflows it requires in its lifetime minus the weight of the product itself (“Was ist Ökologie?”). LCA, however, is a more comprehensive tool that gives information about many aspects of a product’s impact on the environment, not just its material inflows.

Figure 2 shows the procedure for performing a full LCA according to ISO 14040 and 14044:2006. LCA is not just about collecting data, it is also about interpreting that data. Researchers may choose to elaborate on certain aspects of a product’s environmental impact, such as its emissions, its energy consumption, or the raw materials used to manufacture it. How researchers choose to assess their results is based on what type of LCA they wish to perform. There are three broad categories of LCAs:

- **Stand-alone LCAs** are used to better understand a single product and point out any areas of its life cycle that have an especially large environmental impact.
- **Accounting LCAs** compare more than one product. These studies may be used to understand which product is the best choice, or which products are not up to speed. They are also used for eco-labeling to help the public understand what kind of consumer choices they are making.
- **Change-oriented LCAs** are performed with the goal of reducing a product’s (or multiple products’) environmental impact. Not only is an initial LCA of an existing product performed, but alternative options are tested to see how they affect the product’s environmental impact for better or worse (Baumann and Tillman 63).

LCA may be performed by industry, government policymakers, or private research operations for a variety of purposes. It can be applied to virtually any product, material, or structure imaginable. Depending on where boundaries are drawn and what the researcher’s ultimate goals are, significant gaps or manipulations in a product’s life cycle may be found in the LCA, and the variability between separate LCAs of similar products can be astonishing. Details of LCA methodology follow in Chapter 2.
1.2 LCA and Structures

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 that goes into concrete (Figure 3). Despite the fact that material consumption has grown much faster in the rest of the world than in the United States, the US 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 were considered renewable (Matos and Wagner 110). The Worldwatch Institute estimates that world building construction is responsible for 40% of the stone, sand, and gravel, 40% of the energy, and 16% of the water used globally in 1999. Buildings consume half of the European Union’s the total energy and emit half its annual carbon dioxide production throughout their life cycles (Dimoudi and Tompa 86). Although steel is a largely recyclable resource, it comes with high energy requirements. Construction materials such as concrete are more difficult to recycle, and as essentially nonrenewable resources they contribute more to total material consumption (Matos and Wagner 110, 113).
Because of numerous innovations reducing energy use during the operational phase of a building, the embodied energy due to a building’s materials and construction is becoming a larger percentage of a building’s total energy over its lifetime (Dimoudi and Tompa 86). Therefore, it is essential to investigate the embodied energy of structures and determine ways to reduce this energy in the same way operational energy has already been reduced. This could be accomplished by changing the structural system of the building to use different or fewer construction materials. Life cycle assessment is an essential tool to help civil and structural engineers understand how they can contribute to lowering the embodied energy of any structure. The potential for paradigm shifts in structural design due to the lessons learned from LCA could be significant.

LCA studies tend to focus either on residential structures or commercial structures. Because these two types of structure have different structural designs and energy consumption, it is important to study both separately; and because concrete and steel, along with timber, are the most heavily used structural materials, especially in commercial buildings, there is a great deal of dispute among researchers regarding which of these materials is more environmentally friendly (Carroll et al, Panarese, Weisenberger, and Worrell et al, to name a few). The steel and concrete industries both campaign for the acceptance of their materials as the more sustainable choice, yet their research into this matter is not necessarily objective. A look at the range of studies performed on structures so far reveals biases, discrepancies in data, and inexplicable results. The numbers are even less credible for commercial
structures because very few comparable studies have actually been performed. The question of concrete versus steel in commercial buildings requires more extensive, third-party research before it can be definitively answered.

1.3 Problem Statement

Research on commercial structures has been spread out across the globe. Few existing studies assess buildings in the United States and Canada, and these studies have chosen to emphasize different units and results, as will be shown in Section 3. Because data from other countries is not relevant to North American structures, the study of commercial structures in North America requires expansion before conclusions can be made about embodied and operational energy in these buildings.

The purpose of this study is to assess the variability of life cycle assessments for commercial buildings, accomplished in two ways. First, an assessment of existing studies illuminates the differences between the approaches used by researchers so far, and identifies areas for improvement. Second, the creation of a model in current software, which analyzes different types of concrete and steel as raw materials, gives an example of variability in one isolated step of building life cycles and weighs the conclusions against the limitations of the software. Goals for future study are recommended, emphasizing how variability may be reduced in LCAs of commercial structures over their complete life cycles that include material production, construction, use, maintenance, and end-of-life phases.
2. Literature Review of LCAs and Their Variability

2.1 Steps in a Formal Life Cycle Assessment

The following steps in a formal life cycle assessment are outlined in ISO 14040:2006 and ISO 14044:2006. A description of the methodology is given in order to outline appropriate usage of LCA for the built environment.

2.1.1 Goal and Scope

The goal of a life cycle assessment is dependent on the type of LCA being performed, as described in Section 1.1 (Baumann and Tillman 24). The researcher might wish to know which structure has less of an environmental impact than its counterparts, or how a structure might be improved to lower its impact. A goal should also describe the study’s intended audience, whether it be a client from a company, a government creating regulations, or the general public (ISO 14040:2006 11).

Central to the scope is the definition of a functional unit, which is the unit being analyzed throughout the steps of the LCA and to which all inflow and outflow quantities are adjusted (ISO 14040:2006 12). If two or more items are being compared, their functional units must be the same (Baumann and Tillman 76).

For example, if a study compares two or more structures to each other, then the functional unit might be defined as a single-family, 2,000-square-foot home in Boston, Massachusetts. It would not make sense to analyze one home in Boston and another in San Francisco, because the building materials and fuel costs to transport those materials would be different in each city. It also would not make sense to perform an accounting LCA of one 2,000 ft² home and one 2,000 ft² office building, because those buildings have different uses. It would be misleading to conclude that an office building is “worse” than a home of the same size because it has higher energy consumption, because there are reasons for that energy use based on the structure’s purpose. It might be acceptable and useful to perform stand-alone LCAs of both structures, but it is unacceptable to compare them to one another as equals.

Research into the life cycle of a product can involve thousands of individual flows. Depending on the goal, scope, and time frame of the project, a researcher might not have time to include every single flow at such a minute level of detail, or might be interested only in specific phases of the life cycle, so boundaries must be defined (ISO 14040:2006 12). A study of concrete’s manufacturing process may or may not include resources for capital such as a machine that makes the cement. It also may or may not include data on how byproducts are recycled for other purposes, an issue known as allocation that could reduce or increase the concrete’s environmental impact (4).
2.1.2 Inventory Analysis

Inventory analysis encompasses the collection and modeling of data. Data is formed into a flowchart model of processes, which are comprised of individual inflows and outflows (Baumann and Tillman 26). The flows are scaled to the model’s functional unit for every process based on available data. The data quality is entirely dependent on available information about the product, so data should be cross-checked between more than one source to make sure it is reliable (ISO 14040:2006 13). At the end of the inventory analysis, the researcher should have numbers representing the total amounts of emissions, waste, energy consumed, and resources used throughout the entire flowchart (Baumann and Tillman 26).

Although there are specific calculation procedures for performing an LCA inventory analysis by hand, these procedures have been mostly superseded by computer software. Programs such as SimaPro (www.pre.nl/simapro) and GaBi (www.gabi-software.com), both developed in Europe, allow users to create an inventory using information collected by the user or taken from databases included in the software. Typical databases include those developed by the software companies, as well as databases like Ecoinvent which have been compiled from years of data collected by research companies or governments. A major shortcoming is that most are centered on European information. LCA, while extremely popular in Europe, has not caught on as quickly in North America, so users must perform more of their own data collection or substitute European values where necessary (Johnson 64).

2.1.3 Impact Assessment

In LCA, it is not sufficient to simply assemble an inventory model and obtain some numbers from a computer program. The next step is to study the impact of these numbers by transforming them into the effect they have on the environment. Impact assessment makes the results of an LCA easier to communicate and comprehend. It also separates out important information from the vast array of results that a program is capable of producing, condensing it into a selection of “environmental impact categories” (ISO 14040:2006 14). Categories are generally divided among the three broad topics of resource use, human health, and ecological consequences (Baumann and Tillman 131).

ISO 14040:2006 offers general methods for performing impact assessment so that the researcher does not have to develop his or her own methods every time. The steps in a formal impact assessment include:

- Selection of desired impact categories.
- Classification of inventory results in the appropriate impact categories.
- Characterization of impact in each category using calculations.
• Optional analysis such as *weighting* of impacts in different categories, so that they can be compared to one another, and *normalization* of the data, showing how it relates to reference values (15).

In choosing impact categories, one should make sure they represent a complete picture of the product’s environmental impact, while not becoming bogged down in too many details. Often, impact assessment presents an opportunity to study the impact on aspects of the life cycle which could not be included in the inventory, such as land use or toxicity to humans (ISO 14044:2006 17).

Weighting is often the most subjective portion of a complete life cycle assessment. Because impact categories are being compared to one another, and importance is assigned based on factors chosen by the researcher, it is easy to manipulate the process to downplay certain impact categories or favor one product if an accounting LCA is being performed (Baumann and Tillman 132, 143). It is important to be transparent about the choices made in weighting so that the audience can understand “the full extent and ramifications of the results” (ISO 14044:2006 22).

### 2.1.4 Interpretation

LCA involves iteration of the defined steps. Interpretation is necessary to identify the most important aspects of the impact assessment, check the validity of the results, redo aspects of the LCA that need more work, and communicate conclusions and recommendations in appropriate ways (ISO 14040:2006 16). It is important to both compare results to previous studies and improve the quality of the current study. Interpretation also brings up the problem of variability in life cycle assessments, a major shortcoming of the process described in further detail below.

### 2.2 LCA’s Weak Points

Like any scientific process, life cycle assessment is not immune to human interests. As mentioned above, the scope of an LCA is subject to a great deal of interpretation. System boundaries can be adjusted to include or exclude key processes or flows, and two LCAs of the same product may produce drastically different results. Impact assessment can be manipulated to highlight certain impact categories and downplay others. Depending on the goals of the researcher and the client, an LCA may be tailored to produce results which will put the client’s product in a favorable light (Baumann and Tillman 34). LCA should be a strict scientific process that produces similar results in similar situations, but the reality is that a researcher can produce virtually any result desired with enough manipulation of the numbers.
2.2.1 LCA and Sustainability

Environmental, economic, and social concerns are often described as the “triple bottom line” of sustainability and sustainable development (Hacking and Guthrie 77) (Figure 4). Any attempt toward true improvement in sustainability must consider all three pillars, not just one or two. LCA deals mainly with the environmental aspect of a product’s impact, and it is difficult or impossible to incorporate economic and social concerns in most cases (ISO 14040:2006 vi). While cost can sometimes be quantified in impact assessment, it is not normally part of a life cycle inventory. Social issues are extremely broad and usually too qualitative to put in an LCA model; only those factors that can be quantified, such as a carcinogenic emission’s impact on human cancer rates, can be considered in impact assessment. Therefore, LCA presents only a partial picture of how a product may impact sustainability concerns from a truly holistic viewpoint.

2.2.2 Variability

Because LCA models are so dependent on data quality, and because researchers can interpret their life cycle assessments however they wish, variability is a problem hindering acceptance of LCA as an objective practice. As will be seen in Section 3, LCAs about the same products or materials can have wildly different results. Because of this problem, it is important to critically review LCAs so that their results can be assessed in comparison to one another. There are several analysis tools that can be used to assess the validity of a single LCA and the variability of multiple LCAs about the same subject.

Dominance analysis is used to identify the phases of the life cycle that have the most environmental impact (Baumann and Tillman 189). For example, instead of reporting the carbon dioxide emissions for the total life cycle, a researcher might choose to compare carbon dioxide emissions of
different processes and highlight the process with the highest global warming potential. A contribution analysis is used to compare environmental loads to one another (191). The relative impact of carbon dioxide and sulfur dioxide might be compared based on the functional unit, to identify which emission category needs the most attention.

An uncertainty analysis factors in the range of data that was found for a certain flow or process, showing how the results might change across the range. This is important because an LCA model allows only for the use of single data points at a time, and uncertainty analysis provides a way to incorporate data from other sources that should be considered (ISO 14040:2006 5). Conversely, sensitivity analysis is used when only one value is available for a flow or process, and a possible range of other values needs to be explored to judge the impact of these values (ISO 14044:2006 22).

When several LCAs are under scrutiny, sensitivity and uncertainty analysis can be used to quantify and visualize the differences between the studies and the reasons for these differences. Such tools are vital to eliminating the weak aspects of LCA models and creating more useful models in the future.
3. Assessment of Existing Studies

3.1 Introduction

Performing life cycle assessments of construction materials is not a new concept. Because materials such as concrete and steel are used in such massive quantities, as described above, their environmental impacts have long been a subject of interest. As far as commercial structures are concerned, however, research has been scattered and not always useful.

What follows is a brief examination of seven prominent life cycle assessments performed on steel, concrete, and their application in commercial buildings. Although most of the studies address the use and maintenance phases of a building, analysis of these sections is not included in the review because the focus of this study is on structure and construction. The papers, summarized in Table 1, have been chosen to represent a wide variety of goals and hypotheses, and this lack of continuity must be considered when analyzing their usefulness to a researcher who has a specific functional unit and scope in mind. They are being examined in order to determine how the research of building life cycles can be standardized and improved in future studies.

<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
<th>Year</th>
<th>Journal</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eaton, K.J., and A. Amato</td>
<td>A Comparative LCA of Steel and Concrete Framed Office Buildings</td>
<td>1998</td>
<td>Journal of Constructional Steel Research</td>
<td>Five 4- and 8-story buildings</td>
</tr>
<tr>
<td>Junnila, Seppa, and Arpad Horvath</td>
<td>Life-Cycle Environmental Effects of an Office Building</td>
<td>2003</td>
<td>Journal of Infrastructure Systems</td>
<td>One 5-story, 15,600 m² building</td>
</tr>
<tr>
<td>Guggemos, Angela Acree, and Arpad Horvath</td>
<td>Comparison of Environmental Effects of Steel- and Concrete-Framed Buildings</td>
<td>2005</td>
<td>Journal of Infrastructure Systems</td>
<td>Two 5-story, 4400 m² buildings</td>
</tr>
<tr>
<td>Kofoworola, Oyeshola F., and Shabbir H. Gheewala</td>
<td>Life Cycle Energy Assessment of a Typical Office Building in Thailand</td>
<td>2009</td>
<td>Energy and Buildings</td>
<td>One 38-story, 60,000 m² building</td>
</tr>
<tr>
<td>Jönsson, Asa, Thomas Björklund, and Anne-Marie Tillman</td>
<td>LCA of Concrete and Steel Building Frames</td>
<td>1998</td>
<td>International Journal of LCA</td>
<td>Seven buildings, size unspecified</td>
</tr>
<tr>
<td>Johnson, Timothy Werner</td>
<td>Comparison of Environmental Impacts of Steel and Concrete as Building Materials</td>
<td>2006</td>
<td>N/A (MIT Thesis)</td>
<td>Two 100,000 ft² buildings, stories unspecified</td>
</tr>
</tbody>
</table>

Table 1: Summary of Reviewed Studies.
3.2 Studies

3.2.1 Eaton & Amato (1998)

Researchers at the Steel Construction Institute in the United Kingdom have produced a comprehensive life cycle assessment of steel and concrete office buildings. In this study focusing on the structural frames of typical buildings, the researchers analyzed their construction and operational phases, with attention given to the possibility of recycling the materials afterwards. Not only were both four- and eight-story buildings assessed for a 60-year lifespan, but each building was studied using five different structural systems, and there were also variations in the mechanical and HVAC systems investigated. Construction and demolition were omitted because of a lack of available data, and transportation emissions were calculated using UK averages.

A number of conclusions and suggestions for future study are made. The assessment shows that it is possible to include both embodied and operational energy and/or CO2 of a building in a single LCA model, paving the way for future similar studies. Surprisingly, there is very little difference in emissions between steel and concrete framing in either building type, and the 8-story building, which uses a more complicated building design, has less embodied energy than the more basic 4-story building. Considering three steel and two concrete frame types, the embodied energy varies between just 2.5 and 2.9 GJ/m² for the 4-story building (Table 2). The embodied energy of the rest of the construction (HVAC, façade, etc.) is approximately 2.5 times that of the structural frame’s embodied energy, and the total life cycle energy including use is 10-15 times higher than initial embodied energy for these buildings (Table 3). Operational energy consumption overtakes embodied energy at anywhere from 4 to 11 years after building construction, depending on the ventilation systems used.

<table>
<thead>
<tr>
<th>Type of structural system</th>
<th>Embodied energy (GJ/m²)</th>
<th>Embodied CO2 (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel frame, Slimfloor beams, with precast concrete slabs</td>
<td>2.6</td>
<td>251</td>
</tr>
<tr>
<td>Steel frame, composite beams and slabs</td>
<td>2.6</td>
<td>241</td>
</tr>
<tr>
<td>In-situ reinforced concrete frame and slabs</td>
<td>2.5</td>
<td>286</td>
</tr>
<tr>
<td>Steel frame, cellular beams, and composite slabs</td>
<td>2.9</td>
<td>259</td>
</tr>
<tr>
<td>Concrete frame, precast concrete hollow core units</td>
<td>2.7</td>
<td>333</td>
</tr>
</tbody>
</table>

Table 2: Variation of embodied energy and carbon dioxide in 4-story structural systems. Source: Eaton and Amato.
<table>
<thead>
<tr>
<th>Contribution</th>
<th>Energy (GJ/m²)</th>
<th>CO₂ (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial embodied energy and CO₂ in the structural frame, floors, and foundations</td>
<td>2.6</td>
<td>241</td>
</tr>
<tr>
<td>Initial embodied energy and CO₂ in the rest of the structure</td>
<td>6.3</td>
<td>482</td>
</tr>
<tr>
<td>Other lifetime additions to embodied energy and CO₂ (refurbishment, etc.)</td>
<td>14.6</td>
<td>1091</td>
</tr>
<tr>
<td>Operational energy and CO₂ – lights and small power</td>
<td>33.6</td>
<td>2295</td>
</tr>
<tr>
<td>Operational energy and CO₂ – heating and ventilation</td>
<td>36.0</td>
<td>2239</td>
</tr>
</tbody>
</table>

Table 3: Energy figures for steel-framed building with composite beams and slabs. Source: Eaton and Amato.

The researchers stress that while concrete frames have slightly higher overall CO₂ emissions than steel frames, the variations found in the study are insignificant. Both steel and concrete frames perform up to UK standards for good building practice, and the supposed operational benefits of concrete construction due to its thermal properties do not appear to make a difference in the full LCA. Granted, the researchers have performed the study in order to “dispel myths that steel is not an environmentally friendly construction material,” and quantitative suggestions for reducing the energy of steel or concrete are not discussed. The main point they wish to make is that the embodied and operational energies of buildings can be further compared and reduced using LCA models.

Although minor aspects of the building’s life cycle are left out, such as construction and disposal, this is the case with many LCAs. Data simply is not available for many details of the life cycle process. One might think that these details add up to create a significant gap in the model, but because they are common to so many different models, they are often collectively ignored because of their insignificant energy contributions.

This study excels at providing information in useful units of measurement. Embodied and operational energy consumption in the hypothetical office buildings is reported in either energy units of GJ/m² or carbon dioxide units of kg/m². Reporting energy consumption and greenhouse gas emissions using a unit of area (square feet, square meters, etc.) is especially useful for construction applications; it allows the reader to instantly understand the environmental impact of any building or structure, regardless of its size, and buildings of different sizes can be compared using the same metric.

3.2.2 Junnila and Horvath (2003)

These researchers from Finland and the United States published a life-cycle analysis of an office building in Finland. Their brief history of life-cycle assessment of buildings makes several apt comments about the state of LCA: “...it is still very difficult to find comprehensive information about the life-cycle
aspects of offices.” Residential buildings have been better-documented, and more information is needed about various types of office buildings. Additionally, “Building systems (structural, HVAC, electricity usage, and lighting) are rarely included [in LCAs], despite the fact that in practice most of the buildings are designed by building systems....”

This LCA is of a single office building, so it does not involve comparison between two different types of structures. The structure consisted of three five-story sections that were all framed in cast-in-place concrete. The complex had a 50-year lifespan and an area of 15,600 square meters. The researchers were in a unique position to collect data about the material input and output flows in real time as the building was designed and constructed. They also gathered data from Finnish industry about emissions, which lacked only a few minor areas of data.

Life cycle assessment was performed in five phases corresponding to the most important stages of the building’s life: building materials, construction, use, maintenance, and demolition. The model is by far the most comprehensive available on a single office building, including transportation between all phases. The phases were analyzed for their impact on five chemical equivalents that contribute to environmental impact: climate change due to carbon dioxide, acidification due to sulfur dioxide (SO₂), smog creation (H₂C₄), eutrophication due to phosphate (PO₄), and heavy metals represented by lead (Pb) (Table 4). The table is further broken down into a two-page list detailing the contribution of each step in the construction, use, and disposal phases. For example, steel contributes to the most tons of CO₂, kg of H₂C₄, and kg of Pb, while the concrete frame contributes to the most kg of SO₂ and PO₄. It can also be deduced that the concrete for the frame makes up 65% of the total transportation weight for construction.

<table>
<thead>
<tr>
<th>Aspect of building</th>
<th>Tons CO₂</th>
<th>kg SO₂</th>
<th>kg H₂C₄</th>
<th>kg PO₄</th>
<th>kg Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building materials</td>
<td>4,800</td>
<td>19,000</td>
<td>7,600</td>
<td>1,900</td>
<td>7.4</td>
</tr>
<tr>
<td>Construction</td>
<td>820</td>
<td>5,800</td>
<td>530</td>
<td>960</td>
<td>0.3</td>
</tr>
<tr>
<td>Electrical service</td>
<td>25,000</td>
<td>59,000</td>
<td>4,900</td>
<td>5,500</td>
<td>3.8</td>
</tr>
<tr>
<td>Heating service</td>
<td>11,000</td>
<td>25,000</td>
<td>2,400</td>
<td>2,300</td>
<td>1.2</td>
</tr>
<tr>
<td>Other services</td>
<td>3,900</td>
<td>11,000</td>
<td>2,600</td>
<td>4,000</td>
<td>0</td>
</tr>
<tr>
<td>Maintenance</td>
<td>1,600</td>
<td>8,400</td>
<td>5,700</td>
<td>850</td>
<td>2.1</td>
</tr>
<tr>
<td>Demolition</td>
<td>440</td>
<td>4,400</td>
<td>680</td>
<td>720</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>48,000</strong></td>
<td><strong>130,000</strong></td>
<td><strong>24,000</strong></td>
<td><strong>16,000</strong></td>
<td><strong>15.0</strong></td>
</tr>
</tbody>
</table>

Table 4: Environmental Impacts of Office Building with 50 Years of Service Life.
Source: Junnila and Horvath.

This study is an excellent example of what an LCA of a building should be. Data is explained and represented in several different ways to explain how units and phases can affect the numbers. The
results are broken up into building components, such as structural, HVAC, and electrical, so that the impact due to the structural system can be easily deduced. In this case, the structural system contributed to climate change, smog, and heavy metal impacts more than any other component.

The authors acknowledge that not much can be accomplished with the results from an LCA of just one building. Multiple building studies could allow a sensitivity analysis to see which components of the model vary the most from structure to structure. And because this building is in Finland, it cannot represent typical office buildings in North America. But the comprehensive tables created from the results could serve as a “checklist” for future LCAs or actual building projects. The data can also be trusted because it was completed during the building’s construction using firsthand reports, not after the fact when data may be less available or reliable.

### 3.2.3 Guggemos and Horvath (2005)

Arpad Horvath also collaborated with Angela Guggemos two years after the Finland study to perform LCAs of concrete and steel office buildings in the United States. Five-story office buildings with an area of 4400 m² were compared using steel and concrete frames at a hypothetical location in the Midwestern United States. Detailed flow charts were constructed to model the construction process for each frame type. A full building model was constructed, not just a structural frame. Transportation distances were assumed for that specific region, so as to model a typical Midwestern building as closely as possible.

The model was analyzed twice, once with respect to the full life cycle and once on the construction phase only. These two analyses are considerably different. Steel and concrete frames have results which are almost exactly the same for their full life cycles in terms of energy and several types of emissions (PM₁₀ refers to particulate matter) (Table 5). Concrete emitted slightly more mono-nitrogen oxides (NOₓ), while steel emitted slightly more carbon monoxide and sulfur dioxide. Other emissions, most importantly carbon dioxide, were more or less equal for both. But concrete releases more emissions in the construction phase than steel (Figure 5: Steel vs. Concrete Frame Construction Phase Inventories). Figure 5).

<table>
<thead>
<tr>
<th>Structure</th>
<th>Energy (10 TJ)</th>
<th>CO₂ (Gg)</th>
<th>CO (Mg)</th>
<th>NOₓ (Mg)</th>
<th>PM₁₀ (Mg)</th>
<th>SO₂ (Mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel-frame building</td>
<td>36</td>
<td>26</td>
<td>38</td>
<td>72</td>
<td>9</td>
<td>100</td>
</tr>
<tr>
<td>Concrete-frame building</td>
<td>36</td>
<td>26</td>
<td>34</td>
<td>76</td>
<td>9</td>
<td>98</td>
</tr>
</tbody>
</table>

Table 5: Summary of Life Cycle Inventories.
Source: Guggemos and Horvath.
The authors also depict energy use at different stages of the life cycle, so that the relative impact of these phases can be compared to one another (Figure 6). However, the use phase of the building is not included, which is a major shortcoming because it is important to know how the materials and construction phases compare to the use phase. Although it was not investigated, there are clearly other aspects of the building’s life cycle where steel causes more emissions than concrete. So while it is understood that concrete frames are more damaging to the environment due only to the material production, construction, and end-of-life phases, it is impossible to make a clear conclusion from this study about which material creates a more environmentally harmful building over its 50-year lifespan.

A typical Midwestern office building obviously differs from a building in California, Massachusetts, or Hawaii. For a comprehensive study of office building energy use and emissions to be credible, these regional differences must be taken into account. Temperature and transportation
distances are two of the most important factors that vary from region to region. This study is only so useful for someone assessing a building in a different region of the country, and a better study would compare buildings using a handful of regional variations.

The authors compare their model to a similar Swedish study done in 1996 by Björklund et al. The Swedish numbers for a building’s embodied energy are considerably smaller than the US buildings’ embodied energy, and Björklund also found that concrete had more emissions than steel frames overall. While the Swedish study is older and there are probably inconsistencies in the data, the comparison illustrates how different United States studies can be from those in other parts of the world due to different practices and policies. The data from international studies included in this literature review cannot be assumed for further North American study.

3.2.4 Kofoworola and Gheewala (2009)

This study focused on a recently erected 38-story, concrete-framed office building in Bangkok, Thailand. Instead of performing a traditional LCA, the researchers completed a life cycle energy analysis (LCEA), which focuses purely on energy use rather than emissions and other aspects of a full LCA model. The purpose of the study was to encourage updates to the Thai building code regarding energy use, and most of the paper focused on how energy can be reduced during the building’s operational phase. However, the researchers also acknowledged that the embodied energy of the building after construction is second only to operational energy, and there are ways to reduce this embodied energy as well.

The data used for this study was Thailand-specific. Embodied energy of various building materials was obtained from databases maintained by the Thai government. Energy use data contained some quirks that would not be found in an American building, such as the fact that Thai citizens are accustomed to a higher building temperature than a typical American, and thus do not require as much air conditioning to be comfortable. An EIO-LCA methodology was used to obtain building material data, while process-based LCA methodologies were used for all other phases of the building’s 50-year lifespan. The energy consumption according to phases in the building’s life cycle is represented by a pie chart (Figure 7). “Manufacture” refers to the production and transportation of the raw materials, while “construction” refers to the assembly of the materials on site.
Total embodied energy for the building was found to be 375 terajoules, corresponding to approximately 6.8 GJ/m². Approximately 78% of this energy originated from the concrete and steel building materials (Figure 8), and this embodied energy corresponded to about 15% of the building’s operational energy over its projected lifetime. The embodied energy values computed in the study closely matched those of existing governmental data, and previous energy studies estimate a building’s embodied energy per square meter as ranging from 3.4-19.0 GJ/m². The researchers attributed the building’s high embodied energy to the large quantities of material required to construct a reinforced concrete frame. Although it is not stated explicitly, a steel-framed structure would presumably use less material and have a lower embodied energy.
could reduce the building’s embodied energy by 8.9%, corresponding to a total life cycle energy reduction of about 1.5%. This figure could be even higher if measures were taken to recycle the concrete as well. Current practices in Thailand dictate that concrete rubble be dumped in a landfill, but this rubble could be used in roads and other infrastructure. It was found that 9.2 GJ of energy could be saved if the rubble from this particular building were used as aggregate somewhere else, eliminating the need to produce new aggregate.

This paper represents an in-depth study of a building’s total energy use over its life, but it is not comprehensive enough because it does not examine greenhouse gas emissions or other environmental impacts. It also analyzes a single building that is not necessarily representative of all office buildings in its region.

3.2.5 Jönsson, Björklund, and Tillman (1998)

Researchers in Sweden performed a full LCA, according to ISO guidelines, on seven hypothetical building frame types. According to the authors, “...the need to create systems models above the building material level to assess the environmental consequences of using alternative building elements and frame structures is generally recognized.” Additionally, past research that they investigated indicated that there was no significant difference between concrete and steel frames. Their research showed otherwise. The following frame types were investigated:

- “In-situ cast concrete frame (office)
- “In-situ cast concrete frame (dwelling)
- “Precast concrete frame (office)
- “Precast concrete frame (dwelling)
- “Steel/concrete frame (office)
- “Steel/concrete frame (dwelling)
- “Steel/steel frame (dwelling).”

The functional unit was defined as a square meter of floor space, which is the most basic and adaptable functional unit for a building. Variations in building materials were accounted for, and the researchers strove to analyze average Swedish buildings, not the “best available technology.” The study encompassed only a comparison of the seven frame types as is, not how they could be improved.

The results of the inventory are displayed using a series of charts showing different impact categories, emphasizing that there is no one clear winner among the seven frames. One frame might use a lower mass of materials, but require higher energy use during construction. Emissions are shown in
terms of CO₂, NOₓ, sulfur oxides (SOₓ), chemical oxygen demand (COD), and hazardous and non-
hazardous wastes. The operational energy use is also described both in and of itself, and by taking into
account the embodied thermal savings of materials such as concrete.

A formal impact assessment is carried out using three established European methods—EPS,
Environmental Themes, and Ecoscarcity—giving the reader a sense of how the results can be skewed or
altered based on the differing parameters (Figure 9, Figure 10, and Figure 11). It also allows the reader to
make the most important deductions about the study—for example, that Frame 7 has the highest
environmental impact in all three methods.

This study represents the most detailed and formal use of the ISO life cycle assessment
guidelines. It serves as a good model for future studies, which of course should be undertaken using
North American data, methodology, and impact assessment.

Figure 9: Environmental Impact Using the EPS Method.
Source: Jönsson et al.
Figure 10: Environmental Impact Using the Environmental Themes Method.
Source: Jönsson et al.

Figure 11: Environmental Impact Using the Ecoscarcity Method.
Source: Jönsson et al.
3.2.6 Cole and Kernan (1996)

Performed with structures in Toronto and Vancouver in mind, this Canadian study analyzes the life-cycle energy use of hypothetical three-story office buildings framed in wood, steel, and concrete, with and without underground parking garages. All results are reported for the overall building and in terms of GJ/m² (Figure 12). In the case study, steel frames always have the highest embodied energy no matter how the data is manipulated, and wood frames the lowest. The parking garage increases the structure's embodied energy by 21-38%, depending on the frame material. The building envelope and the structure are always in first and second place for percentage of total embodied energy, but trade places depending on the type of material.

![Figure 12: Embodied Energy of Structure. Source: Cole and Kernan.](image)

The authors also discuss the concept of "recurring" or "additional" embodied energy, which comes from replacing materials over the building's lifetime. This recurring embodied energy can add up to a significant amount when the life of the building is extended from 25 years up to 50 or 100 years (Figure 13). The recurring embodied energy in a building with a 100-year lifespan may be two or three times larger than its initial embodied energy. One also cannot anticipate the changes in materials that may occur over the building's lifetime, which may increase or decrease the embodied energy predicted today. The main conclusion, though, is that recurring embodied energy does not differ markedly between building materials, no matter what the building's lifespan.

Despite the clear results stating that steel has the highest embodied energy, the authors are quick to point out that embodied energy can sometimes make up only 5% of the building's total energy consumption over its lifetime, so the difference between structural materials becomes less significant in this light. The buildings sampled in the study also do not represent a broad enough range of office
buildings in Canada to make definite conclusions about energy use per square meter in a typical building.

![Figure 13: Recurring Embodied Energy (No Underground Parking).](image)

**Source:** Cole and Kernan.

### 3.2.7 Johnson (2006)

An MIT graduate student performed a similar LCA study of concrete and steel building frames for his Master of Science thesis. He chose to analyze energy consumption, resource depletion, and carbon dioxide emissions, and compared embodied to operational energy of hypothetical structures. Johnson chose to analyze the concrete and steel required to construct a 100,000 square-foot building in Boston, Massachusetts. He considered this functional unit to be the smallest useful unit for those interested in sustainable design of commercial buildings. Although he assumed the building to be an office structure, he did not specify a number of stories, only the square footage. The system boundary included raw material extraction, production, manufacture, and construction phases only, not use or disposal phases.

The main shortcoming in the thesis is that it uses the Ecoinvent database for the majority of the inventory analysis data, and this database uses European figures. Johnson used these numbers for his North American study due to a lack of better data. He did supplement Ecoinvent data with personal fieldwork he conducted in the Boston area, mostly to understand the processes involved in steel and concrete production.

Johnson performs only minimal impact assessment because, as he writes, the inventory analysis speaks for itself. All three of his chosen environmental impact categories are within the same order of
magnitude for both materials (Figure 14), although steel has fewer carbon dioxide emissions and less resource depletion than concrete (the two are virtually the same in terms of energy consumption).

These values are converted into units per square foot (Table 6), and the difference in resource depletion becomes more noticeable, while the other two categories still show small or negligible differences.

![Figure 14: LCA Results in Three Impact Categories.](source)

<table>
<thead>
<tr>
<th></th>
<th>CO2 emissions (kg)</th>
<th>Energy Consumption (MJ)</th>
<th>Resource Depletion (100 kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>12.4 kg/SF</td>
<td>102.1 MJ/SF</td>
<td>2.8 Mg/SF</td>
</tr>
<tr>
<td>Concrete</td>
<td>16.4 kg/SF</td>
<td>102.5 MJ/SF</td>
<td>8.8 Mg/SF</td>
</tr>
</tbody>
</table>

Table 6: LCA Results by Square Foot.

Source: Johnson.

Johnson also gives statistics on embodied energy, carbon dioxide, and resource depletion broken down by process and product for both materials. By examining past reports, he makes the conclusion that the differences in embodied energy between the two materials are so small that it doesn’t matter which is used. Operational energy is a more worthwhile area of study if one is interested in reducing energy use throughout a building’s life cycle. He does, however, identify a need to reduce carbon dioxide emissions and resource use in concrete production. Steel wins in those two categories, while embodied energy is a draw.

This thesis describes steel and concrete manufacturing processes in detail based on personal interviews with New England industry, but the quality of the data falls short. The life cycle assessment is incomplete, and North American data should be used to make the model valid and useful to the industry in Boston. The model could also benefit from the use of computer software that would make data easier to condense and understand. The calculations provided, while thorough, are difficult to sift through and

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compare to the final values highlighted in the text. More impact assessment techniques should be performed, specifically weighting, to make the LCA measure up to ISO standards, even though Johnson explicitly states that it is not his intent to produce a study that is fully compatible with ISO.

3.3 Variability in the Studies

Table 7 shows a comparison of the seven studies. The number of buildings included in the study is shown, along with whether the buildings exist in real life or are only ideal designs created by the researchers. The area of the world in which the buildings are sited is specified. The units that the researchers chose to report their findings are listed, whether they are units of mass, energy, or emissions. Finally, the table indicates whether the study followed formal ISO standards for an LCA or not. Although a study may be very comprehensive and provide useful information to the reader, LCAs that conform to ISO standards are accepted as the most valid.

It is clear from the comparison that there is no consensus on which units should be measured for a full LCA of a structure. Two studies focus only on energy, while only one study incorporates waste masses into its impact assessment. Three studies measure emissions other than carbon dioxide in addition to the standard carbon dioxide equivalent measurement. Although some of these studies admit to covering only a portion of the full spectrum of LCA measurements available, such as the Thai study

<table>
<thead>
<tr>
<th>Study</th>
<th>Eaton &amp; Amato</th>
<th>Junnila &amp; Horvath</th>
<th>Guggemos &amp; Horvath</th>
<th>Kofoworola &amp; Gheewala</th>
<th>Jönsson et al</th>
<th>Cole &amp; Kernan</th>
<th>Johnson</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of buildings studied</td>
<td>10</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>7</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Real or ideal?</td>
<td>Ideal</td>
<td>Real</td>
<td>Ideal</td>
<td>Real</td>
<td>Ideal</td>
<td>Ideal</td>
<td>Ideal</td>
</tr>
<tr>
<td>Country</td>
<td>UK</td>
<td>Finland</td>
<td>USA (Midwest)</td>
<td>Thailand (Bangkok)</td>
<td>Sweden</td>
<td>Canada (2 cities)</td>
<td>USA (Boston)</td>
</tr>
<tr>
<td>Units reported</td>
<td>GJ/m², kg-CO₂/m², MW-h, kg mats, kg CO₂, kg SO₂, kg H₂C₄, kg PO₄, kg Pb</td>
<td>TJ, Gg CO₂, Mg CO, Mg NOₓ, Mg PM₁₀, Mg SO₂</td>
<td>TJ, GJ/m²</td>
<td>kg mats, MJ, kg CO₂, kg NOₓ, kg SO₂, COD/unit, kg waste</td>
<td>GJ, GJ/m²</td>
<td>kg CO₂, kg mats, MJ, kg CO₂/ft², kg mats/ft², MJ/ft²</td>
<td></td>
</tr>
<tr>
<td>Full ISO LCA?</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No; LCEA only</td>
<td>Yes</td>
<td>No</td>
<td>No; LCI only</td>
</tr>
</tbody>
</table>

Table 7: Comparison of Reviewed Studies.
that performs only a life cycle energy assessment (LCEA), it is useless to compare these studies with others because of their different scopes.

An uncertainty analysis was performed to visualize the variability between these studies. Figure 15 and Figure 16 depict the analysis using two units, kilograms of carbon dioxide and gigajoules of embodied energy. In cases where the study encompasses more than one concrete or steel building, the number shown represents an average of the values for all concrete or steel buildings studied. The Kofoworola and Cole studies are omitted from Figure 15 because they do not report carbon dioxide emissions, and the Junnila study is omitted from Figure 16 because it does not report embodied energy. The Junnila study only reports carbon dioxide emissions for a concrete building, and the Kofoworola study only reports embodied energy for a concrete building, so steel values are not shown for these two studies. Otherwise, values from all the studies have been normalized into appropriate units for each graph.

The graphs show some major differences between studies and make the variability even more obvious. Most notably, the steel values differ by almost an order of magnitude between the Guggemos and Jönsson studies for both carbon dioxide and embodied energy. It makes no sense that two of the most easily understandable metrics for quantifying LCA results produce such different results from study to study. But Johnson also compares his results to those of Guggemos and Horvath, and notes that the higher values in the Guggemos study are probably due to “more comprehensive” data collection that includes materials such as foundations and cladding in its material considerations (90).

![Figure 15: Carbon Dioxide Due to Materials and Construction in Reviewed Studies.](image-url)
The size of the buildings varies in the studies, because the term "commercial building" is applied to a wide variety of structures which may have very little similarity to one another in size and function. Therefore, the carbon dioxide values were converted again to represent kilograms of carbon dioxide per kilogram of material where possible (Figure 17), allowing global warming potential to be measured in a more basic unit that remains the same regardless of building size. The unit, named the carbon intensity factor (CIF), is dimensionless. Unfortunately, the building structures’ approximate weights could be extrapolated only from the Junnila, Guggemos, and Johnson studies.

Figure 17: Carbon Intensity Factor, or Kilograms of Carbon Dioxide per Kilogram of Structural Material.
Because the Junnila study measures only a concrete building, the CIF of steel frames can be compared for just two of the studies. However, the CIF graph shows that the Guggemos study again has produced a much higher global warming potential than the other studies, regardless of material and unit conversion. It is not fully understood why this study varies so much from the others, but it illustrates the potential for variability in studies based on the system boundary and method of data collection.

The functional units and reporting styles of these studies were so different from one another that compiling these graphs required extensive unit conversion. Merely glancing at the studies without performing an uncertainty analysis reveals no useful information about how they compare. Because a key component of LCA is communication of information in a useful manner to the intended audience, this lack of uniformity represents a major shortcoming of LCA studies of commercial buildings.

3.4 Areas for Improvement

The seven studies described above represent some of the most detailed assessments of commercial buildings performed to date. While many other studies exist, they are scattered across the globe and their adherence to formal LCA standards varies. Many are similar to the included articles. The most important conclusion about the body of work on commercial structures is that there is a major lack of research in the United States. More studies must be performed in the United States that do not use data from Europe or any other part of the world.

In addition to not being consistent in their measurements, the studies above simply do not examine enough buildings. In order to provide reasonable estimates for the energy consumption of typical commercial structures in a country or region, a study should measure hundreds or even thousands of buildings, not just a few. The Finnish study was valid because it gathered data as the building was being constructed, and thus had a very complete inventory for its LCA. But a single building is not representative of the larger body of Finnish commercial buildings, so the study is only somewhat useful in the broader scope of building LCAs.

These studies also do not include enough real buildings. While it is perfectly valid to design what the researchers perceive as “typical” buildings in a certain region, it would ultimately result in a more complete LCA to gather data from real structures, as in the Finnish and Thai studies. In this way, estimates can be made from the world’s existing structures, not an idealized version of what engineers perceive most of these structures to look like. Data should be collected on the prevalence of recycling and the energy use associated with the reuse of materials from real structures. Every effort should be made to present a complete cradle-to-grave picture of every building in the study, and the ideal sample
of buildings will make up for those buildings where sufficient data cannot be collected. Idealized structures should be used only to check data and identify outliers or unusual structures among the spectrum of existing buildings that have been incorporated into the study.

Finally, an important component of United States life cycle assessments is regional variation. Broad assumptions may be made in a small country like Thailand with a fairly uniform climate, but the United States is a large country with many different climates, and regional variation in material availability and transportation distances varies widely as well. While the study by Guggemos and Horvath on structures in the Midwest is a good start, it cannot represent structures throughout the United States. Multiple building models should be created to account for a set number of regions in the country.

In short, LCAs such as those reviewed in this section should have much broader scopes, in terms of the results they assess and the number and types of buildings they study. Life cycle inventories must use data that is accurate by country and region, and researchers should complete an impact assessment that covers a broad variety of impact categories which also apply specifically to the region of the world under scrutiny. While there is no doubt that the reviewed studies have been useful to the LCA and engineering communities, there is still much ground to cover before reasonable estimates can be made of the impact such buildings have on the environment, especially in the United States.
4. Life Cycle Assessment of Steel and Concrete Using GaBi

4.1 Goal and Scope

The goal of this life cycle assessment is to analyze the environmental impact of steel and concrete as raw materials for use in Boston, Massachusetts, and compare them to one another using an accounting method in a basic short-term LCA. GaBi 4, an LCA computer program, is used to perform the assessment. The functional unit is one ton of hot-rolled structural steel members and one ton of poured reinforced concrete. The assessment is preliminary, and should not be accepted as final values for these materials. Because the main focus has been on carbon dioxide in reviewing past studies, the carbon intensity factor (CIF) of the models is measured and discussed.

To create a more comprehensive picture of commercial buildings in the United States, it is necessary to approach building life cycles one step at a time. Since there is significant interest in the environmental impact of steel and concrete in these structures, the first step is to analyze the raw materials individually before incorporating them in structural frame models. Later, each step of a building frame’s construction, maintenance, and demolition can be systematically analyzed to create a comprehensive model of embodied energy in a variety of typical American commercial structures. The model can then be applied to steel and concrete frames with different designs.

A second goal is to assess the validity of results obtained through GaBi by comparing the results to those of previous studies using the CIF. Data is taken from reliable sources and inputted with processes from GaBi’s databases, using North American values whenever possible, but it is possible that this data may be incorrect or inappropriate for the region of interest. The variability of the numbers provides clues to how they may be interpreted to emphasize certain results.

4.2 Inventory Analysis

Inventory analysis was performed by creating six models in GaBi, for three types of steel structural members and three reinforced concrete mixes. Screenshots of these models are shown in Appendix B51. Each component of the model represents a process that is composed of individual inflows and outflows. While most of these flows already existed in GaBi’s databases, some had to be created using data from other sources. GaBi’s in-house data for the United States was used in many cases, with some exceptions where only German data was available.
4.2.1 Steel

The processes to create hot-rolled structural steel were obtained from a life cycle inventory of steel production in the United States and Canada performed by the Athena Institute. The materials required to produce a ton of steel in the United States were obtained from the inventory charts in the report, assuming production of three typical structural members: a heavy steel truss section, an open web joist section, and an HSS section (“Cradle-to-Gate” 74).

Additional information about the steel production process was obtained from Johnson. Recycled steel scrap is estimated to make up 95% of the finished product at a steel manufacturing plant in Arkansas (46), although this number is superseded by the varied numbers in the Athena report. The steel truss section uses 82% scrap, the open web joist uses 90% scrap, and the HSS tube uses only 15% scrap (“Cradle-to-Gate” 74). Since the Athena inventory represents an average in US steel mills for different types of structural steel, these numbers are preferred.

The scrap at the Arkansas plant is usually domestic and arrives by truck and rail from across the country. For this inventory, it is assumed that the scrap comes by truck rail from sources that are 500 miles away on average. The virgin steel is made from pig iron that can come from a number of foreign sources (Johnson 46), and here a worst-case scenario is assumed where the steel comes from China by ship and is trucked from the port to the plant. Finally, it is assumed that the finished steel is shipped from Arkansas to Boston by rail and trucked short distances to the fabrication and construction sites. Diesel fuel use is assumed for all transportation processes (“Cradle-to-Gate” 74).

4.2.2 Concrete

The basic components of poured reinforced concrete are Portland cement, coarse aggregate (made up of large crushed stones), fine aggregate (composed of sand and small gravel), water, air, and steel rebar (Figure 18). The mix of concrete is subject to some interpretation, and Portland cement is sometimes replaced with other materials, such as fly ash.

![Figure 18: Typical Components of Concrete. Source: http://www.cement.org/basics/concretebasics_concretebasics.asp.](image-url)
The processes to create steel rebar in a ton of reinforced concrete were obtained from the aforementioned study performed by the Athena Institute ("Cradle-to-Gate" 74). A quantity of 62.5 kg of #4 and #10 steel rebar per cubic meter of reinforced concrete is assumed (Johnson 121), which corresponds to 52 pounds of rebar per ton of concrete. The materials required to produce 52 pounds of typical rebar in the United States were obtained from the inventory charts in the report. The same transportation processes as in the steel life cycle inventory were assumed based on Johnson (46).

If a ton of typical reinforced concrete contains 52 pounds of rebar, the concrete weighs 1948 pounds. Based on the Portland Cement Association’s typical concrete mix for structures by volume, shown in Figure 18, water constitutes 16% of the mix by volume, so the corresponding dry weight of the other materials is 7.1% air, 13.1% cement, 48.8% coarse aggregate, and 31% fine aggregate. However, this is only one mix, and in reality mixes vary from project to project. A 2002 Portland Cement Association study lists a variety of typical concrete mixes, three of which have been chosen for this study. Two mixes contain only Portland cement, and have slightly different unit weights. The third replaces 20% of the cement by volume with fly ash, a common substitute (Nisbet et al 9). The mixes are reproduced in Table 8. The numbers shown were converted into pounds per 1948 pounds of concrete for use in the GaBi models.

<table>
<thead>
<tr>
<th>Concrete mix description</th>
<th>Mix 1</th>
<th>Mix 2</th>
<th>Mix 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>28-day compressive strength, psi</td>
<td>5,000</td>
<td>3,000</td>
<td>3,000</td>
</tr>
<tr>
<td>% fly ash</td>
<td>0</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Unit weight, lb/ft³</td>
<td>148</td>
<td>145</td>
<td>145</td>
</tr>
<tr>
<td>Concrete raw material, lb/yd³ concrete</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement</td>
<td>564</td>
<td>376</td>
<td>301</td>
</tr>
<tr>
<td>Fly ash</td>
<td>0</td>
<td>0</td>
<td>75</td>
</tr>
<tr>
<td>Water</td>
<td>237</td>
<td>237</td>
<td>237</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>2,000</td>
<td>1,900</td>
<td>1,900</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>1,200</td>
<td>1,400</td>
<td>1,400</td>
</tr>
<tr>
<td>Total</td>
<td>4,001</td>
<td>3,913</td>
<td>3,913</td>
</tr>
</tbody>
</table>

Table 8: Concrete Mixes for GaBi Models.
Source: Nisbet et al 9.

Johnson assumes that cement is produced at a plant in Catskill, New York, using clinker from a nearby quarry and gypsum shipped from Spain to a port at Albany, New York. The cement is then trucked to Albany and taken by rail to a storage facility in Boston. Fine aggregate is quarried at Ossipee, New Hampshire, while coarse aggregate is quarried at the North Shore in Massachusetts. All ingredients are trucked to a concrete facility in Everett, Massachusetts; then the ready-mixed concrete is taken by truck to the construction site. Steel rebar is created from both domestic steel scrap brought by rail from
within a 500-mile radius (33), and foreign virgin steel assumed to be from China in a worst-case scenario. The Athena study estimates the percentage of scrap to be 93% of the finished rebar. The travel distances were incorporated into the model, assuming the use of diesel fuel (“Cradle-to-Gate” 74).

The Portland Cement Association’s 2002 life cycle inventory of concrete uses data from a number of sources regarding energy use for different steps of the concrete production process (Nisbet et al 11). Energy use for aggregates was divided into energy use of crushed stone production and energy use of sand and gravel production, although in GaBi aggregate had to be divided into silica sand and large gravel. Energy for concrete production at the plant was estimated to be .896 MBtu per ton (12).

4.3 Impact Assessment

Two impact assessment methods were chosen to assess the life cycle inventory in GaBi. TRACI, which stands for Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, is a method created by the Environmental Protection Agency for life cycle assessment in the United States (Bare et al, 49). TRACI contains twelve impact categories that stem from an inventory of four “stressors”: land use, chemical emissions, water use, and fossil fuel use. Special attention is given to human health categories, including carcinogens (53).

EDIP is a method developed in Denmark that assesses five impact categories: global warming, ozone depletion, acidification, eutrophication, and waste. It gives attention to toxicity and human health in work environments (Baumann & Tillman 166). Although EDIP is not tailored to the United States, it was chosen to provide comparison with TRACI. The 2003 version was used in this impact assessment, since it is the most recent update to the method.

BEES, or Building for Environmental and Economic Sustainability, is a second US-focused method developed by the National Institute of Standards and Technology. It is not available in GaBi, however, which is why EDIP was substituted. GaBi’s limited selection of methods is a weakness when it comes to reporting a spectrum of results and acknowledging variability.

Carbon dioxide is reported in units of weight in both methods, making it easy to compare them, and it is clear that the values do not differ significantly between the two methods. Figure 19 shows the carbon dioxide values from both methods converted into the carbon intensity factor, or kilograms of carbon dioxide emissions per kilogram of material, and the difference between the two methods is visually negligible.
As expected, the concrete containing fly ash has the lowest CIF of all the concrete mixes, and its CIF is also lower than that of the steel heavy truss and HSS tube. Although it may seem obvious to choose the second concrete mix over the first, it is important to remember that the first mix has a higher compressive strength and may be structurally necessary for some projects. The fly ash concrete mix in this assessment has the same compressive strength as the second mix, but it is possible to create a mix with fly ash that has a higher compressive strength, and it would necessarily have a slightly higher CIF that would still be lower than that of the first mix.

The steel HSS tube has the highest CIF because it contains a much higher percentage of virgin steel than the two other steel members, and this virgin steel is assumed to come from China, a much farther distance than that of any of the other transportation processes in all six models. It is important to consider a worst-case scenario where a material may come from halfway around the globe, because globalization of industry and resource extraction has become more and more of a reality throughout the 20th and 21st centuries.

4.4 Interpretation

Several elements of these materials' life cycles are missing from the GaBi models due to the short time frame of the study, making this a preliminary LCA that still needs revision. Data about manufacturing processes and factory capital involved in producing these materials was not available in sufficient detail. Again, part of the problem is that not enough information exists about these processes in the United States. And instead of going into detail about the production of such materials as virgin...
steel and concrete aggregates, generic processes were taken from GaBi’s databases that probably omit many important specifics of the real processes. There is reason to believe that some mass quantities are missing from the GaBi models, especially in the three steel models, due to the limited data.

While educated guesses were made about transportation based on Johnson’s research, transportation distances are subject to variability. The models represent just one possible source for concrete or steel, when in reality a project in Boston may derive materials from a totally different source in another part of the country. The assumptions made are an inherent weakness of any life cycle inventory, because they will always have numerous alternatives that should be investigated in an uncertainty analysis.

The data obtained about steel production from the Athena study is difficult to understand. Large quantities of steel scrap are required for structural steel production, but these numbers do not make sense and are not explained. The waste that would logically follow from these quantities is also not accounted for. While the data was accepted for the current models, it should be investigated and compared to data from alternative resources to improve the validity of the models.

Because this study assesses only the production and transportation of raw materials to their construction destinations, certain processes are left out that must be accounted for in a more comprehensive study of concrete and steel life cycles. The energy required to pour concrete, along with the necessary formwork, is not included, nor are the welds and bolts required to erect steel frames. Human labor is not considered because it is difficult to incorporate worker resources into life cycle inventories.

In conclusion, the life cycle assessment requires more data and improvement before it can be considered a valid, robust model of steel and concrete. For the purposes of this study, it is sufficient to make preliminary conclusions about the impacts of these two raw materials in terms of their carbon intensity factor, but the CIF values must also be compared to those of past studies, as will be discussed in Section 5.
5. Discussion

5.1 Variability of LCA Results

Studying three concrete mixes and three types of structural steel members has shown that GaBi is both a powerful tool for life cycle assessment and one that can produce questionable results. United States data is not always available for desired flows and processes, meaning that the user must spend more time creating handmade processes for which there may not be reliable data. Due to the mix of data from other sources and “shortcut” data within the program, discrepancies arose in the models that had no easily discernible source. Data cannot be reliable unless it has been backed up by other sources, which could have very different results. Because of the limited scope of this study, very few data resources were researched and used, and their reliability must be questioned. Using different sources could produce very different results.

The software itself also had some problems that could not be solved within the time frame. The mass quantities in the steel models were inexplicably small compared to the input flows and processes used. The complexity of the program is such that it was impossible to figure out how to fix the problems without more in-depth training on the finer points of the software. Because the discrepancies were probably due to the data taken from the program’s databases, it became clear that the completeness of this data must be called into question in future projects. Performing a quick but reliable LCA in a short time frame proves to be a difficult task when problems such as these are encountered.

The variety of structural members introduces another element of variability into the models. The choices were somewhat arbitrary, with the goal of modeling a broad range of concrete and steel variations. But these choices are insufficient to represent all steel and concrete construction in the country. Modeling many types of concrete mixes and steel members would be more useful in the creation of full building frame life cycle assessments, but it would also be an arduous task requiring a large project scope and time frame. So it can only be concluded that the average CIF of all three steel members is higher than the average CIF of all three concrete mixes, but some steel members have a lower CIF than some concrete mixes.

Finally, these models apply only to structures in Boston. Construction practices can vary by region, and the contents and production of the materials will almost certainly vary based on the plant and the original source of the material. Transportation distance, of course, introduces major variability, and these models represent worst-case scenarios in terms of source and transportation to illustrate
results at the extreme end of the spectrum. In reality, materials may come from much closer sources, changing the impact assessment drastically.

5.2 Comparison to Past Studies

Just as in the studies described in Section 3, the GaBi LCA is formulated for just one region of the country, making it meaningless for other regions. While the site-specificity of LCAs is extremely useful, it also limits the scope of any single LCA, and creates more work for the researcher because LCAs have to be performed many times to cover different regions. The variability of the LCAs that have been performed makes them more difficult to compare to one another, and the weak GaBi models introduce another level of confusion.

Figure 20 shows the carbon intensity factor of the three reviewed studies depicted in Figure 17 as well as the CIF of the current study. The current study’s CIF values compare favorably with those of the Junnila and Johnson studies, while the Guggemos study is again much larger. Despite the high CIF of the HSS tube steel model in GaBi due to the high percentage of virgin steel, the average CIF of steel is still lower than in any of the reviewed studies – 0.18 as opposed to 0.23 and 0.78. The low CIF values in the GaBi models are probably due to the problems identified in the data and the simplicity of the models, which have a relatively small system boundary and omit many processes that would have been difficult to model in the program.

![Figure 20: Carbon Intensity Factor of Three Reviewed Studies and Averages from Current Study.](image)

Further research into published CIF values for steel reveals even more variability. Table 9 shows a variety of CIFs taken from industry and published papers in different countries. The CIFs range from 0.42
to 2.53, highlighting a lack of consensus about the CIF of steel. The variations in steelmaking practice among different countries cannot be this large, and it is likely that the methods of data collection vary widely among these sources. It also is unclear whether these numbers apply to 100% virgin steel production, or production that includes recycled steel scrap. It makes sense that virgin steel would have a higher CIF than recycled steel, and it can be assumed that the high CIFs from BlueScope Steel and Tata Steel are probably referring to the virgin steel processed at their plants.

<table>
<thead>
<tr>
<th>Source</th>
<th>CIF Estimate(s)</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>BlueScope Steel</td>
<td>2.53</td>
<td>2005 company report for operations in Oceania</td>
</tr>
<tr>
<td>Price et al</td>
<td>1.03</td>
<td>1996 estimate for China</td>
</tr>
<tr>
<td>Sandberg et al</td>
<td>0.42</td>
<td>2001 estimate for Fundia plants in Sweden</td>
</tr>
<tr>
<td>Tata Steel (Sharma et al)</td>
<td>1.2, 1.7, 1.9</td>
<td>Estimates for three steelmaking processes in global operations</td>
</tr>
<tr>
<td>Worrell et al</td>
<td>0.5</td>
<td>1994 estimate for US</td>
</tr>
</tbody>
</table>

Table 9: Selection of Published CIF Values for Steel Production.

Based on this assortment of numbers, the steel CIFs from the GaBi models are still too low, but could reasonably fall within the low range of CIF estimates if the models were adjusted to include better data. The CIFs calculated from the reviewed studies in Section 3 are also rather low, and reinforce the theory that steel containing recycled scrap has a CIF on the low end of the range. Better consensus among researchers about the CIF of steel production is needed to move forward with research about the environmental impact of steel.

One positive aspect of the GaBi models is that they are more versatile than some past studies, because they are a first step that can be implemented in larger LCA models for full buildings. Nailing down the environmental impact of the raw materials will allow them to be confirmed and implemented regardless of building type. Confidence in the smaller steps will reduce the potential for variability when full life cycle models are completed.

Like the reviewed studies, the GaBi impact assessment selects data that is the most important to report. Carbon dioxide is discussed in detail because it can be easily converted into a CIF and compared to the assortment of studies reviewed, but other impact assessment categories are left out because of insufficient data, and because the purpose of this study is to illustrate variability among assessments, not complete a thorough LCA. This is the danger in the communication of LCAs to the intended audience and to the public. Because of time and data considerations, the GaBi models are incomplete, and it is difficult to make any definitive conclusions about which material has a lower CIF and overall...
environmental impact unless further research is performed. LCAs should have broader time frames to include all relevant information, not just what the researcher has time for and wants to study in detail. Lack of time and detail explains why there is so much variability among the body of research performed on commercial structures so far.

5.3 Future Goals

The most important goal for future expansion of this study is to obtain more data. Collaboration with industry will help to ensure that data is accurate and comprehensive. A longer time period is needed to establish contacts within the concrete and steel industries, collect data, and implement it into the GaBi models. Because GaBi's databases are lacking so many processes that are fundamental to the production of concrete and steel, these processes must be created by hand in the future.

Once the data quality of these models is improved, they can be expanded to include the contraction, use, and demolition phases. The basic information about the raw materials can be applied to any type of building in any region of the United States, assuming transportation distances are adjusted. Four to five regions within the country should be defined in order to generalize these regional estimations in an efficient but accurate manner. Within these regions, a number of buildings can be developed that vary in square footage and height. Fieldwork should be performed to obtain a variety of data from real buildings, not just theoretical buildings designed for the sole purpose of life cycle assessment.
6. Conclusion

This thesis has proposed a concrete intensity factor for comparing the results of past, present, and future life cycle assessments of commercial structures. The variability of past studies, and the questionable software results that have been illustrated in GaBi, make it necessary to determine better data sources and standardize communication of results through use of the CIF in future studies.

Based on a selection of seven representative studies, published values range from 120 to 570 kilograms for concrete and 80 to 680 kilograms for steel of carbon dioxide emissions per square meter of usable floor area. Published values range from 880 to 9540 megajoules for concrete and 700 to 8180 megajoules for steel of embodied energy per square meter.

Six preliminary models of various concrete mixes and structural steel members were created in GaBi in order to compare the software’s results to those of the reviewed studies, none of which used GaBi. A functional unit of one ton of hot-rolled structural steel and one ton of poured reinforced concrete was chosen, and the models were analyzed using two impact assessment methods, one American and one European, to determine carbon dioxide emissions and calculate a CIF.

The dimensionless CIF ranges from 0.14 to 0.45 for concrete and 0.18 to 0.78 for steel, based on both the published values and the current study in GaBi. The variability of these numbers, as well as steel’s deviation from industry CIF values, means it is impossible to make any significant conclusions about the environmental impact of steel and concrete or the advantage of one material over another from this study. The problem lies not in the unit of measurement used, but in the quality and sources of data. Some studies are over a decade old, and were performed when life cycle assessment was not as prolific and not as many sources of data were available. Other studies, such as that by Guggemos and Horvath, have surprising results, the reasons for which cannot presently be determined. Regional differences around the world increase variability even further, and not enough research has been done in the United States to form a consensus about LCA results in this country.

Building materials constitute a significant percentage of the raw materials used in the United States today, so it is crucial to understand and reduce their environmental impact if a sustainable society is to be achieved. The variability of these studies shows that extensive work is still needed before the environmental impact of typical commercial structures can be quantified in a useful manner. The ultimate goal of building LCAs should be to develop estimates for the embodied and operational energy of typical buildings in various regional and size categories, based on data from both real and idealized structures, so that developers, clients, and designers can make educated estimates about the environmental impact of the buildings they are constructing and using.
Appendices

A. References


“Cradle-to-Gate Life Cycle Inventory: Canadian and US Steel Production by Mill Type.” The Athena Sustainable Materials Institute, 2002. PDF.


Steel Open Web Joist

The names of the basic processes are shown.

US: Iron and steel
production mix USLCI [b]
US: Iron, sand casted
USLCI [b]
US: Steel scrap
USLCI [b]
GLO: Container ship / ocean
ELCD/PE-GaBi [b]
GLO: Truck-trailer > 34 pl.[b]

96.394 kg
907.19 kg
907.19 kg
1857.7 kg
1857.7 kg
1857.7 kg
219.08 kg
219.08 kg
219.08 kg
27500 dwt/
ocean
27 t/
payload
27 t/
payload
40 t total cap. / 27 t payload
FDG: Rail transport cargo - Diesel PE [b]
FDG: Truck-trailer > 34 pl.[b]
FDG: Rail transport cargo - Diesel PE [b]
FDG: Truck-trailer > 34 pl.[b]
FDG: Rail transport cargo - Diesel PE [b]
FDG: Truck-trailer > 34 pl.[b]
FDG: Rail transport cargo - Diesel PE [b]
Steel HSS Tube

GaBi 4 process plan: Mass [kg]
The names of the basic processes are shown.

US: Iron and steel production via USLCI [b]
approx. 27,500 dwt / ocean
40 t total cap. / 27 t payload
US: Steel scrap
907.19 kg

GLO: Container ship / plz
910.36 kg
GLO: Rail transport cargo - Diesel PE [b]
201.81 kg
GLO: Truck-trailer 34 plz
- 40 t total cap. / 27 t payload
HSS tube cargo - Diesel PE [b]
201.81 kg

US: Structural steel for HSS tube
907.19 kg
GLO: Rail transport cargo - Diesel PE [b]
201.81 kg
GLO: Truck-trailer 34 plz
- 40 t total cap. / 27 t payload

USLCI [b]
Concrete Normal 1

GaBi 4 process plan Mass [kg]
The names of the basic processes are shown.

- US: Power grid mix PE
- US: Portland cement, at plant USLCI [b] 84.862 kg
- US: Truck-trailer > 34 p7 GLO: Rail transport cargo - Diesel PE [b]
- US: Concrete Production
- US: Power grid mix PE

- US: Silica sand
- (Excavation and processing)
- GLO: Truck-trailer > 34 p7 GLO: Rail transport cargo - Diesel PE [b]
- US: Concrete Production

- DE: Limestone, gravel
- (gran size 32/63) PE
- GLO: Truck-trailer > 34 p7 GLO: Rail transport cargo - Diesel PE [b]

- US: Iron and steel, production mix USLCI [b]
- GLO: Container ship / plant USLCI [b] approx 37500 dt / ocean ELCD/PE GaBi [b]
- GLO: Truck-trailer > 34 p7 GLO: Rail transport cargo - Diesel PE [b]

- US: Iron, sand casted
- GLO: Truck-trailer > 34 p7 GLO: Rail transport cargo - Diesel PE [b]

- US: Steel scrap
- GLO: Truck-trailer > 34 p7 GLO: Rail transport cargo - Diesel PE [b]

Figure 24: GaBi Model of Normal Concrete Type 1.
Concrete Normal 2
GaBi 4 process plan: Mass [kg]
The names of the basic processes are shown.

US: Power grid mix PE

US: Portland cement, at plant USLC (b)

GLO: Truck-trailer > 34 pe

40 t total cap. / 27 t payload
Euro 3 (local) PE (b)

84.862 kg

US: Silica sand

[Excavation and processing] PE

GLO: Truck-trailer > 34 pe

40 t total cap. / 27 t payload
Euro 3 (local) PE (b)

315.98 kg

DE: Limestone, gravel

[grain size 32/63] PE

GLO: Truck-trailer > 34 pe

40 t total cap. / 27 t payload
Euro 3 (local) PE (b)

428.83 kg

US: Iron and steel, production mix USLC (b)

1.5295 kg

US: Iron, sand casted

USLCI (b)

GLO: Container ship / PE

aprox. 27500 dwt / ocean ELC/PE GaBi (b)

3.4762 kg

GLO: Truck-trailer > 34 pe

40 t total cap. / 27 t payload
Euro 3 (local) PE (b)

3.4762 kg

US: Steel scrap

GLO: Truck-trailer > 34 pe

40 t total cap. / 27 t payload
Euro 3 (local) PE (b)

47.023 kg

GLO: Rail transport cargo - Diesel PE (b)

47.023 kg

US: Concrete production

907.19 kg / Euro

3 (local) PE (b)

US: Power grid mix PE
Concrete Fly Ash

GaBi 4 process plan Mass [kg]
The names of the basic processes are shown.

US: Power grid mix PE  0 kg
US: Portland cement, at plant USLCI [b]  67.935 kg
US: Power grid mix PE  0 kg

GLO: Truck-trailer > 34 pE, 40 t total cap / 27 t payload / Euro 3 (local) PE [b]
GLO: Italian cement [b]  27500 dwt / ocean PE [b]

US: Silicone sand (Excavation and processing) PE  315.98 kg
US: Power grid mix PE  0 kg

GLO: Truck-trailer > 34 pE, 40 t total cap / 27 t payload / Euro 3 (local) PE [b]
GLO: Container ship / pE, approx. 27500 dwt / ocean ELCD/PE GaBi [b]

DE: Limestone, gravel (grain size 32/63) PE  428.83 kg

US: Iron and steel, production mix USLCI [b]  3.4762 kg
US: Power grid mix PE  0 kg

GLO: Truck-trailer > 34 pE, 40 t total cap / 27 t payload / Euro 3 (local) PE [b]
GLO: Limestone, gravel (grain size 32/63) PE  3.4762 kg

US: Steel scrap  47.023 kg
US: Power grid mix PE  0 kg

GLO: Truck-trailer > 34 pE, 40 t total cap / 27 t payload / Euro 3 (local) PE [b]
GLO: Rail transport cargo - Diesel PE [b]

US: Structural steel for XL structure [b]  22.68 kg
US: Power grid mix PE  0 kg

GLO: Rail transport cargo - Diesel PE [b]