Comparison of Environmental Impacts of Steel and Concrete as Building Materials Using the Life Cycle Assessment Method

by

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Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of

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Abstract

In the United States, the construction industry accounts for almost 75% of total raw material used. This is an obvious drain on natural resources and has a major impact on the surrounding environment. Construction materials are also responsible for a relatively large portion of the global CO_2 emissions. The commercial construction industry is dominated by the use of steel and in-situ concrete as building materials. It is intuitive then, to state that these two materials and their respective production flows have a significant impact on the environment, simply because of the amount of material being produced and consumed in the building industry today. In addition, due to drastic increases in energy prices and potential shortages in the future, the amount of energy consumed in the production of construction materials (embodied energy) and the amount of energy used over a projected life span (operational energy) are becoming increasingly more important to builders, designers, and owners of buildings.

The growing trend in the United States, and elsewhere in the world, is towards eco-friendly design. In the last several years, the concrete and steel industries have spent significant resources to promote their material as the optimum solution for sustainable building design. Because natural resource consumption, air emissions, and the amount of embodied energy are all important drivers for the push towards sustainability, this study will compare those factors and quantify the differences between what is necessary for the construction of concrete- and steel-frame structures.

The purpose of this thesis is to utilize the Life Cycle Assessment (LCA) method to compare the environmental impacts created by the steel and concrete construction industry at the lowest common performance level, in this case the structural shell of a typical building in a given geographical area. The study will include all major product systems and material flows involved with concrete or steel construction and quantify their impacts in terms of total energy requirement, natural resources consumed, and harmful air emissions, specifically as they relate to global warming potential.

Thesis Supervisor: Jerome J. Connor
Title: Professor of Civil and Environmental Engineering

Acknowledgement

This project would not have been possible without the unconditional support of my entire family, especially my wife Amy and three children Hannah, Emma and Quinn, who put up with the long hours, especially at the end, and gave me the necessary time and push to finish this project. I love you.

Professor Connor was an inspiration and a continual source of knowledge, motivation and good conversation. Thank you.

I dedicate this thesis in memory of my grandfather, Edwin T. Johnson, who bravely served with the 531st Engineer Shore Regiment during World War II and whom, I believe, would be very proud of the accomplishments of all his grandchildren.

Timothy W. Johnson
12 May 2006

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1 *Introduction and Organization*

1.1 **Introduction**

The commercial construction industry in the United States is dominated by the use of steel and reinforced cast-in-place concrete as building materials. Their respective applications in the built environment are well noted since the beginning of the 20th century. They have very different characteristics in terms of strength, stiffness, density, and constructability. A brief comparison of steel and concrete, in terms of their positive and negative attributes, is described in Table 1.1.

Table 1.1. Concrete and Steel Characteristics for Construction

	Characteristics
Steel -	+ High strength to weight ratio + Tensile and compressive strength + Ductility + Accurate connection settings
	- Fire-proofing required - Expensive rigid connections (weld)
Concrete -	+ Formable; molded to any required shape + Durable + Fire resistant + Rigid connections
	- Compressive strength only - Labor-intensive

Source: (Madsen, 2005)

The concrete and steel industries have competed for construction market share throughout their history. Differences in labor skill level and wages, material availability and cost, and structural performance characteristics are the normal decision-making factors used by architects and engineers to choose the most suitable building material for their specific location and building type (Barry, 2001). Boston, for instance, is dominated by the use of steel as a primary building material because of its historical lack of skilled concrete laborers, according to Milford Reynard, the chief estimator of Linbeck Construction in Boston. A recent trend in the United States construction industry is towards 'green' buildings and sustainable design. This has led to an additional criterion for determining what material to use.

The emergence of the United States Green Building Council (USGBC) and its Leadership in Energy and Environmental Design (LEED) standards, as well as comparable agencies in Europe, has shown that there is a growing concern over the environmental impacts created by the built environment. Since 2000, 337 building projects have achieved certification and 2,969 are registered under LEED-NC (USGBC Fact Sheet, 2006). The number of buildings achieving a LEED-NC certification has nearly doubled every year since 2000, the year the LEED-NC rating was introduced. This trend is depicted in Table 1.2. If the current trend in certification continues over the next 10 years, LEED certified buildings will account for the majority of new construction in the United States (Kibert, 2005).

Table 1.2. LEED-NC (New Construction) Statistics

	2005	2004	2003	2002-00
LEED NC Registrations	2161	1792	1095	624
LEED-NC Certified Projects	285	167	82	38
LEED NC Total Square Footage (SF)	>244	>217	>144	>80

Source: (USGBC New Jersey Chapter, 2006)

Coincidentally, the rise of sustainable construction practices has led to severe competition among the two major commercial building materials, steel and concrete, each claiming to be the 'best' choice and touting their performance in terms of sustainability.[1] But which material is better? Can a single research study answer that? The simple answer is no; the scope of the first question is far too broad and comprehensive to obtain a definitive answer. The answer really depends on the intended purpose and scope of the comparison. If those elements are clearly defined, a legitimate comparison can be achieved.

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[1] The official organizations related to steel and concrete have included sustainability as a major topic on both official websites and in associated journals. These organizations include the American Institute of Steel Construction (AISC), American Concrete Institute (ACI), Portland Cement Association (PCA), etc.

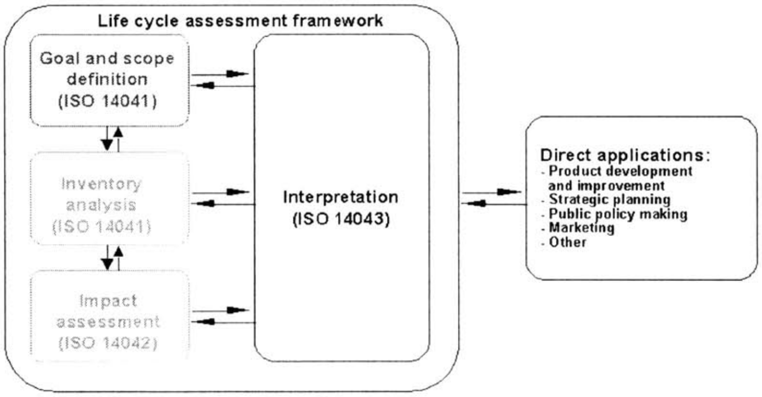
1.2 **Life Cycle Assessment Method**

Industrial ecology is certainly not a new field of study, but it is emerging now, along with environmental management and sustainable design, as an important research area for developing solutions to today's environmental challenges posed by the built environment (Graede and Allenby, 2003). Several analysis methods are utilized in conjunction with the study of industrial ecology and environmental management; one of these methods is Life Cycle Assessment (LCA). The LCA methodology was established in the 1990s by the Society of Environmental Toxicology and Chemistry (SETAC) and later formalized by the International Standards Organization (ISO) as a means to assess environmental impacts of a product system (BCL, 2003). The LCA method is used because it is well suited for the intended purpose of this research study; a comparison of two materials.

1.2.1 *Methodology*

According to the ISO standards, the LCA method is "a technique for assessing the environmental aspects and potential impacts associated with a product." (ISO14040, 1997, p.1). The importance of the LCA method is its adherence to set guidelines for data collection and evaluation, as well as interpretation of results. The LCA method allows for direct comparison between two materials by ensuring the context of the comparison is sound. The ISO established the necessary structure and academic guidelines to serve as a legitimate decision-making tool for product comparison in the relevant industry being studied (ISO 14040, 1997; Kotaji et al, 2003).

Figure 1.1. Life Cycle Assessment ISO Framework



Source: (BCL, 2006)

Using the Life Cycle Assessment (LCA) method, shown in Figure 1.1, this thesis compares concrete and steel as building materials in terms of well defined environmental impacts, with the intent to answer the question raised in the earlier section; which material, concrete or steel, is the 'better' choice when it comes to sustainable decision-making in building and structural design?

1.2.2 *Terminology*

Certain terminology is used throughout this report to provide clarity and conciseness. These critical LCA terms are defined below and taken directly from the ISO standards (ISO 14040, 1997; ISO 14041, 1998).

Product System ≡ collection of unit processes connected by flows of intermediate products which perform one or more defined functions

Unit process ≡ smallest portion of a product system for which data are collected when performing a life cycle assessment; unit processes are linked by product flows, intermediate flows, and elementary flows

Elementary Flow ≡ material or energy entering or leaving the system being studied, which has been drawn from or discarded into the environment without previous or subsequent human transformation

1.3 **Environmental Impacts Defined**

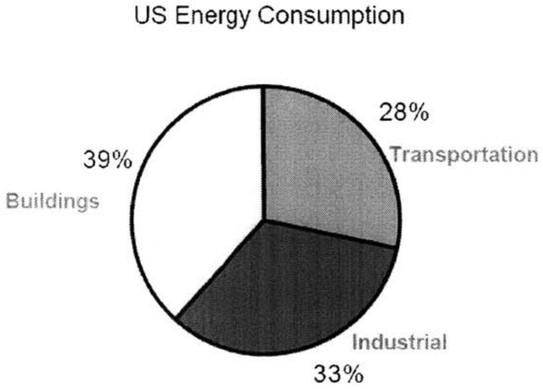
The three environmental concerns that serve as the focus for this study are 1) energy consumption; 2) harmful air emissions and their impact on global warming; and 3) depletion of the limited supply of natural resources. The basis for choosing these three environmental factors is discussed in greater detail in the following sections.

1.3.1 *Energy Consumption*

This research study focuses on consumption of energy because of its relevance in today's world. Increased energy prices and instability in the major oil producing countries have placed energy at the top of national political discussions and industrial sector challenges. The potential for energy shortages in the not so distant future has spurned debate on the necessity of alternative energy sources and the need to improve energy efficiencies in existing systems (Kibert, 2005).

Rising energy prices have a drastic effect on the built environment. Buildings are a large consumer of energy in the United States, accounting for 39% of total energy consumption. (DOE Building Energy Databook, 2005). This fact is represented in Figure 1.2.

Figure 1.2. United States Energy Consumption by Sector, 2005[2]



Source: (DOE Building Energy Databook, 2005)

Building energy consumption can be subdivided into two categories; 1) embodied energy defined as the energy used in its construction and pre-use phase; and 2) operational energy defined as the amount of energy required to operate and maintain the structure, including; providing heat, air-conditioning, lights, water, etc, for the building occupants (Kibert, 2005). The relationship between embodied and operational energy is highlighted

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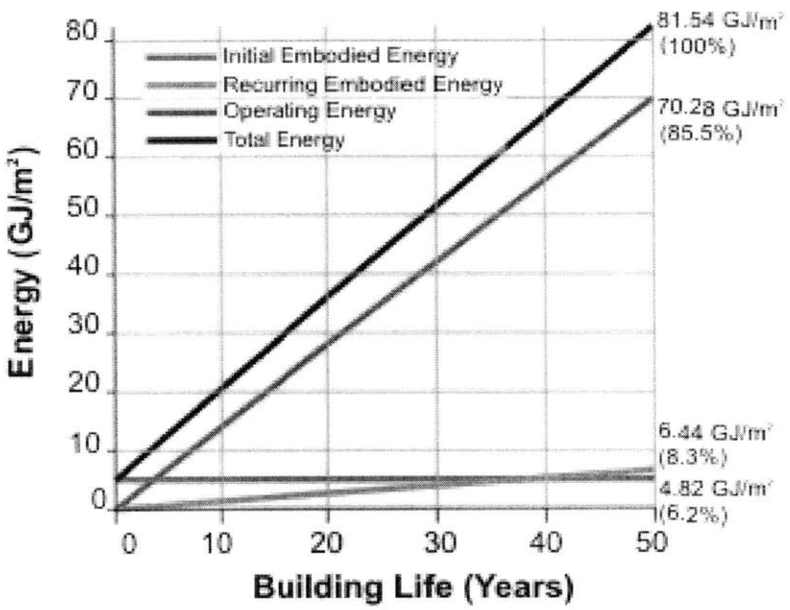
[2] It is safe to assume from the pie chart that a percentage of the other major energy consuming sectors are attributable to the building industry (transportation and production of construction materials) resulting in potentially an ever greater percentage of energy consumption attributed to buildings.

in Figure 1.3. While several sources have shown that operational energy far outweighs embodied energy accounting for an estimated 80% to 90% of total building energy (Cole and Kernan, 1996; Kotaji et al, 2003), the figure below highlights the relationship between operational and embodied energy relative to the life span of the building. Because average building life spans are decreasing and operational energy efficiency is improving, the relevance of embodied energy is increasing and its impact on the environment can not be ignored (Canadian Architect, 2006).

Figure 1.3. Embodied vs. Operational Energy



Source: (Cole and Kernan, 1996)

1.3.2 *Air Emissions*

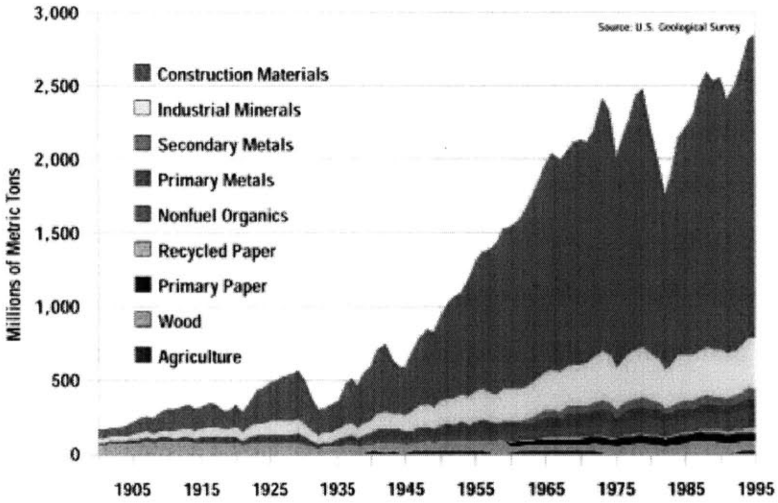
Harmful air emissions have become a major issue in today's world due to the effects of global warming and discernable climate changes over the past decade. According to the Natural Resources Defense Council (NRDC), global warming is the most complex environmental issue of our time. (2006). The Kyoto Protocol of 1997 placed CO_2 emission, in particular, at the forefront of environmental policy issues. The facts are that the building industry is the largest contributor to the total upstream CO_2 emissions accounting for 7% of the United States' annual global greenhouse gas emissions

(McMath and Fisk, 1999). CO_2 and other hazardous emissions from steel and concrete are examined because of their obviously harmful effects.

1.3.3 *Resource Depletion*

The construction industry accounts for a vast majority of the raw materials consumed in the United States, as shown by Figure 1.4. This enormous consumption rate, nearly two billion metric tons per year, poses a major environmental challenge because of the limited supply of natural resources on hand. The extraction and use of natural resources has significant potential impact on the environment (Graedel and Allenby, 2003).

Figure 1.4. Raw Material Consumption in the United States by Sector, 1900-1995



Source: (Matos and Wagner, USGS, 1998)

The utilization of cast-in-place concrete and steel as building materials is deeply entrenched in the construction industry and without practical substitutes their use is unlikely to disappear. Therefore, engineers, planners, architects and manufacturers realize that the solution to the environmental challenges must come from the method in which these materials are either produced, constructed, and/or re-used (Kibert, 2005; Graedel and Allenby, 2003). Newer concretes with recycled admixtures and the refinement of the steel manufacturing process to nearly 100% recycled content are just some examples of the industries' solutions to the environmental challenges related to their materials. The concrete and steel industries still, however, impact virgin raw materials. This thesis, using the LCA method, compares the environmental impacts associated with the two materials and highlights the critical unit processes where potential solutions to the resource depletion issue can be found.

1.4 **Research Objectives**

This research study applies the LCA methodology in order to compare concrete and steel when they are used as building materials. The major goals of this research study are to:

1) Provide a detailed life cycle analysis of steel and concrete on a tangible and performance-level basis in terms of energy consumption, harmful air emissions, and natural resource depletion.

2) Determine the sensitivity between operational and embodied energy in typical buildings of today.

3) Serve as a tool to compare construction materials in terms of sustainability on the individual building level and identify areas for potential improvement.

1.5 **Organization**

The remaining outline of this thesis follows the LCA methodology set forth in ISO 14040 series standards and published SETAC reports and depicted in Figure 1.1. The chapters are as follows:

Chapter 2: Goal Definition and Scope

Chapter 3: Process Flow for Concrete

Chapter 4: Process Flow for Steel

Chapter 5: Definition of System Boundary

Chapter 6: Inventory Analysis

Chapter 7: Interpretation of Results

2 *Goal Definition and Scope*

2.1 Goal Definition

The first step in conducting an LCA is to clearly define the goals of the analysis. It is critically important to state the intended purpose and application of the study (Graedel and Allenby, 2003; Kotaji et al, 2003). The essential elements of goal definition are outlined in the following sections.

2.1.1 *Purpose*

The purpose of this thesis is to compare the environmental impacts associated with steel and cast-in-place concrete, as they relate to the building construction industry on the 'micro-level'. The 'micro-level' for this study is defined as the lowest comparable performance application level for the two materials, in this case a single building. This will be discussed further as the functional unit of the LCA is defined in later sections. This study uses the 'micro-level' of construction to quantify the environmental impact of these major building materials in terms of energy consumption, global warming potential, and natural resource depletion at an appropriate and usable level for building designers.

2.1.2 *Target*

The results of this study are intended primarily for educational use and therefore not subject to critical review in accordance with the ISO 14040 standard.[3] The LCA outlined in this research study could be used as a baseline for determining the optimal material in a given geographical area in terms of the major environmental impacts and challenges discussed earlier. The results may be used to aid the construction industry make better choices in determining eco-friendly materials and construction practices.

Because of the regional nature of this comparison and the fragmented nature of the construction industry, the study would need to be modified to account for regional differences in construction practices and material production. The process for getting

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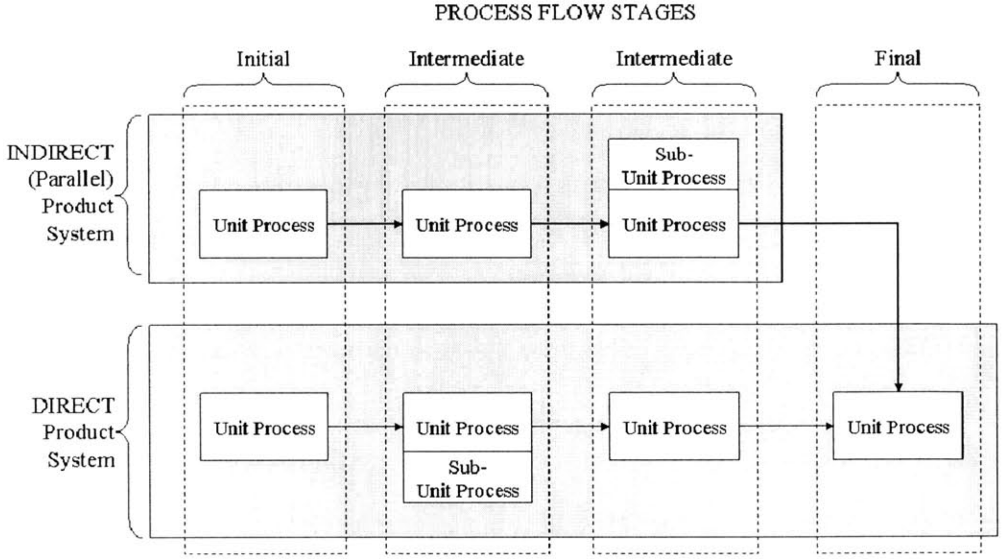
[3] According to the ISO 14040 (1997), the use of an LCA to support comparative assertions requires critical review to decrease negative effects on external interested parties. This report will not undergo a critical review because the results are primarily used for educational purposes only.

steel to the construction site in Boston will be different than Chicago, and the procedures for cast-in-place concrete in Boston will be different than the procedures in Miami.

2.1.3 *Subject*

The comparison of steel and cast-in-place concrete when used as the primary building material for the construction of a single building ('micro-level') is the subject of this LCA. Construction, as described in this section, includes all direct and indirect product systems relevant to the erection of a building. This research study is not simply a comparison of the amount of steel and concrete required (direct flows), but includes the parallel production flows of those materials, other than steel and concrete, that are essential components of the respective construction process (see Figure 2.1 for general framework used to develop the material process flows). These indirect flows include, but are not limited to, the manufacture of formwork for use in concrete construction and the application of fireproofing in steel construction. All direct and indirect production steps are included in the process flow diagrams for the respective materials, highlighted in Chapters 3 and 4.

Figure 2.1. General Framework for Process Flow Description



2.2 **Scope**

There are several studies and reports regarding the environmental impact of steel and concrete on a national level encompassing a very broad scope. One of these studies

(Low, 2005) and the Inventory of U. S. Greenhouse Gas Emissions report issued by the EPA (2005) make reference to raw data on total production output and air emissions for the entire United States.[4] Comparing CO_2 emissions and energy requirements for the entire concrete or steel industry ('macro-level') does not provide an accurate determination of environmental impact on the single building level, where it matters for sustainable design. In order to produce tangible results as they relate to sustainable construction, this LCA is intentionally narrow in breadth. It attempts to compare steel and concrete at the lowest possible common performance level in terms of the construction industry, as defined by the functional unit description in the next section.

The scope is also narrow in depth. It concentrates solely on the pre-use phase of buildings and therefore this LCA is further defined as a cradle-to-gate analysis of the respective building materials.

2.3 Functional Unit

The purpose of the functional unit in the LCA methodology is to provide "a reference to which the inputs and outputs are related." (ISO 14040, 1997, p.5). It is a critical piece of information for executing a proper assessment and ensuring a legitimate and accurate comparison of materials. The functional unit must correspond to results being achieved. In the case of this study, simply comparing a given volume of concrete and steel is flawed, because the materials have different performance characteristics and structural properties. For instance a cubic meter of concrete has very different performance characteristic than a cubic meter of steel. The backbone of this research study, and any LCA for that matter, is defining a functional unit that serves to equate the respective materials on a comparable performance basis (ISO 14040, 1997). Therefore, the functional unit for this LCA is defined as:

The amount of material (steel or concrete) required for the structural frame of a 100,000 square foot, multi-story commercial office building in Boston, MA.

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[4] The EPA provides a yearly review of total emissions in its Greenhouse Gas Report, which provides details on a national and state level. According to the Low (2005) study, 800 Mt of concrete was consumed in the United States in 1996 resulting in 145 Mt of CO_2 being emitted.

2.3.1 *Justification for Functional Unit*

1) A single building is used because it represents the lowest common performance application between the two materials. A column or beam could be considered as the basis for the functional unit, but a beam or column does not have a clearly usable function in the built environment, whereas a building has a clearly defined function.

2) An office building is used because it is a typical building type and common platform for sustainable design. In terms of LEED ratings, commercial office buildings account for the second highest share of LEED certifications, at 16% (USGBC Fact Sheet, 2006). 'Green' buildings are also encouraged by government agencies and private industry sectors to meet new regulatory mandates for sustainable design or fulfill new corporate mission statements on environmental awareness. In most cases these sectors are interested in developing office space.

3) The city of Boston is chosen for the geographical location due to its proximity to construction industry sources. The access to construction industry personnel is essential for data collection. It is possible to shift this study to any other metropolitan area, but it would require obvious changes to the process flows and production data.

4) A multi-story, 100,000 square foot (SF) building is used as a representative size of new construction in the New England area. This ensures that standard construction procedures are used on the construction of the functional unit.

2.3.2 *Inherent Assumptions*

1) Inherent in this functional unit is the assumption that the commercial building would meet existing building codes for the City of Boston and the State of Massachusetts and would be considered equal in terms of use, occupancy and performance.

2) This functional unit also implies that all required steps for construction will be included. This refers to direct, as well as indirect process flows. Concrete construction is not simply pouring the concrete (direct flow); it involves the production of formwork to hold the concrete in place as it sets and the production of steel reinforcing bar to provide tension resistance (indirect flows).

3) The building is assumed to be an ordinary, mid-range office space that would require sensitivity to cost during its design and planning phase.

4) The functional unit is for the structural frame of the building only.

5) All site work is considered to be equivalent and therefore negligible.

6) Foundations are not included because they are normally concrete for both materials. While the total weight of the two structures will vary and create different foundation requirements, this difference is outside the definition of the functional unit.

7) Floor slabs are included in the functional unit. For the concrete-frame a square grid beam and slab form is assumed. Concrete floor slabs are also used for the steel-frame structure and concrete is considered a product system of the overall steel process flow and included in the inventory analysis as such.

8) Exterior and interior walls are not part of the functional unit.

9) Exterior cladding and finishes are not included in the functional unit because these systems are irrelevant to the study. While there might be slight differences in how cladding is applied to the different frame systems, these differences are negligible and therefore not included in the LCA.

2.4 **"Most Widely Used" Method**

According to Tom Taylor an estimator for Suffolk Construction in Boston, each construction project is unique and no two projects are completed or conducted in the exact same way. They can vary drastically depending on scheduled timeline, special considerations, and site location. Most general contractors have standard operating procedures for the conduct of a job, but each construction project will require different materials and varying sub-contractor relationships, thus leading to a different process flow for each individual construction job, irrelevant of the primary building material used. Obviously this poses a challenge in the development of a quantifiable process flow. Without a defined process flow, for either concrete or steel, the LCA method becomes invalid and immeasurable (UNEP, 1996).

To solve this issue, a material flow called the 'most widely used' (MWU) method is created for this study. The phrase 'most widely used' is defined as the predominant method for steel or concrete material to be manufactured, shipped to, and erected on a typical construction-site in the metro-Boston area. This method captures and utilizes the Boston construction industry's most common and typical construction procedures into one single and defined flow. The MWU method is derived primarily through interviews conducted with local construction firms, sub-contractors, and related businesses and uses the following assumptions in its development.

2.4.1 *Minimum Thresholds*

A simple majority (>50%) is used to define the minimum threshold for the MWU method. For example, if two out of three concrete contractors said that they use a certain brand-name formwork the most, on a typical job involving the defined functional unit, then the specific information on that brand-name formwork is used in the MWU method. Similarly, if the steel mill stated during an interview that they normally deliver 75% of their beams by rail, then rail transportation is used in the MWU method for steel. These numerical percentages were obtained by specific interviews with industry personnel.

In some cases, due to complexity of the data collection process or the lack of a defined predominant use, a certain flow is assumed without reaching the minimum threshold. For instance in the case of fireproofing, weighting the different fireproofing materials in terms of use, each with a different production process, would have severely complicated the data analysis and was considered beyond the scope of this study. A typical fireproofing was selected that provided the most detail on its production.

2.4.2 *Backwards Modeling*

In both cases, steel and concrete, the process flow charts are derived by figuratively working backwards from the construction site. Several of Boston's large general contracting firms were interviewed to determine their most typical operating procedures and construction material uses. In most cases the large general contracting firms had relationships with several sub-contractors and material manufacturers. These sub-contractors also provided insights into specific construction practices for the local Boston area. For example, if the major Boston general contractors stated that they typically only use three concrete sub-contractors for the size of our assumed project (100,000 square feet), then those sub-contractors were contacted to determine their typical procedures in the construction process. The backward model ensures that the relevant sub-contractors, finished material manufacturers, and initial production facilities are properly included in this research study. It also allows important intermediate steps and flows to be identified in the process, to include intermediate transportation hubs and bulk material storage sites.

2.4.3 *Regional Characteristics*

Obviously the MWU method for Boston is going to be different in other geographical areas within the United States. In some cases there might be subtle differences that can be neglected, but in other cases the difference would be significant enough to skew the results. It is important to note that defining the functional unit for this LCA in terms of a very specific geographical area is unavoidable. The only way to make a true comparison between the use of concrete and steel as building materials is to assume a location and use the relevant flows for that region.

This is one drawback of the narrow scope of this study and the very specific functional unit used. The procedures outlined in this LCA can be translated into different regions, but it would require a complete re-evaluation of each step of the process flow, especially in terms of transportation requirements and finished material manufacturing. For example, while most quarries operate in similar fashions across the United States, certain raw materials are more abundant in certain areas than others and this would affect the process flow. Simply stated, the MWU method for Chicago might not be the same for Boston, or New York, or Miami and is thus un-transferable without significant effort and resource.

2.4.4 *Proprietary Issues*

The nature of this study is that it requires very specific information on production flows for single industries and even sometimes single production facilities. Because the construction industry is a very competitive, cost-driven market and procedures, man-hours required, and production rates are kept proprietary, specific and detailed information was extremely hard to obtain. For instance, the fireproofing manufacturer does not want to make public his production formula and is therefore unwilling to provide any additional information beyond what could be found on a very succinct summary located on a published material safety data sheet (MSDS). This makes it nearly impossible to track material inputs, waste removal, and energy requirements which are critical when looking at the life cycle of a given finished product or material. This was true to varying degrees across the entire spectrum of the data collection. In this case, assumptions to the MWU method are made using the best available information.

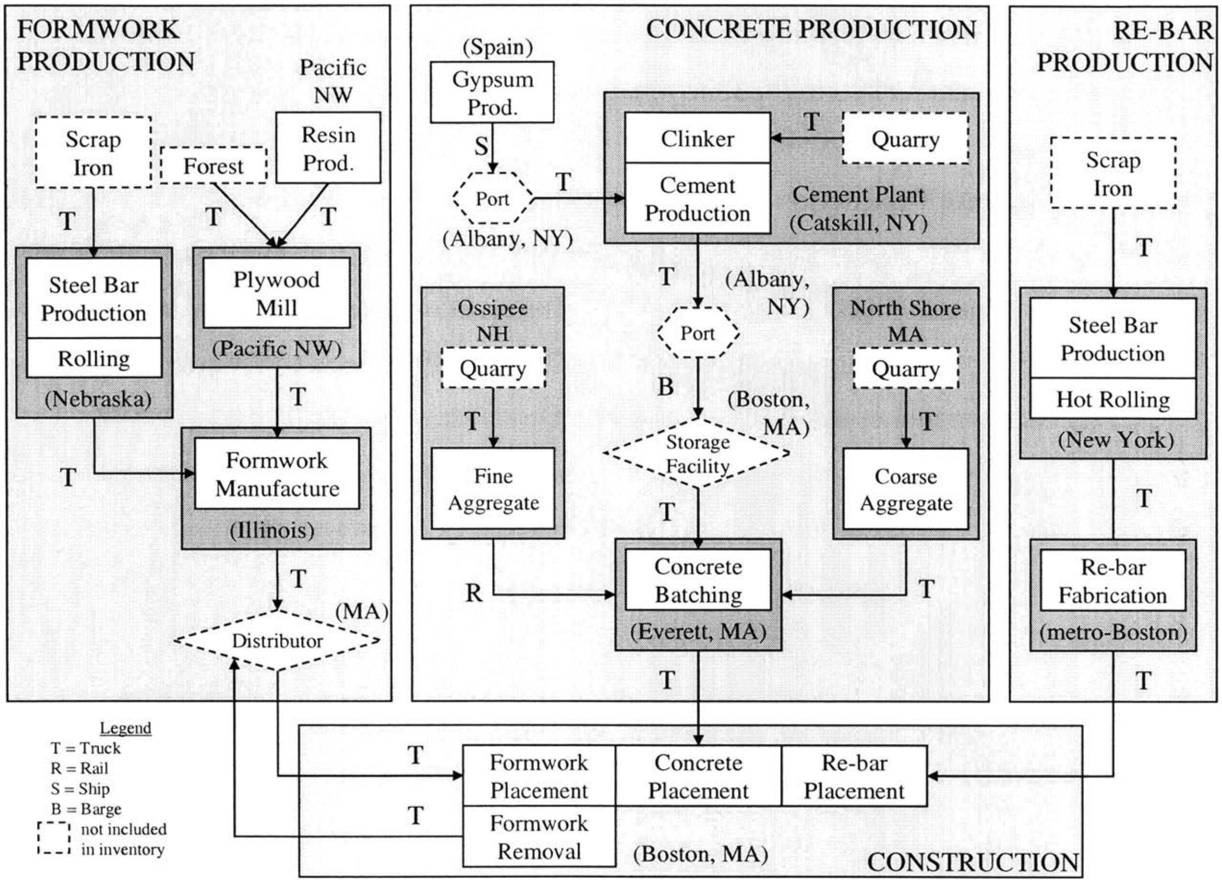
2.4.5 *Time Frame*

Determining the time frame to use for the MWU is another consideration that affects the steel and concrete material process flow. The construction industry is very cyclical and this has a major effect on the MWU method. The predominant or most common method today may not be the same tomorrow. Subtle changes in world markets have effects on the local construction industry. Time frame for this study as it relates to the MWU method will be current conditions in the concrete and steel market.

3 *Concrete-Frame Construction Process Flow*

3.1 Process Flow Description

Figure 3.1. Process Flow Diagram for Concrete



The process flow chart for cast-in-place concrete using the MWU method is shown in Figure 3.1 above. For this study, the process flow was broken down into four major components, or main product systems. The term 'product system' is defined in Chapter 1. The main product systems for the construction of concrete buildings are listed below:

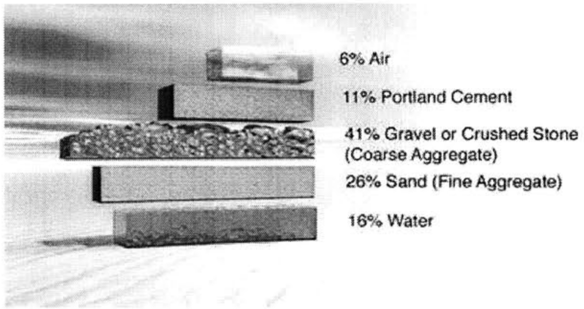
1) Concrete Production
2) Formwork Production
3) Reinforcing Bar Production
4) Construction

These product systems are depicted as the four lightly shaded boxes on the flow chart in Figure 3.1 and will be used as the framework for the inventory analysis. Each production system contains unit processes (shown as the white boxes on Figure 3.1) which contain the elementary inputs and outputs used as the reference for data collection. The four product systems are discussed in greater detail in the next several sections. The detailed discussion includes a general process description of each system and then a specific discussion of data related to the functional unit and the MWU method.

3.2 Concrete Production

Simply stated, the production of concrete involves the batching (or mixing) of all major inputs in a standard ratio. The major inputs of typical concrete include Portland cement, fine aggregate, coarse aggregate, water and additional admixtures (if required).[5] Figure 3.2 depicts the major components of concrete.

Figure 3.2. Typical Concrete Composition



Source: (PCA, 2006)

Concrete is produced at batching facilities where the component materials are gravity fed through hoppers by specific ratio and then mixed. Generally, there are two types of batching systems, a wet-batch system and a dry-batch system. The main difference is that in the wet-batch system (also referred to as a central mix system) the components are mixed at the batch plant prior to loading on the mix truck, where in the dry-batch system,

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[5] For this LCA, an ordinary Type I/II 3,000 psi concrete is used. This type of concrete is normal for the type of construction in Boston used in the construction of our functional unit building (Project Manager, Turner Construction, personal communication).

the components are mixed in the truck en-route to the job-site. In the United States 80% of the concrete batching facilities use the dry batching system (NRMCA, 2006).

In terms of the MWU method, nearly all of the major construction companies in Boston utilize two ready-mix concrete (RMC) companies to provide their concrete material, Boston Sand & Gravel (BS&G) and Aggregate Industries (AI). These two companies have relatively equal production capacities and receive their inputs in similar fashions. This study refers to BS&G data, attained through interviews with personnel associated with BS&G, to determine specific production flows. Portland cement is delivered by bulk carriers (trucks) from a cement storage facility just north of downtown Boston. The coarse aggregate is trucked from rock quarries on the north shore of Massachusetts, while the fine aggregate (sand) is delivered via rail from quarries in southern New Hampshire. The transportation asset and relevant locations are depicted on the flow diagram. BS&G uses a central mixing system.

3.2.1 *Cement Production*

The production of Portland cement is an essential component (sub-unit process) of concrete production. There are 109 active cements plants in the United States, with only four located in the northeast region[6] (van Oss, 2004). A graphic description of the overall process is shown in Figure 3.3.

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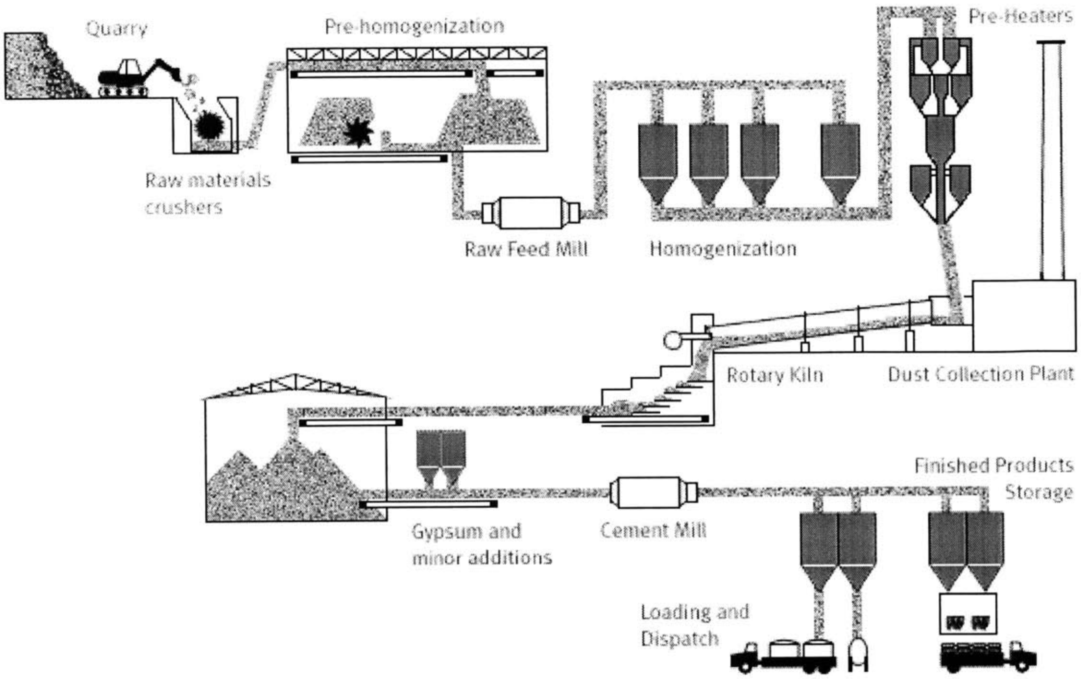
[6] Northeast region is considered New York and Maine. There are three plants in New York and one in Maine. One of the plants in New York is used as a baseline in this study.

Figure 3.3. Cement Production Process



Source: (PCA, 2006)

Raw materials including limestone, sand, and iron ores are extracted from quarries (see Table 3.1 for basic chemical components of cement), blended and crushed into a powder. This powder is then fed through a kiln, where the input raw materials are chemically combined under extreme heat (known as pyro-processing) into a material called clinker. The clinker is then cooled and ground with a small amount of gypsum into a very fine powder. This powder is Portland cement (PCA, 2006; ACI Educational Bulletin, 2001).

Table 3.1. Basic Chemical Components of Portland Cement

Basic Chemical Components	**Typical Raw Materials**
Lime (CaO)	Limestone
Silica (SiO_2)	Sand
Aluminum (Al_2O_3)	Shale, Clay, Bauxite
Iron (Fe_2O_3)	Shale, Clay, Iron Ore, Mill Scale

Source: (ACI Educational Bulletin, 2001)

Clinker production is the most energy intensive portion of this process with temperatures reaching over 1800° C. Because of this, Portland cement accounts for 94% of the energy used to produce concrete, but only accounts for 12% of the volume (Wilson, 1993). The pyro-processing also accounts for a large amount of CO_2 emitted as a by-product of calcination, which occurs in the kiln at roughly 900° C. Calcination is the chemical process where limestone ($CaCO_3$) is converted to lime (CaO) and CO_2 at very high temperatures (Chaturvedi and Ochsendorf, 2004).

$$CaCO_3 \rightarrow CaO + CO_2$$

Estimates show that over 50% of the CO_2 emissions from cement production are due to the calcination process and the remaining is due to release of CO_2 during the burning of fossil fuels (Hendricks et al, 1998; Choate, 2003).

In reference to the MWU method for the metro-Boston area, Portland cement is produced at cement production plants and shipped to the bulk storage facilities mentioned in Section 3.2. The cement production facility that services the specific metro-Boston area storage silo is located in the Hudson River valley of upstate New York. This cement plant is co-located with a limestone quarry for obvious efficiency reasons. Specific process flow information on the plant, gained through interviews with the Quality Control manager Andrew Lessard, indicates that the limestone is mined directly on site and transported to the primary crusher (distance is under one mile). The mined limestone contains enough sand and clay (with aluminum and iron) not to require additional inputs from outside sources (refer to Table 3.1). In some instances, when required, additional sources of iron ore are delivered via truck from local sources. These sources of iron are normally by-products of a separate industrial process (i.e. slag/mill scale). The cement plant, used for this study, uses a wet process to control the raw material inputs. This system is the older and less efficient method. Only 25% of cement plants utilize this older technology (van Oss, 2004). Primary heat source for the kiln is coal. Roughly 80,000 tons of coal is consumed per year at this facility. Electricity provides the energy source for operation (turning) of the kiln and all additional production machinery to include the crushers and grinders.

The primary product output from this cement production facility is Portland Type I/II. The cement is shipped in bulk to local storage facilities in Boston by barge, down the Hudson River and up the Atlantic coast. Trucks deliver the cement from the cement plant to Albany, New York where it is loaded onto barges. Any solid waste produced is transferred to local landfills and incinerators.[7]

3.2.2 *Aggregate Production*

Aggregate required for concrete batching is divided into two categories; 1) coarse aggregate (gravel/crushed rock) and; 2) fine aggregate (sand). The coarse aggregate is derived by extracting rock from quarries and iteratively crushing and sifting it to specific size. The fine aggregate is derived in a similar fashion and in some cases from the same process, with one or two additional production steps (EPA(b), 1995). These steps are included in the separate inventory analyses.

For the purpose of the MWU method, sand is extracted in quarries in Southern New Hampshire and shipped directly via freight rail. The coarse aggregate, gravel/rock is mined at local quarries in the north shore of Massachusetts and delivered to the batching facility by truck. This information is derived from the BS&G baseline batching facility information discussed in Section 3.2.

3.3 **Formwork Production**

Formwork is a necessary and critical component of the cast-in-place concrete construction industry. For the purpose of this report, the manufacturing of formwork and all of the sub-unit processes are considered an indirect (parallel) product system, as opposed to the direct production of concrete itself. Forms are usually constructed of different types of plywood, but can also be made of plastic or steel. The three main types of plywood used in forms are High Density Overlay (HDO), Medium Density Overlay

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[7] Disposal site is assumed to be within a 40 mile radius for inventory purposes.

(MDO) and B-B plywood (APA, 2003). Their use is dependent on the exposure and finish level of the concrete walls or column to be poured. See Table 3.2 for description. There are several major formwork manufacturers in North America and in Northern Europe that compete for business in the United States. These companies use local distributors and sales personnel to market their product to the construction industry.

Table 3.2. Types and Characteristics of Plywood (used in Formwork Manufacture)

Form Type	Quality	Uses	Use Duration (Times Re-used)
HDO	Highest	Smooth, flawless concrete surface finish	20-50*
MDO	High	Flat concrete surface finish	N/A
B-B	Moderate	Uniform concrete surface finish	5-10

* could be as high as 200

Source: (APA, 2003)

The concrete column in this study is assumed not to be exposed and will therefore not require a high level of finish. According to Steve Montero a foreman for S&F Concrete Contractors, the most common form type for use in constructing the functional unit is a standard size B-B Plyform, from one of the domestic manufacturers.[8]

Frequently, formwork is rented to the contractor on a temporary per job basis. Regional formwork distributors will stock several standard size forms directly from the manufacturer. This distributor is considered an intermediate step and no elementary flows are associated with it. Only location, as it relates to travel distances, is relevant to the inventory analysis.

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[8] Symon's SteelPly form system is assumed in conjunction with the MWU method. This system utilizes a BB plywood face with steel bracing.

3.3.1 *Plywood Production*

Plywood is manufactured by layering several layers of wood veneer with resin. There are several grades of plywood and they are typically milled in the Pacific Northwest or Canada, near abundant sources of wood. In the United States the primary wood source is Douglas Fir, considered softwood.

For the process flow outlined in Figure 3.1, the plywood mills are assumed to be located within 50 miles of harvesting site. The raw logs are transported by truck to the plywood mill. Electricity is the main source of energy for production. The resin required for production is assumed to be manufactured within a 100 mile radius of the plywood mill for the purpose of the inventory analysis. These assumptions were attained through telephone interviews with M. Kline at the Engineering Wood Association (APA) Resource desk.

3.3.2 *Steel Section Production (for Formwork Bracing)*

The requirement for steel bracing is included in the formwork product system and in the overall process flow for concrete-frame construction. A small-sized angle section is assumed, based on interviews with Tyler Shannor, representing Symons Forms. The steel production process is detailed further in future sections and Chapter 4.

For the MWU method, the steel is manufactured at a regional steel mill and transported via truck. The Nucor-Norfolk bar mill in Nebraska is used as a baseline for location and recycled content (Nucor Norfolk, 2006).

3.4 **Reinforcing Bar Production**

The third major component of any cast in place concrete job, besides the formwork and concrete, is the reinforcing bar (re-bar). Reinforcing steel bar is produced in steel bar mills using the (EAF) continuous mini-mill process throughout the United States. The EAF is a steel-making process described in greater detail in Chapter 4 (steel process flow). Typically, re-bar is available from local warehouses and distributors that stock typical sizes and lengths. Re-bar is then fabricated and formed into steel cages based on specific construction diagrams and project specifications.[9]

Based on information gathered from both re-bar fabricators and concrete contractors for the MWU method, it is determined that most re-bar for use in Boston is obtained from regional suppliers. These regional suppliers receive steel bar from varying bar mills based on availability and several other factors. For the purpose of defining a single flow, a regional EAF mini-mill is used for this study. The closest facility, a mill in New York, is used as a base line for re-bar production data and location assumptions. This particular mill utilizes 100% recycled content to produce the steel bar (Nucor Auburn, 2006). In most cases the re-bar is fabricated at an off-site location near the construction site. For the process flow outlined in this study, the sub-unit process of steel re-bar fabrication is included in the inventory analysis. The steel bar is transported via truck throughout the entire flow process, from mill to fabricator to construction site (Project Manager, Harris Rebar, Inc., personal communication). The relevant locations are on the process flow diagram in Figure 3.1.

3.5 Construction

A typical construction site involving cast in place concrete involves the integration of formwork placement, re-bar installation, and concrete pouring. These are all essential unit processes of any cast-in-place concrete construction project. In-situ concrete construction is typically tasked to a sub-contractor directly by the general contractor. The concrete sub-contractor usually handles all three processes on the job site (Project Manager, Turner Construction, personal communication). There are several major concrete contractors that work in the Boston market, who will serve as the basis for the data collection and assumptions. The elementary flows considered for construction are primarily energy use (related to major equipment usage and power generation requirements on-site) and waste removal.

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[9] The re-bar is usually fabricated off-site, shipped to the construction site, then formed into the necessary cages prior to concrete pouring (Project Manager, Harris Re-bar, personal communication)

3.5.1 *Formwork Placement*

Standard size forms are clasped together to create column formwork on-site. The number of columns per floor usually determines the number of formwork molds built. Normally, on a daily basis, a certain number of forms are being poured and a certain amount of forms are being broken down and moved to a different column location for additional pouring. This is a typical rotation at a job site according to contractors interviewed (Montero, personal communication). Formwork is used for the columns. Floor slabs and beams are usually poured using shoring systems. These shoring systems are typically aluminum or steel with a significant usable life. In this case the shoring system is neglected due to its relatively long life span.

Typically, on a job in Boston, most forms are erected by manual labor without the use of cranes or machinery (Montero, personal communication). There is no measurable energy input, beyond manual labor (which is outside the system boundary). The formwork requirement, in regards to the functional unit, is for the columns only. The assumptions for inventory purposes are listed in Appendix A-1.

3.5.2 *Reinforcing Bar Placement*

The installation of re-bar is usually done prior to the formwork being placed. Column formwork is then placed around the re-bar cage and the concrete is poured. For this study, it is assumed that steel re-bar cages are formed on-site, using manual labor and lifted into place with cranes. It typically takes 5-10 minutes per cage for crane operations. This is accounted for in the study. Waste steel is piled for removal. This study assumes a 1% loss of steel re-bar when it is assembled into cages on-site (Montero, personal communication).

3.5.3 *Concrete Placement*

Normally on a multi-story project concrete is placed using either a bucket or pump truck. As stated earlier, the RMC used in Boston is centrally mixed and ready to be poured immediately upon leaving the batching facility. The mix truck delivers the pre-mixed concrete to the site and the pump truck or bucket delivers the concrete to the necessary level and location on the job site.

The inputs for the concrete placement unit process are the concrete, its transportation requirement, and the energy required to operate major equipment during the pouring of concrete. This includes the operation of the mix truck and pump truck at idle, as well as any additional generators on site to provide power to tools, vibrators, etc. Energy use is incorporated into the inventory analysis using assumptions and equations listed in Appendix A-1 and A-2.

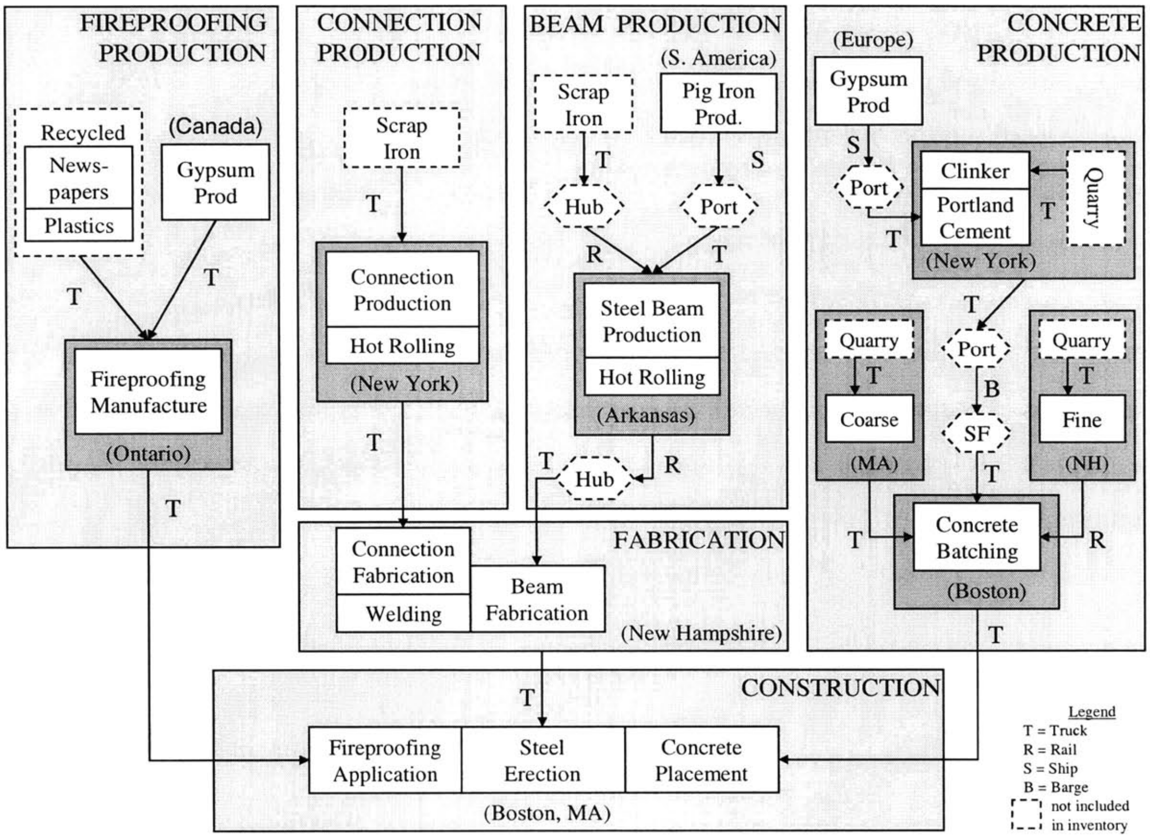
3.5.4 *Formwork Removal*

Formwork is removed once the concrete sets. This process flow is included to account for the loss of forms due to normal wear and tear. For instance on a typical job 10% of the forms are lost to wear and tear and need to be replaced (Montero, personal communication).

4 *Steel-Frame Construction Process Flows*

4.1 Process Flow Description

Figure 4.1. Process Flow Diagram for Steel (MWU)



The process flow chart for steel using the MWU method is shown in Figure 4.1. For this study, the steel process flow was sub-divided into the six product systems listed below:

1) Steel Beam Production
2) Steel Connection Member Production
3) Steel Fabrication
4) Fireproofing Manufacture
5) Concrete Production (for floor slabs)
6) Construction

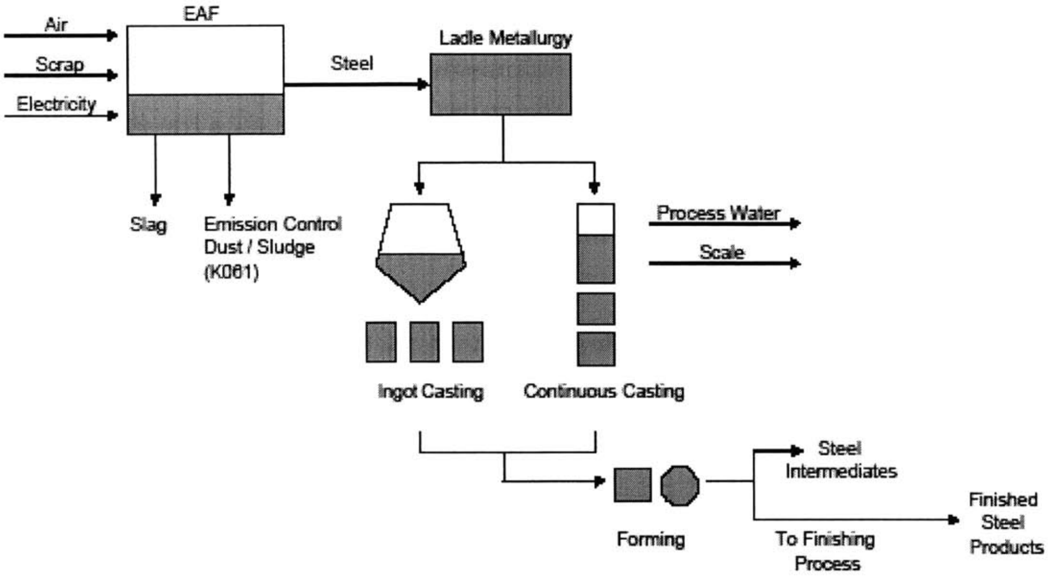
These six product systems are depicted as the main (lightly shaded) boxes on the flow chart in Figure 4.1 and will be used as the framework for the inventory analysis. Each production system contains unit processes (shown as the white boxes on Figure 4.1) which contain the elementary inputs and outputs used as the building block for data collection. The six product systems are discussed in greater detail in the next several sections. The description includes specifics of typical production and then discussion of relationship to Boston and the MWU method (used in this study).

4.2 **Steel Beam Production (Wide-Flange)**

All steel beams made in the United States are produced in 'mini-mills' using electric arc furnace (EAF) technology to turn a mixture of iron scrap (recycled iron and steel) and small inputs of virgin iron into structural steel. The percentage of recycled content used in EAFs across the United States steel industry is 96%, according to the Steel Recycling Institute (2005). These EAF facilities are called 'mini-mills' because they utilize a single continuous process to turn the raw materials into finished sections. While EAF steel is not as pure as virgin steel, it meets all necessary standards for structural members (Fenton, M., 2004). The basic steps in the 'mini-mill' steel-making process are depicted in Figure 4.2.

The first step is the receipt of the scrap iron. The scrap is weighed, checked with a radioactive sensor and then sorted (with quality control measures) into piles ready for use. The scrap, depending on established production mixes, is then mixed with the virgin (pig) iron and placed in the EAF. The EAF uses electrodes to melt the scrap mix. The liquid iron is then ladled and de-sulphurized, the oxygen is removed, and metal alloys are added (depending on the type of steel). The molten liquid is then casted, where it is converted from liquid to solid by cooling. The casted steel than continues to the reheat furnace where it is descaled, scarfed, and then hot-rolled into standard sections. Steel can be either cold formed or hot rolled into its standard shapes. All structural steel beams (wide-flange sections) are hot-rolled. The wide-flange section is then cooled, straightened, cut, tested and bundled for shipment. The single continuous process is completed at the same facility, hence the 'mini-mill' concept (EPA, 2004).

Figure 4.2. "Mini-mill" Production Process



Source: (EPA, 2004)

In the development of the MWU method it was shown that a majority of the steel jobs in Boston do utilize domestic steel. This can vary however, depending on price, steel availability, and rolling schedules (Taylor, personal communication). In some cases, general contractors will purchase steel from overseas suppliers. With enough lead time, fabricators and contractors can ensure that the sections they need are available from domestic steel mills. Using information obtained from regional fabricators this study assumes the use of domestic steel and the linkages in the inventory analysis are developed from domestic manufacturers.

Based on our set threshold we utilized a single domestic steel producer as our MWU. This steel producer, Nucor Yamato Steel (NYS), located in Arkansas, is a major steel supplier to the Northeast and the largest steel producer in the United States. According to its recycled content verification letter, the NYS 'mini-mill' uses a 95% recycled content to produce its wide-flange sections. The remaining balance is pig iron received from foreign sources. The recycled scrap is obtained from local scrap yards using an average 500 mile radius (NYS, 2006). The scrap iron is transported by trucks to a rail head. The scrap is then railed and unloaded at the steel EAF production facility to begin the EAF production process. Without specific data, the study assumes pig iron from South America because of proximity to the Southeast United States. The specific information on the inbound shipment of pig iron is shown on the process flow diagram (see Figure 4.1).

The EAF process is very energy intensive. A large majority of the energy requirement is electrical, provided by local electricity companies. The reheat furnace requires its own source of energy for its heat generation and in the case of the NYS mill it consumes natural gas. Oxygen and chemical energy is also used in the EAF, but is considered outside the system boundary.

Because of the size and weight of the finished steel members, manufactures like to transport their finished product via rail or barge. The NYS mill, located in Arkansas stated that they shipped roughly 30% by rail, 60% by truck and the rest by barge. In the case of Boston, fabricators receive their shipment via rail, so rail serves as the baseline for the MWU method.[10] Any steel that is wasted during the process is immediately recovered and recycled into the piles for use in the EAF furnace.[11]

4.3 Steel Connection Production (Angle Section)

Steel that is used for the production of connections are typically angle sections or plate steel. Most angles are produced using the EAF and hot-rolling process described above in Section 4.2. However, as a general rule, angles are produced in different steel 'mini-mills' than wide-flange sections.

Typical steel connection sections used in steel fabrication are produced in the United States with a greater predictability than the steel wide-flange beams. This is due to the fact that fabricators rely on typical angle section sizes to fabricate the steel connections.

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[10] In regards to outbound shipment for NYS a majority is via truck (60%); however shipment to the Northeast is accomplished by rail.

[11] Specific information contained in this section regarding steel-making process flow was obtained through interviews with Dhiren Panda, Quality Control Representative at NYS.

The structural engineer establishes the end support requirement and fabricators have enormous flexibility to create the actual dimension and type of the connection. In most cases, the fabricator will meet the end support requirements, by using a standard angle size. This allows the fabricator to keep a regular stock of typical angle sizes and establish a relationship with certain steel manufacturers. In very rare cases are connection steel sections drawn from overseas sources. Steel fabricators normally receive their angle sections from the nearest steel bar mill (Steve Coates, Engineer at Novel Iron Works, personal communication).

The 'mini-mill' that is assumed for the MWU method as the supplier of steel angle sections to the fabricator is a Nucor mill located in Auburn, New York. This mill produces steel angle sections using 100% recycled steel (Nucor Auburn, 2006). The scrap iron is delivered by truck from local scrap yards assumed to be within 100 miles of the Auburn mill. Because of a shorter delivery distance, a truck is also used as the transportation link between steel producer and steel fabricator (Sales Manager, Nucor Auburn, personal communication). See Figure 4.1 for relevant locations and method of transport.

4.4 Steel Fabrication

Steel fabrication, which involves the cutting, drilling and fitting of the raw steel members to meet the project specifications, is usually accomplished by a steel fabricator. These fabricators are usually sub-contracted directly by the general contractor to perform this essential activity. Fabricators are responsible to interpret the construction documents, receive the steel, determine the required fabrication, create connections, and bundle the steel for shipment to the job-site (Coates, personal communication). Beam sections and connection sections are combined during this phase of the process flow, but have separate fabrication methods prior to being connected. The primary output from the steel fabrication shop is a 'combined member' ready for erection at the construction site.[12]

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[12] This study uses the term 'combined member' to define the output of the fabricator. This 'combined member' is a combination of the steel wide-flange beam and four angle section connections. The combined section is used as a link between the inventories. See general assumptions in Appendix B-1.

4.4.1 *Beam Fabrication*

Structural beams are fabricated under the following basic steps.[13] The steel is unloaded at the site, normally by truck delivered either directly from the mill or from a local railhead. The fabricator stocks some common member sizes, but in the optimal case and in most cases prefers to order steel sections directly from the mill to avoid unnecessary waste. The ordering and shipment process usually takes 4-6 weeks. Once received the members are tagged by job number and begin the in-line process. First, the beams are cut to the required length by heavy duty band saws. The ends of structural members are then drilled to provide for bolted connections. This is primarily done with a drill, but in some cases a punch is used. The members are then passed to a plasma cutter if copes or irregular angles need to be cut.

Each section is then handed over to a steel fitter, whose job is to layout, grind and fit the section in accordance with the shop drawings. At this point the fitter will either bolt the connections or temporarily tack the connection, if a welded connection is required. The cost and resource requirements for bolted connections are minimal and therefore preferred. The combined section (steel beam with angle end connections) is then sent through quality control and passed to the welding section to turn any temporary tacks into permanent welds using a gas metallurgic arc welding process. Most fabrication shops have multiple stations for both fitting and welding.

If painting is required the combined section undergoes surface preparation before painting occurs (either sand blasting or hand sanding). The combined sections are then bundled by job, loaded by phase and shipped out according to the construction schedule. Today, a large portion of the fabrication is fully automated using sophisticated CNC machines and software.

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[13] The fabrication process outlined in this section was gained from interviews with the engineering section during a facility walk-through visit at Novel Iron works. (Coates, personal communication);

There are several steel fabricators that operate in New England. Only a few have the ability to fabricate on a large scale to meet the needs of the defined functional unit (100,000 sf). For the MWU a single source steel fabricator is used for flow information.

4.4.2 *Connection Fabrication*

Connections are fabricated in a slightly different fashion than primary steel beams prior to fitting. They are fabricated on a different line than the wide-flange sections. If plates are required they are cut by a large press or automated plasma torch. Angle sections are cut using a press and holes are typically punched, not drilled. If required, connection members will be cut using the plasma cutter for complicated angles and irregular cuts (Coates, personal communication).

Connections are fabricated at the same facility as the wide-flanges. This is obvious and intuitive. The wide-flange sections and connections are welded or bolted at the fabrication shop to the greatest extent to avoid expensive connections at the job site. In most cases the connections are bolted connections, but in some case welds need to be done in accordance with engineer specifications.

4.4.3 *Welding*

According to the industry, roughly 15% of the connections at the fabrication shop are welded, but this can vary for each different project (Coates, personal communication). When a weld is required this study assumes that the weld is a sub-unit process of the connection fabrication rather than the wide-flange fabrication. This allows for easier tracking of the data in the inventory analysis phase of the LCA.

4.5 **Fireproofing Production**

Building codes require fireproofing to be applied to steel-frame structures. Because of this code requirement, the production of fireproofing is a major indirect product system and parallel flow when analyzing steel as a building material. There are two general types of steel fireproofing, intumescent paint and cementitious based spray-on fireproofing. In general, the spray-on fireproofing is used in the majority of steel buildings in the United States. An estimated 95% of steel building use spray-on type fireproofing (Frank Neuwirth, Business Development Manager, Carboline Company, personal communication). This is mainly due to cost considerations because intumescent paints cost four times as much as traditional spray-on fireproofing. Spray-on fireproofing is further broken down into three categories as described in Table 4.1.

Table 4.1. Categories of Spray-on Fireproofing.

	Density (lbs/ft3)	Designed for	Typical Uses
Low Density	15	Concealed areas No abrasion requirement	Commercial buildings
Medium Density	22	Exposure to moisture Abrasion resistance required	Gymnasiums, pools Mechanical rooms
High Density	40	Exposure to indirect weather Abrasion resistance required	Stadiums Manufacturing plants

Source: (All South Subcontractors, Inc., 2006)

The main differences between the categories are their thresholds to moisture exposure, durability, and of course, cost. These factors are the main decision-making criteria for selecting the appropriate type of spray-on fireproofing. Typically spray-on fireproofing consists of either gypsum or Portland cement combined with additives like plastics, cellulose, and/or vermiculite. Each spray-on fireproofing manufacturer has a specific product formula, which is highly-protected and not publicly disclosed.

With regards to the inherent assumptions of the functional unit, this study used low-density fireproofing because the structural steel will not be exposed to moisture. According to Boston contractors, the most widely used low density spray is Monokote MK-6 (Taylor, personal communication; Scott Littlejohn, Century Drywall, personal communication). Due to the proprietary nature of the industry, the highest level of detail for specifics on MK-6 composition[14] and process flow[15] is obtained from a publicly

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[14] Monokote MK-6 consists primarily of gypsum, polystyrene, and cellulose. The proportions of the three primary materials (gypsum, cellulose, and polystyrene) have a wide range on the MSDS. For the purpose of the study the following percentages were assumed; Gypsum (85%), cellulose (7.5%) and polystyrene (7.5%). The cellulose and polystyrene are gained from recycled sources.

[15] The fireproofing is manufactured in Ontario, Canada and normally shipped by truck in bags.

released MSDS and product website (Grace, 2006). The transportation linkages are assumed from discussions with contractors and product sales representatives and are depicted on the process flow diagram (John Colby, Sales Representative for Grace Construction, personal communication; Steve Bass, Plant Manager, personal communication).

4.6 **Concrete Production**

An integral part of steel frame construction is the placement of concrete. Steel frames require a concrete floor slab system. In a typical floor slab only minimal reinforcement is required due to the composite action of the steel decking used to support the concrete floor slab.

In terms of the MWU method, a simple six inch concrete slab is assumed for the flooring systems. The product system consists of the concrete production and placement on-site of the given volume of concrete disregarding any steel reinforcement. Concrete production for the steel process flow uses the same steps outlined for the MWU in Section 3.2. The amount of concrete required is calculated below:

Slab Depth		Floor Area		# of Floors		Total Volume of Concrete
6 in	x	25,000 ft^2	x	4	=	50,000 ft^3

4.7 **Construction**

The main unit processes on a steel construction site are the erection of steel and the application of fireproofing. These processes are described in the following sections. The flows considered in this section are the energy consumed (in terms of equipment use) and waste removal.

4.7.1 *Steel Erection*

Steel erection is the actual joining of fabricated sections on the construction site. Steel erection is normally sub-contracted to steel erectors. Their responsibility is to simply join the steel pieces together and perform any necessary field connections. The steel erectors work closely with the fabricators to ensure the correct phasing of the steel. Construction equipment includes cranes and generators, which serve as the energy consumers during steel erection.

For the MWU method, energy consumption is determined by taking the erection rate multiplied by the fuel consumption rate of the crane and generator. For this study a 200 ton crane is assumed. The total energy use calculations are shown in Appendix B-1. An erection rate of four to five 'combined members' per hour is used (Richard Burns, Vice President, Daniel Marr & Son Co., personal communication).

The percentage of welds done on a typical construction site is also included as a sub-unit process. On a typical job in Boston, 9% of the connections are welded based on industry research range of 8-10% (Burns, personal communication). The welding of connections on-site impacts the energy required and is included in the process flow and inventory analysis.

4.7.2 *Fireproofing Application*

Fireproofing manufacturers will typically only allow licensed contractors to apply their product in order to protect themselves from wrongful application and potential law suits.

In Boston, there are two main sub-contractors who apply this type of fireproofing, Century Drywall and Component Spray Fireproofing. The application procedures are relatively basic. The dry mix is combined with water at the job site and sprayed on using hose apparatus. The mix is applied in board feet units which are a surface area and thickness measurement per linear feet of steel members. The fireproofing is transported to site directly via truck from the manufacturer. The elementary flows considered here are energy use by the pump and waste generated. According to Scott Littlejohn of Century Drywall, 10% of the spray is lost and added to the waste pile on a typical job.

4.7.3 *Concrete Placement*

The procedures for concrete placement in the steel process flow are relatively identical to the steps described in Section 3.5.3. The underlying assumption is that concrete for the floor slabs uses the same BS&G data used in the concrete process flow. The only difference is the amount of concrete poured and the assumption that no re-bar is required. The calculation for energy use and the percentage of waste concrete is assumed to be the same and is included in Appendix B-1.

5 *Defining the System Boundary*

5.1 System Boundary

A critical step in the LCA method is defining the system boundary. Essentially, the system boundaries establish limits of the study and any process outside the boundary is ignored. The system boundary helps reduce the LCA to a manageable size by eliminating non-essential unit processes and elementary flows (Kotaji et al, 2003).

For improved clarity the system boundary will be defined in relationship to four major process flow stages. These stages are raw material extraction, initial production, finish material manufacture, and construction. All unit processes within each of these stages and the transportation requirements that link these stages are considered within the overall system boundary, unless otherwise noted. The system boundaries also include all elementary flows (both inputs and outputs) that relate to the environmental impacts that are the subject of this study. The included inputs are energy consumption and secondary natural resources, like water. The elementary flow outputs included in the system boundary are waste removal and harmful air emissions, specifically those that impact global warming. Air emissions that relate to human toxicity and acidification are also tracked as secondary effects. A graphic depiction of the system boundaries for both concrete and steel are shown in Figures 5.1 and 5.2, respectively. Exclusions from the system boundary will be defined in later sections.

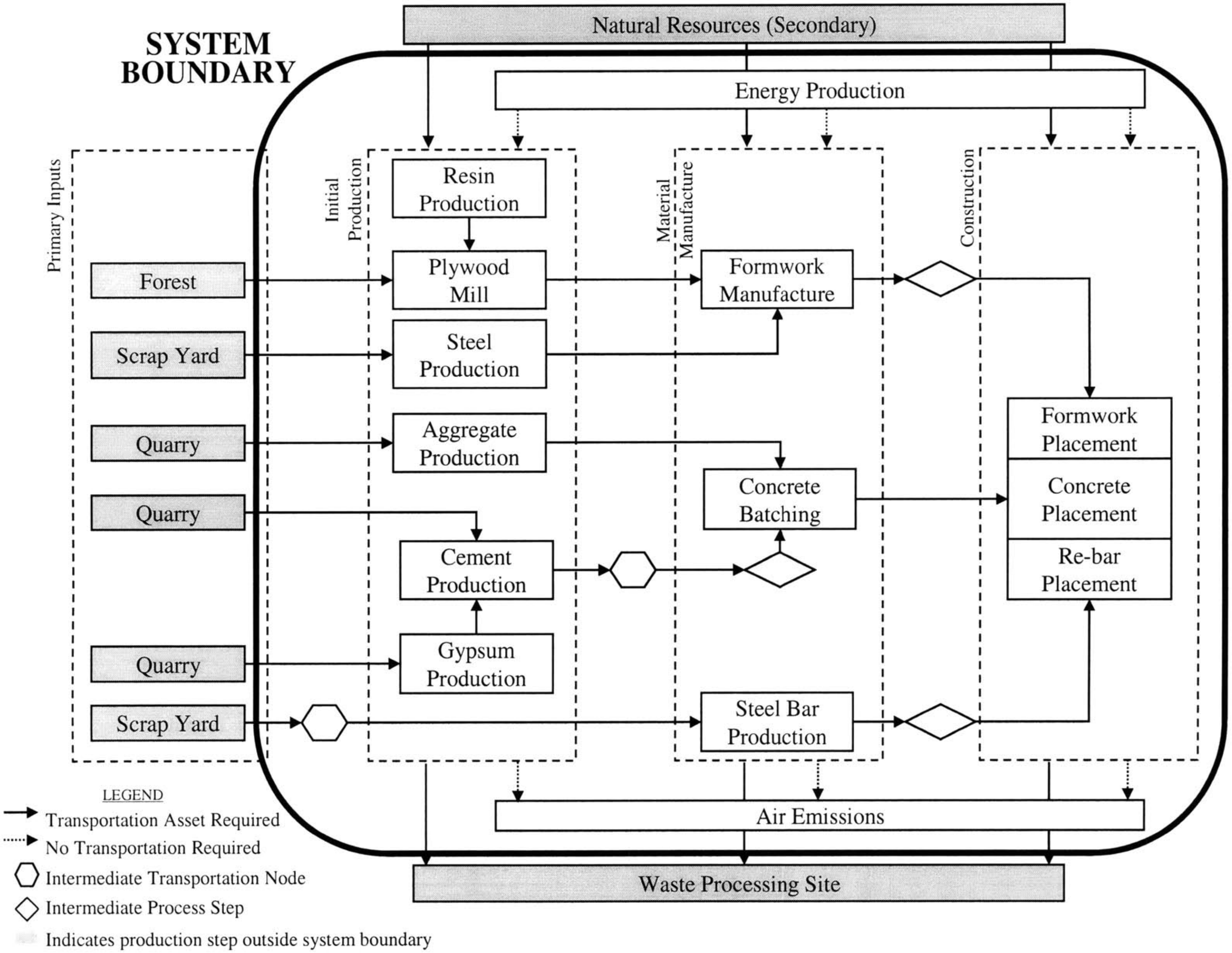

Figure 5.1. Concrete System Boundary

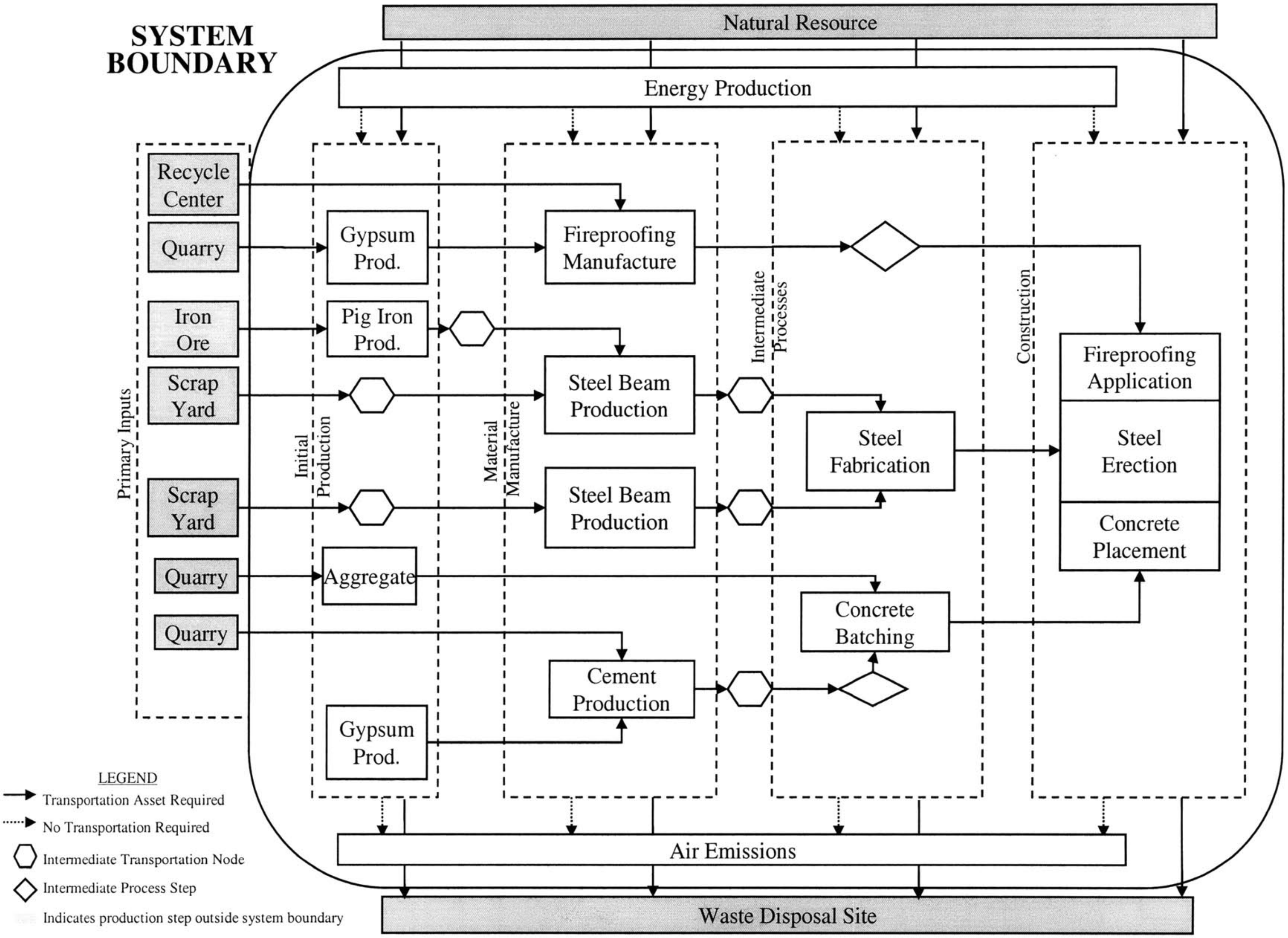

Figure 5.2. Steel System Boundary

5.1.1 *Raw Material Extraction*

The processes involved in raw material extraction are outside the system boundary. The system boundary begins at transportation from the extraction site to the initial production facility. For example, the transportation requirement from the quarry to the primary crusher at the cement production plant is included. The boundaries do not include the machinery (scooper/loader) or resources (blasting) to complete the actual extraction. In addition, the production processes at the local scrap yard, where scrap iron is collected for steel mills are not included, only the transportation from that scrap yard is within the system boundary. Clearly defined, the system boundary begins as the loaded transportation asset leaves the raw material extraction stage (quarry, mine, forest, gates of the scrap yard, etc.).

5.1.2 *Initial Production*

The initial production processes are within the overall system boundary. These initial production facilities are where raw materials are turned into usable components. Refer to Figures 5.1 and 5.2 to identify the initial production unit processes for concrete and steel.

5.1.3 *Material Manufacture*

The material manufacture stage is where usable materials are turned into finished materials for construction. The manufacturing unit processes for all direct and indirect product systems are included in the system boundary.

5.1.4 *Construction*

On-site construction work is the final process flow stage. The system boundaries end at the erection of the functional unit at the construction site. The system boundary includes all elementary flows to and from this final stage, including the removal of all construction waste.

5.1.5 *Transportation*

All transportation requirements between the four major stages are considered within the system boundary. This includes intermediate transportation nodes such as port facilities and rail heads. If raw materials are shipped from overseas, the transportation requirements from the port facility to the appropriate unit process location are included. These intermediate transportation nodes are not always defined, in these cases the most direct route, using major transportation hubs, is assumed.

5.1.6 *Process Inputs*

1) Primary inputs. These inputs are those that are derived from the previous unit process. They are considered within the overall system boundary and serve as the direct link between two unit processes in the product system. In the case of the initial production stage, the primary inputs are either natural resources or recycled material.

2) Energy Inputs. All energy inputs that relate directly to the production process are included in the system boundary. For example, the energy required to heat a cement kiln is within the system boundary, but the energy required to heat the building for human occupancy is not. The major energy inputs include electricity, natural gas, oil fuel, coal, and diesel. The production of electricity is also considered within the system boundary. The electricity is received directly off the local power grid and the electricity production mix for the specific region is obtained using the EPA Power Profiler website and *eGrid* database.[16]

3) Secondary Natural Resources. These are different than the primary inputs provided above. Secondary natural resource inputs include such raw materials as water and ancillary items that are not directly linked to an initial production facility as a raw resource input. These secondary natural resource inputs are included to capture total resource depletion quantities. The transportation assets to move these secondary inputs are not included. See system boundary exclusions for further details.

5.1.7 *Process Outputs*

1) Finished product. The finished product is within the system boundary and carries all relevant production and process data (on total air emissions, solid waste, etc.)

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[16] The *eGrid* database and Power Profiler webpage http://www.epa.gov/cleanmrgy/powerprofiler.htm provides production mix data and relevant air emissions on electricity production by zip code.

to the next level in the process flow. The finished product from each unit process is within the system boundary and serves as the linkage to the next higher production step.

2) Air emissions. CO_2 emissions that relate to global warming are the main focus, in terms of air emission. Other harmful air emissions that lead to acidification and human toxicity are measured and included in the system boundary as a secondary focus. These air emissions are measure in kilograms per specific unit of production output (normally kilograms). The following table lists the air emissions considered and their impact on the environment.

Table 5.1. Harmful Air Emissions, by Type and Impact

Environmental Impact	Relevant Air Emission
Global Warming	CO_2, Methane
Acidification	NO_x, SO_2
Human Toxicity	NO_x, SO_2, CO, Hg, Pb, Cd, Cr

Source: (UNEP, 1996)

3) Waste removal. Transportation of waste material from production facilities or intermediate facilities is included in the study. The transportation requirements are based solely on weight of all solid waste with final destination to landfill, recycling center, or municipal incinerator. Solid waste disposal distances (40 miles) are assumed constant across all unit processes and completed via truck. Waste amounts are carried forward and disposed of at the product system level. This is done to simplify the inventory analysis without impacted the results.

5.2 System Boundary Exclusions

The system boundaries do not include the following:

1) Mining/Extraction. It is important to remember that the actual mining and extraction operations at the quarry are not included but the material quantity ready for transport is used as the starting point for the overall system boundary.

2) Energy delivery. Energy delivery to both infrastructure and transportation assets are not included in the system boundaries. While the system boundaries include fuel consumption, the transportation and production assets are assumed to have an endless supply of fuel energy due to the complicated nature of tracking fuel supplies.

3) Internal transportation. The transportation requirements for daily non-essential production operations of the facilities are not included. This includes maintenance vehicles, light duty vans, as well as, loading assets at the transportation hubs, such as cranes, forklifts and loaders.

4) Maintenance. Environmental impacts derived from the maintenance of plant machinery and vehicle fleets are outside the system boundary. Maintenance includes normal wear and tear, unscheduled maintenance, and replacement part requirements of the production process and transportation assets. This study assumes that all transportation and production machinery involved in both material overall process flows have nearly the same maintenance requirements and are therefore negligible and excluded.

5) Waste disposal. The actual process of waste disposal is outside the system boundaries. Waste is considered simply on the transportation requirement for moving a determined amount of solid waste.

6) Infrastructure. The building, maintenance, and operation of necessary infrastructure, such as plant facilities and roads, are not included. It is assumed that infrastructure facilities are required for both materials and their impacts can be considered nearly equal and therefore negligible.

7) Worker commutes and manual labor issues. Manual labor and impacts from workers are outside the system boundaries. While the transportation of worker crews to the site can add up to create significant impacts they are beyond the scope of this study.

8) Non-production energy usage. The energy used to heat and maintain facilities on a daily basis is excluded. This will be assumed equivalent between concrete and steel facilities.

9) Land transformation and re-cultivation. This study did not take into account land transformation and the impacts on the environment. For instance, the loss of

woodland area due to the production of the formwork used in concrete construction is outside the boundary and not measured.

10) Transportation of Secondary Raw Materials. The delivery of secondary natural resources, such as water, is excluded.

6 *Inventory Analysis*

6.1 Collecting the data

Data collection is the longest and most resource intensive component of the LCA methodology. This study categorized two main sources of data. The first is the EcoInvent database which provides thousands of process flows across the entire spectrum of manufacturing. The second source is industry research, conducted using phone interviews, site visits, plant operation tours, previous studies, and material specific journals, reports, and websites. Several Federal and State agencies served as valuable sources of information. These included the Department of Energy (DOE), Environmental Protection Agency (EPA), and the United States Geological Survey (USGS).

There are, evidently, gaps with the data collection in this report, but the analysis made due with the best possible data available for a research study of this size, scope, and level. A major hurdle for many LCA research projects is the difficulty in data collection due to the lack of transparency in many production processes, especially those associated with a very competitive industry. This research study represents the research and work done by a single analyst and assumptions, some very broad, were unavoidable in order to complete the analysis. This study makes the best effort to define those assumptions and justify their use.

6.1.1 *EcoInvent Database*

The EcoInvent v1.0 database, established by the Swiss Centre for Life Cycle Inventories, serves as the primary source of data relevant to individual unit processes and elementary flows contained in this study. The database provides input and output figures across thousands of unit processes, from rubber production to solar energy collection, primarily on European facilities (EcoInvent v1.0, 2003). These figures served as the building block for the inventory analysis. Many of these elementary flows (inputs and outputs) were not readily available through the conducted interviews and specific research. The EcoInvent report modules also helped to shape the linkages required in the larger product systems and the tracing of production flows within relevant systems.

6.1.1.1 Reason for Use

The EcoInvent database is used as the primary source of data for this study for several reasons; they are listed below.

1) Completeness. The database contained information on nearly all the unit processes involved with concrete and steel and indirect flows, such as wood, plastics, transportation, energy production and chemicals. All relevant data as it related to the LCA scope and intended purpose is included in the database.

2) Equivalence. The database allowed a baseline to be established instead of relying on separate and uncorrelated data sources for the different production unit processes. This eliminates potential discrepancies between data points, in terms of time, measurement tools, and standard deviations.

3) Availability. The lack of data availability and transparency at the production level in the United States, due to proprietary issues within the steel and concrete industries, made the EcoInvent database a readily available and reliable source for data.

6.1.1.2 Assumptions for Use

This study assumes that the European data is relevant to production processes in North America and more specifically Boston. This is a large "leap of faith", but necessary and justifiable. This study makes no attempt to discuss production differences between the two continents because that is way beyond the scope of this study. The potential differences arise from age of production facilities, location of natural resources, maturity of industrial practices, and governmental regulations. The key to this assumption is that both materials are assumed to be affected equally by the geographical shift of data. If large discrepancies were discovered, modifications to the data were made and quantified. This is not the case in the research conducted.

6.1.2 *Industry Research*

The interviews and discussions with industry personnel is an essential component of this research. This study does not rely solely on the database available, but attempts to derive realistic flows from the field. The industry research serves the following purposes.

1) Determines the MWU method for steel and concrete as building materials. The MWU method for Boston is definitely not part of the European database.

2) Serves as the primary source for the linkages among the unit processes. The transportation requirements in this study are taken directly from the process flow diagrams relevant to the distances between subsequent unit processes.

3) Meets the regional characteristic of the functional unit. Due to the narrow geographical focus, this study needed to determine how local contractors and manufacturers 'conduct their business.'

4) Acts as a verification of EcoInvent production data.

5) Fills any gaps in information and takes over as primary source when data is not available in EcoInvent. For instance the specific process data for cementitious fireproofing is not included in the EcoInvent reports or database. In this case, interviews with fireproofing manufacturers and product websites were used to determine sub-components and production data. It is important to note, however, that some of the sub-component unit processes of fireproofing manufacture, such as gypsum production, are included in the EcoInvent database and therefore used in the inventory analysis.

6.1.3 *Relevant data*

Between both sources of information, only the input and output data pertaining to the three defined environmental impacts is collected. This is the purpose of the system boundaries; otherwise, the study becomes unmanageable and drowns in too much information and data. For instance only specific air emissions are collected in the study. No data on water emission are included, because they are outside the targeted scope of this LCA study.

6.2 **LCA Calculations**

In LCA, the matrix method is used to represent the process data and relevant inputs and calculate the targeted environmental results. In this study, a series of linked spreadsheets are used to conduct the inventory analysis and serve as the 2-D matrix representation of the economic and environmental inputs and outputs as they relate to the unit processes in the overall process flow.

For this study each unit and sub-unit process received its own matrix (Excel spreadsheet) to capture and inventory the gathered data described in Chapters 3 and 4. The results of each sub-matrix are carried forward with the proper scale to the two main material matrices (Appendix A-2 and Appendix B-2) which serve as the representation of the overall process data and provide the targeted environmental results. The set of matrices for concrete- and steel-frame construction process flows are located in Appendix A and Appendix B, respectively.

6.3 **Transportation**

The elementary flows for the transportation assets are based on the EcoInvent database (2003). The modes of travel are determined by industry research as it relates to the MWU method. Because of this, the transportation type in the EcoInvent database had to be scaled to equivalent types used in North America. The following assumptions are used in this study.

1) The EcoInvent data references three types of trucks, based on vehicle tonnage. Their equivalent type truck in the United States is broken down in Table 6.1. The truck types used in the process flows are labeled on the process flow diagrams in Chapters 3 and 4. For this study, the flows associated with a 16T truck out of the EcoInvent database is assumed to be the elementary flows for a medium weight truck found in North America.

Table 6.1. Transportation Asset Compatibility

EcoInvent Category	North American Equivalent	
16T	Medium Weight Trucks	Dual Rear Axel (no trailer)
28T	Heavy Weight Trucks	Tractor Trailer
40T	Heavy Duty	Heavy Duty Dump Quarry Vehicles

2) The differences for rail and water transports are assumed to be negligible. For example the elementary flows associated with a diesel freight train in Europe are relatively equivalent to the flows of an American freight train.

3) Mileage was determined using direct mileage between two locations. For instance the mileage considered for the rail transport of steel from Arkansas to New Hampshire was from direct routes, not the actual route of the train line. Determining the actual travel distance on a rail line requires far too much detail for the scope of this study. There were minor exceptions to this assumption to include barge routes from upstate New York to Boston. Obviously the barge did not travel the direct route (over land), but followed the most direct water route from Albany to Boston.

6.4 Electricity

Electricity production is included in the inventory analysis wherever applicable. The electricity input for each unit process, found in the EcoInvent database, is used to determine the resulting energy consumption and relevant air emissions. This is based on the production mix for the given location of the specific unit process obtained from the EPA *eGrid* database and Power Profiler webpage (2006).

6.5 Concrete Related Inventories

6.5.1 *Concrete Construction*

This inventory serves as the final analysis and the compilation of all other concrete related inventories across the entire process flow. The raw data matrix inventory is located in Appendix A-2 and the considered flows are depicted graphically in Figure 6.1.

The following legend is used to clarify the figures in Sections 6.5 and 6.6.

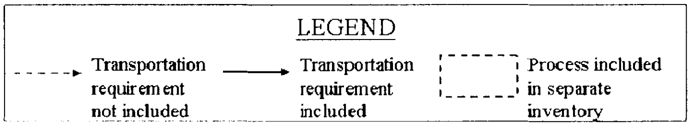
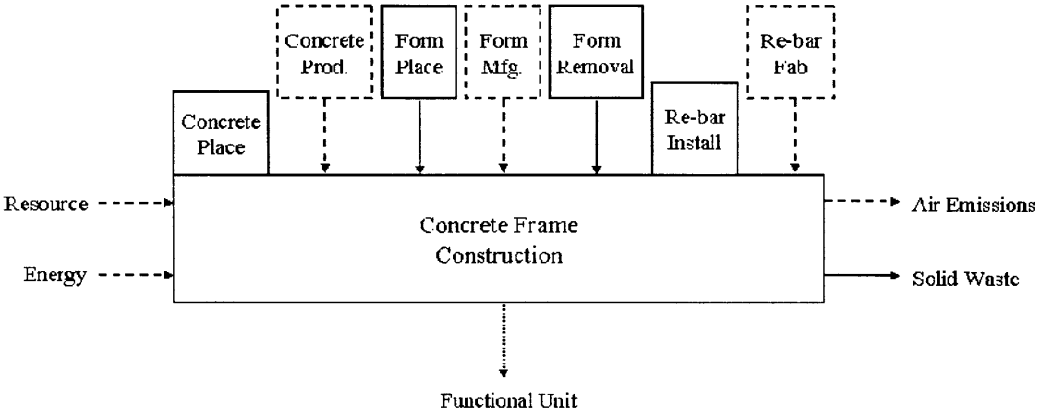


Figure 6.1. Concrete Construction Inventory



1) Primary Inputs.

a) Production data. The production data for the primary inputs (concrete production, formwork manufacturing, and steel re-bar production) are carried forward from the subsequent unit process inventories. Production data on concrete placement, formwork placement, re-bar installation, and formwork removal sub-unit processes is based on industry research.

2) Energy Usage. The energy usage on-site is based solely on industry research and is relevant only to sub-unit processes.

3) Natural Resources (Secondary). Based on industry research. Relevant only to concrete placement, formwork placement, re-bar installation, and formwork removal sub-unit processes in this specific matrix. The natural resource usages from subsequent matrices are carried forward.

4) Air Emissions. Based on industry research. Information on air emissions on the construction site was not available. All of the air emissions in this inventory are due to electricity production, transportation requirements, and on-site power generation.

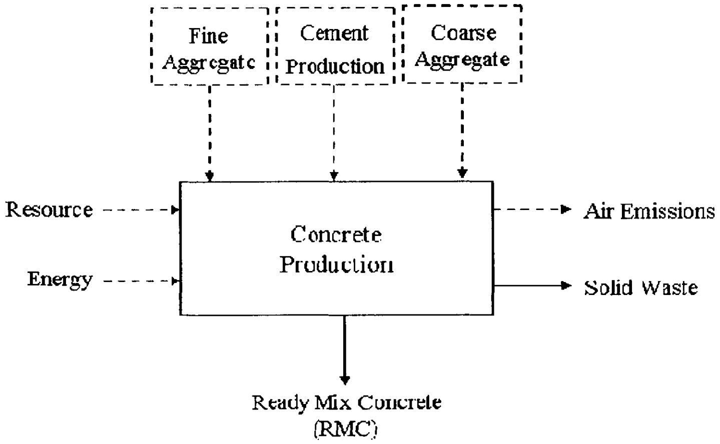
5) Solid Waste. Based on industry research. The transportation requirements to move all construction waste is included in this inventory. Disposal site is assumed to be within 40 miles.

6) Primary Output. The output of this inventory is the functional unit.

6.5.2 *Concrete Production*

The inventory analysis matrix for concrete production is shown in Appendix A-3. The relevant flows are depicted in Figure 6.2.

Figure 6.2. Concrete Production Unit Process Inventory



1) Primary Inputs. The primary inputs for this unit process are aggregate (coarse and fine) and Portland cement. These are considered sub-unit processes.

a) Production data. Production data for concrete batching is based on EcoInvent. The production data for the sub-unit processes are carried forward from their respective inventories.

b) Transportation data. The transportation requirements for the primary inputs are not included in this inventory, but accounted for in previous inventories. The relevant locations and modes of shipment are based on industry research.

2) Energy Usage. Based on EcoInvent.

3) Natural Resources (Secondary). Based on EcoInvent.

4) Air Emissions. Based on EcoInvent. Only relevant emissions are included.

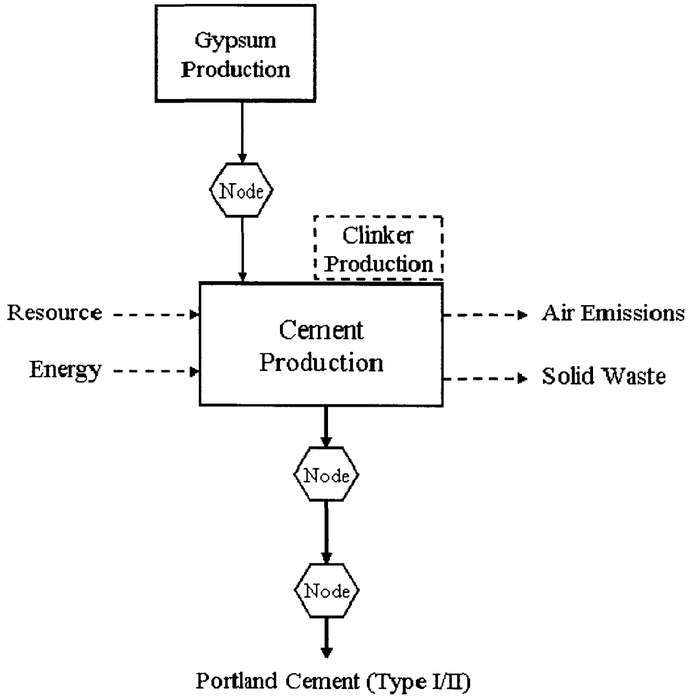
5) Solid Waste. Based on EcoInvent. The transportation requirement to transport total quantity of solid waste to both landfill and incinerator is included in this inventory. Disposal site is assumed to be within 40 miles.

6) Output. The finished product of this inventory is RMC. The shipment of the RMC to the construction site is included as part of this inventory.

6.5.3 *Cement Production*

The inventory analysis matrix for concrete production is shown in Appendix A-4. The relevant flows are depicted in Figure 6.3.

Figure 6.3. Cement Production Sub-Unit Process Inventory



1) Primary Inputs. The primary inputs for this sub-unit process are clinker and gypsum. These are considered component-unit processes.

a) Production data. Production data for cement production is based on EcoInvent. The production data for the component-unit processes are carried forward from their respective inventories.

b) Transportation data. Transportation requirements for only one of the two primary inputs are necessary and included in this inventory. In this case, the required transportation for gypsum is included. The relevant locations and modes of shipment are based on industry research. There is no transportation requirement for clinker because its production is co-located with cement production.

2) Energy Usage. Based on EcoInvent.

3) Natural Resources (Secondary). Based on EcoInvent.

4) Air Emissions. Based on EcoInvent. Only relevant air emissions are included.

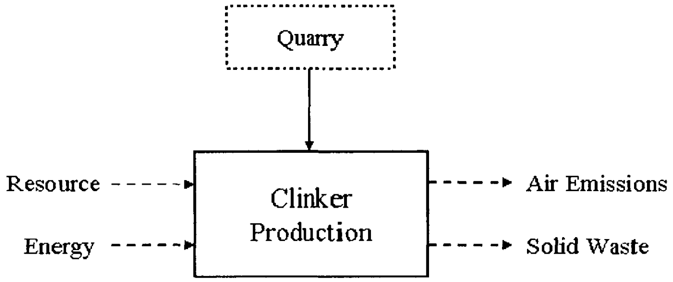
5) Solid Waste. Based on EcoInvent. The transportation requirement to transport total quantity of solid waste to both landfill and incinerator is not included in this inventory. The amount of solid waste (in kg) is carried forward to the concrete production inventory and counted there. Because the study assumed a standard distance to disposal site, this assumption is valid.

6) Output. The finished product of this inventory is Portland cement (Type I/II). The relevant outbound delivery of Portland cement to regional storage silos is included as part of this inventory and locations and modes of transport are based on industry research.

6.5.4 *Clinker Production*

The inventory analysis matrix for clinker production is shown in Appendix A-5. The relevant flows are depicted in Figure 6.4.

Figure 6.4. Clinker Production Component-Unit Process Inventory



1) Primary Inputs. The primary input for this component-unit process is limestone quarry material. This limestone is considered an elementary flow of raw materials.

a) Production data. Production data for clinker production is based on EcoInvent. The production data for the mining of the raw materials is not included because it is considered outside the system boundary.

b) Transportation data. The transportation requirements for the mined inputs are included in this inventory. The relevant mode of shipment and distances are based on industry research.

2) Energy Usage. Based on EcoInvent.

3) Natural Resources (Secondary). Based on EcoInvent.

4) Air Emissions. Based on EcoInvent. Only relevant air emissions are included.

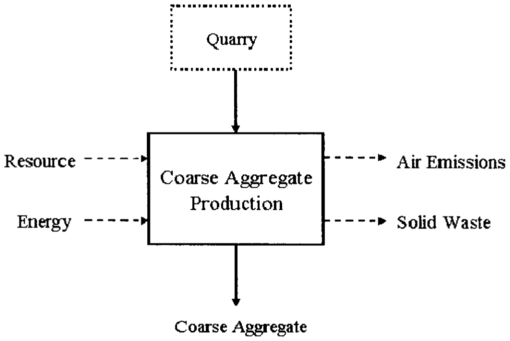
5) Solid Waste. Based on EcoInvent. The transportation requirement to transport total quantity of solid waste to both landfill and incinerator is not included in this inventory, but is carried forward to the next level inventory.

6) Output. The finished product of this inventory is clinker. There is no transportation requirement because clinker production is co-located at the cement production facility.

6.5.5 *Coarse Aggregate Production*

The inventory analysis matrix for coarse aggregate production is shown in Appendix A-6. The relevant flows are depicted in Figure 6.5.

Figure 6.5. Coarse Aggregate Production Sub-Unit Process Inventory



1) Primary Inputs. The primary input for this sub-unit process is quarry material.

a) Production data. Production data for aggregate production is based on EcoInvent. The production data for the mining of the raw materials is not included because it is considered outside the system boundary.

b) Transportation data. The transportation requirements for the mined inputs are included in this inventory. The relevant mode of shipment and distances are based on industry research.

2) Energy Usage. Based on EcoInvent.

3) Natural Resources (Secondary). Based on EcoInvent.

4) Air Emissions. Based on EcoInvent. Only relevant air emissions are included.

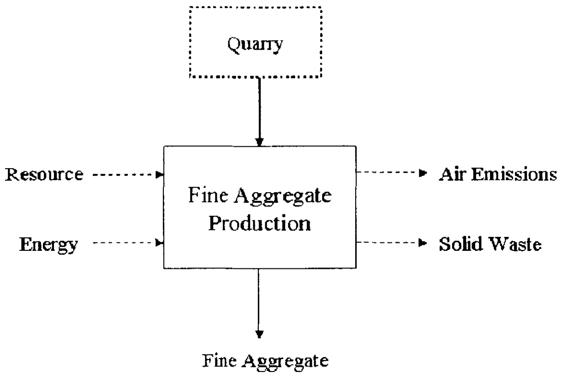
5) Solid Waste. Based on EcoInvent. Quantity of solid waste is carried forward to next level inventory. The transportation requirement for solid waste is included there.

6) Output. The finished product of this inventory is coarse aggregate. The relevant transportation method are based on industry research and included in this inventory.

6.5.6 *Fine Aggregate Production*

The inventory analysis matrix for fine aggregate production is shown in Appendix A-7. The relevant flows are depicted in Figure 6.6.

Figure 6.6. Fine Aggregate Production Sub-Unit Process Inventory



1) Primary Inputs. The primary input for this sub-unit process is quarry material.

a) Production data. Production data for aggregate production is based on EcoInvent. The production data for the mining of the raw materials is not included because it is considered outside the system boundary.

b) Transportation data. The transportation requirements for the mined inputs are included in this inventory. The relevant mode of shipment and distances are based on industry research.

2) Energy Usage. Based on EcoInvent.

3) Natural Resources (Secondary). Based on EcoInvent.

4) Air Emissions. Based on EcoInvent. Only relevant air emissions are included.

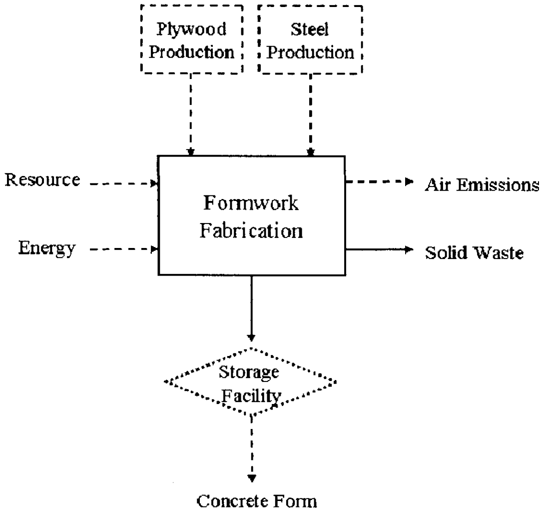
5) Solid Waste. Based on EcoInvent. Quantity of solid waste is carried forward to next level inventory. The transportation requirement for solid waste is included there.

6) Output. The finished product of this inventory is fine aggregate (sand). The relevant outbound transportation method is based on industry research and included in this inventory.

6.5.7 *Formwork Manufacture*

The inventory analysis matrix for formwork manufacture is shown in Appendix A-8. The relevant flows are depicted in Figure 6.7.

Figure 6.7. Formwork Manufacture Unit Process Inventory



1) Primary Inputs. The primary inputs for this unit process are plywood (for surface of form) and steel (for support bracing). The productions of these two primary inputs are considered sub-unit processes.

a) Production data. Production data for formwork manufacture is based on industry research. The EcoInvent database does not contain a formwork module. The production data for the sub-unit processes are based on EcoInvent data and carried forward from their respective inventories.

b) Transportation data. The transportation requirements for the primary inputs are not included in this inventory, but accounted for in the previous inventory level.

2) Energy Usage. Based on industry research and assumptions.

3) Natural Resources (Secondary). There is no information on additional inputs, besides the primary inputs. Based on industry research.

4) Air Emissions. Not available. Based on industry research.

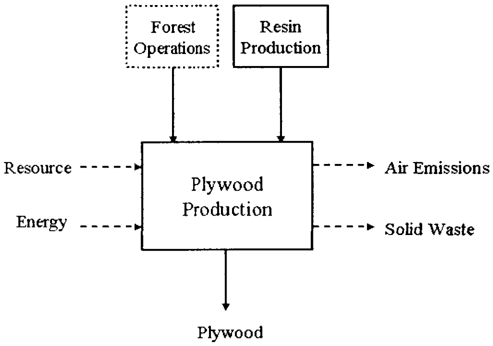
5) Solid Waste. Assumption of waste are made based on industry research and included in this inventory. Transportation requirement for solid waste removal is considered in this inventory.

6) Output. The finished product of this inventory is concrete forms. The shipment of the forms to the regional distributor is included as part of this inventory. The transportation from regional distributor to construction site is included as part of the concrete construction inventory described in Paragraph 6.5.1.

6.5.8 *Plywood Production*

The inventory analysis matrix for plywood production is shown in Appendix A-9. The relevant flows are depicted in Figure 6.8.

Figure 6.8. Plywood Production Sub-Unit Process Inventory



1) Primary Inputs. The primary inputs for the plywood production sub-unit process are the flows from the resin production process and wood raw material.

a) Production Data. The plywood production data is based on EcoInvent. Production data from resin production is also taken from the EcoInvent database and included in this unit process inventory analysis. The production data for forest operations is not included because it is outside the system boundary (as defined in Section 5.2).

b) Transportation Data. The inbound transportation requirements for wood from forest operations and delivery of resin are included in this inventory and based on industry research and assumptions made in the MWU method.

2) Energy Usage. Based on EcoInvent.

3) Natural Resources (Secondary). Based on EcoInvent.

4) Air Emissions. Based on EcoInvent. Only relevant emissions are included.

5) Solid Waste. Based on EcoInvent. Total quantity of solid waste is recycled as an alternate fuel (hog-fuel). There is no waste transportation requirement.

6) Primary Output. The output from this unit process is plywood material. The outbound transportation requirement of the plywood is included. The relevant locations and modes of delivery are based on industry research.

6.5.9 *Steel Bracing Production (for formwork)*

The inventory analysis matrix for steel production is shown in Appendix A-10 with relevant assumptions for its development. The relevant flows are similar to the steel connection production analysis that is discussed in a future section of this report. Please refer to Section 6.6.5 and Figure 6.15 for a detailed description of the steel production process flow that is used for this sub-unit process.

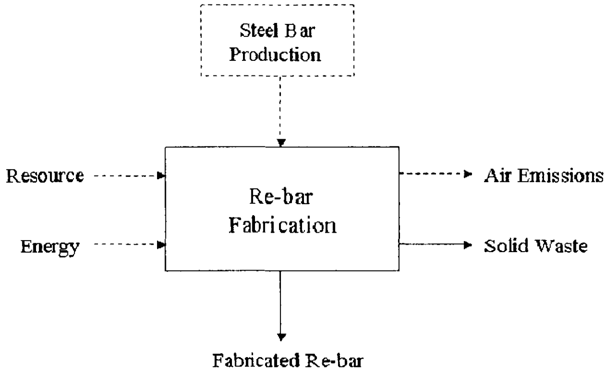
6.5.10 *Hot Rolling (for Steel Bracing)*

The specific inventory analysis matrix for the hot rolling throughput process relevant to steel production (for formwork bracing) is located in Appendix A-11. The general flow and data sources are described in a future section of this report. Please refer to Section 6.6.4 and Figure 6.14 for a detailed description of the hot-rolling sub-unit process.

6.5.11 *Reinforcing Bar Fabrication*

The inventory analysis matrix for re-bar fabrication is shown in Appendix A-12. The relevant flows are depicted in Figure 6.9.

Figure 6.9. Re-bar Fabrication Unit Process Inventory



1) Primary Inputs. None. This is considered a throughput unit process and therefore there are no inputs or sub-unit processes.

2) Energy Usage. Based on industry research. A per kilogram energy consumption rate is assumed based on rough estimates from the data gathered from the steel fabrication shops in the steel process flow. It assumes that electricity is the sole energy source in the re-bar fabrication process.

3) Natural Resources (Secondary). None. At this process step no natural raw materials are required.

4) Air Emissions. Based on industry research. The fabrication shops did not have specific information on air emission because they do not track them. All of the air emissions in this inventory are due to electricity production.

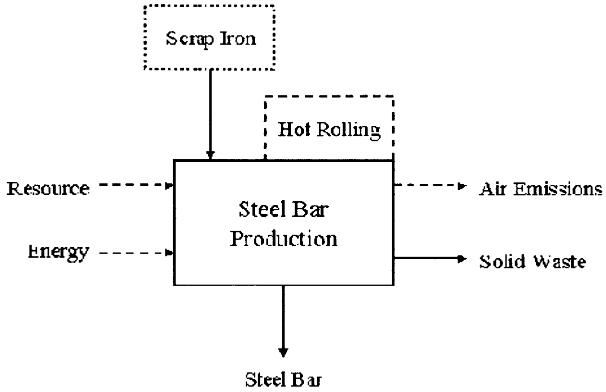
5) Solid Waste. Based on industry research. Solid waste delivery to landfill is included in this inventory.

6) Primary Output. None. This inventory serves as a throughput process and only the production data carries forward to the next level inventory.

6.5.12 *Reinforcing Bar Production*

The inventory analysis matrix for steel beam production is located as Appendix A-13. The inventory uses the following figure as a guide for the inventory data collection.

Figure 6.10. Steel Re-bar Production Unit Process Inventory



1) Primary Inputs. Production data from the hot-rolling sub-unit processes and scrap iron raw material are the primary inputs for steel re-bar production.

a) Production Data. The EcoInvent EAF production data for 100% recycled content is applicable. The production data from the hot rolling sub-unit process are carried forward as primary inputs. The production data for the scrap yard is not included because it is outside the system boundary (as defined in Section 5.2).

b) Transportation Data. The inbound transportation requirement for the scrap iron is included in this inventory. This transportation requirement is based on locations determined and assumed in the MWU method. The hot rolling process is co-located with the EAF so there is no transportation requirement.

2) Energy Usage. Based on EcoInvent.

3) Natural Resources (Secondary). Based on EcoInvent.

4) Air Emissions. Based on EcoInvent. Only relevant air emissions are included.

5) Solid Waste. Based on EcoInvent. Total quantity of solid waste requires transportation to landfill or incinerator assumed to be within 40 miles.

6) Primary Output. The output from this unit process is a typical angle section (measured in kilograms) ready for use as a connection. The outbound transportation requirement of the angle section is included in this inventory.

6.5.13 *Hot Rolling (for Re-bar)*

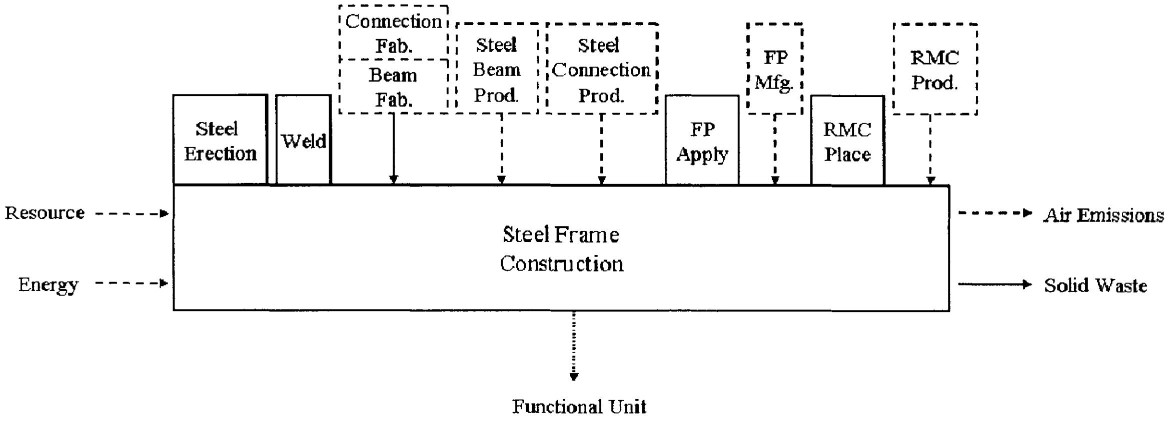
The specific inventory analysis matrix for the hot rolling throughput process relevant to steel re-bar production is located in Appendix A-14. The general flow and data sources are described in a future section of this report. Refer to Section 6.6.4 for a detailed description of the hot-rolling sub-unit process.

6.6 Steel Related Inventories

6.6.1 *Steel Construction*

This serves as the final inventory and is the compilation of all other steel related inventories. This main inventory analysis located in Appendix B-2 and is depicted graphically in Figure 6.11.

Figure 6.11. Steel Construction Inventory



1) Primary Inputs.

a) Production data. The primary inputs for this inventory are the production data from the primary unit processes (steel beam production, connection production, beam fabrication, connection fabrication, fireproofing manufacture and concrete (RMC) production). Primary inputs also include production data on steel erection, fireproofing application and concrete placement.

b) Transportation data. The inbound transportation of the steel from the steel fabricator is included as part of this inventory. The relevant locations and modes of shipment are based on industry research.

2) Energy Usage. Based on industry research. Relevant to steel erection, fireproofing application, and concrete placement sub-unit processes. All other energy figures are carried forward from subsequent level inventories.

3) Natural Resources (Secondary). Based on industry research. Relevant only to the construction site processes. All other natural resources are carried forward from previous matrices and inventories.

4) Air Emissions. Based on industry research. Information on air emissions on the construction site was not available. All of the air emissions in this inventory are due to power generation, on-site equipment usage and transportation requirements.

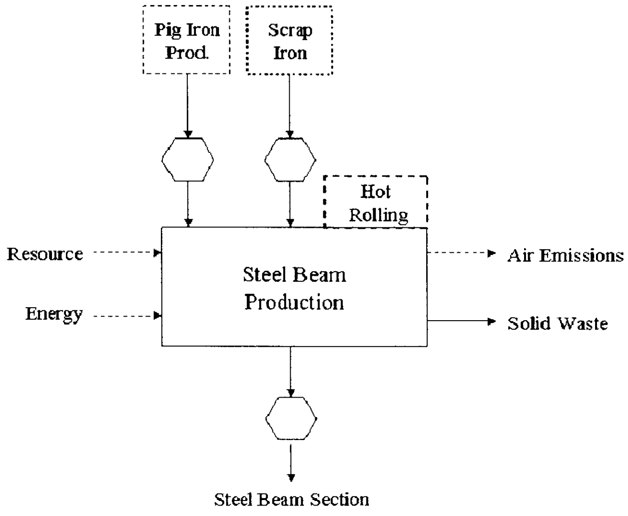
5) Solid Waste. Based on industry research. The transportation requirements to move this waste is included in this inventory. Disposal site is assumed to be within 40 miles.

6) Primary Output. The output of this inventory is the functional unit.

6.6.2 *Steel Beam Production*

The inventory analysis matrix for steel beam production is located as Appendix B-3. The inventory uses Figure 6.12 as a guide for discussing the unit process flow.

Figure 6.12. Steel Beam Production Unit Process Inventory



1) Primary Inputs. The primary inputs for the steel beam production unit process are the flows from the sub-unit processes (hot-rolling and pig iron production) and scrap iron raw material.

a) Production Data. The raw EAF production data is based on EcoInvent for a 100% recycled content. The process flow for the MWU method assumed a 95% recycled content for steel beam production. This inventory accounted for the 5% pig iron requirement. The production data from pig iron and hot rolling are carried forward as primary inputs. The production data for the scrap yard is not included because it is outside the system boundary (as defined in Section 5.2).

b) Transportation Data. The inbound transportation requirements for the pig iron and scrap iron are included in this inventory. This transportation requirement is based on locations determined and assumed in the MWU method.

2) Energy Usage. Based on EcoInvent.

3) Natural Resources (Secondary). Based on EcoInvent.

4) Air Emissions. Based on EcoInvent. Only relevant air emissions are included.

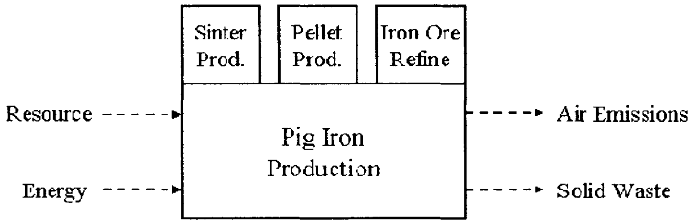
5) Solid Waste. Based on EcoInvent. Total quantity of solid waste requires transportation to landfill or incinerator assumed to be within 40 miles.

6) Primary Output. The output from this unit process is a typical wide-flange steel section (measured in kilograms). The outbound transportation requirement of the finished wide-flange section is included in this inventory.

6.6.3 *Pig Iron Production*

Pig Iron production is a sub-unit process of steel beam production. The inventory analysis is referenced in Appendix B-4.

Figure 6.13. Pig Iron Production Sub-Unit Process Inventory



1) Primary Inputs. The primary inputs for this sub-unit process are the flows from the components. The components are sinter production, pellet production, and iron ore refinement.

a) Production data. Relevant data for pig-iron production and component production are taken directly from the EcoInvent database.

b) Transportation data. Based on EcoInvent. This falls under the transportation rule exception concerning overseas production steps.

2) Energy Usage. Based on EcoInvent for both the pig iron production and sub-unit process production.

3) Natural Resources (Secondary). Based on EcoInvent.

4) Air Emissions. Based on EcoInvent. Only relevant air emissions were included.

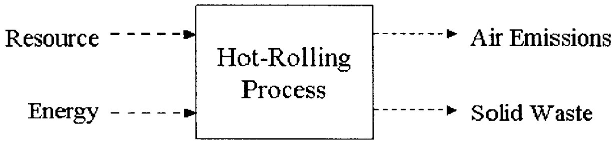
5) Solid Waste. Quantity based on EcoInvent. All solid waste quantities are totaled and carried forward to the next level inventory. The transportation of solid waste is not included in this level inventory.

6) Primary Output. The output from this unit process is pig iron (kg).

6.6.4 *Hot-Rolling (for Steel Beam)*

Hot-rolling is a throughput process of steel beam production co-located at the steel mill. The inventory analysis matrix for this process step is referenced in Appendix B-5. Figure 6.14 serves as a guide for data collection and inventory tracking. This diagram and discussion is referenced in all unit processes that involve hot rolling as a sub process in both the concrete- and steel-frame process flow.

Figure 6.14. Hot Rolling, Steel Sub-Unit Process Inventory



1) Primary Inputs. None. This is considered a throughput process and therefore there are no inputs or sub-unit processes.

2) Energy Usage. Raw data is from EcoInvent. This information is supported by interviews. For our steel mill used in the MWU method the primary energy for the re-heat furnace is natural gas and electricity serves as a secondary resource for production.

3) Natural Resources (Secondary). None. Based on EcoInvent.

4) Air Emissions. Based on EcoInvent. Only relevant air emissions are included.

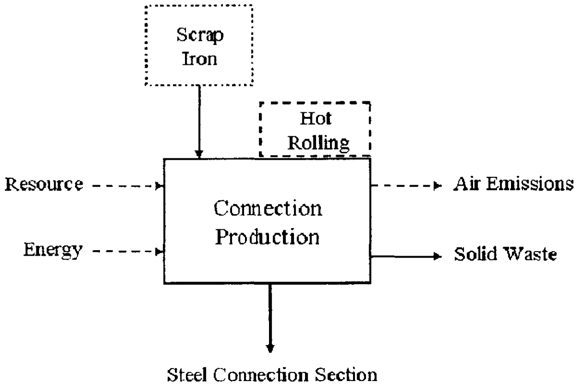
5) Solid Waste. Based on EcoInvent. Solid waste is carried forward to main unit process inventory.

6) Primary Output. None. This inventory serves as a throughput process and only the production data carries forward to the next level inventory.

6.6.5 *Steel Connection Production*

The inventory analysis matrix for connection production is located as Appendix B-6. The inventory uses the following figure as a guide for discussing what is included in each inventory.

Figure 6.15. Steel Connection Production Unit Process Inventory



1) Primary Inputs. The primary inputs for the steel beam production unit process are the flows from the hot-rolling sub-unit processes and scrap iron raw material.

a) Production Data. The EcoInvent EAF production data for 100% recycled content is applicable. The production data from the hot rolling sub-unit process are carried forward as primary inputs. The production data for the scrap yard is not included because it is outside the system boundary (as defined in Section 5.2).

b) Transportation Data. The inbound transportation requirement for the scrap iron is included in this inventory. This transportation requirement is based on locations determined and assumed in the MWU method. The hot rolling process is co-located with the EAF so there is no transportation requirement.

2) Energy Usage. Based on EcoInvent.

3) Natural Resources (Secondary). Based on EcoInvent.

4) Air Emissions. Based on EcoInvent. Only relevant air emissions were included.

5) Solid Waste. Based on EcoInvent. Total quantity of solid waste requires transportation to landfill or incinerator assumed to be within 40 miles.

6) Primary Output. The output from this unit process is a typical angle section (measured in kilograms) ready for use as a connection. The outbound transportation requirement of the angle section is included in this inventory.

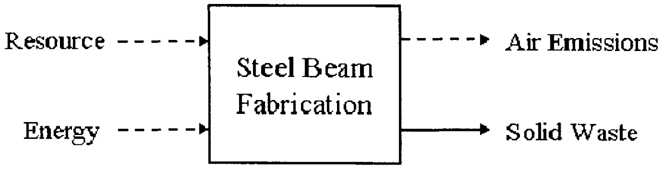
6.6.6 Hot Rolling (for Steel Connection)

The specific inventory analysis matrix for the hot rolling throughput process relevant to steel connection production is located in Appendix B-7. The general flow and data sources are the same as described in Section 6.6.4 and Figure 6.14.

6.6.7 *Beam Fabrication*

The inventory analysis for steel beams fabricated is located in Appendix B-8 and is depicted graphically in Figure 6.16.

Figure 6.16. Beam Fabrication Process Inventory



1) Primary Inputs. None. This is considered a throughput unit process and therefore there are no inputs or sub-unit processes.

2) Energy Usage. Based on industry research. Raw monthly energy consumption rates are converted to rates based on weight of steel fabricated. This was the only means to back into the energy usage at the fabrication shop. This data module was not included in the EcoInvent database.

3) Natural Resources (Secondary). Based on industry research.

4) Air Emissions. Based on industry research. The fabrication shops did not have specific information on air emission because they do not track them. All of the air emissions in this inventory are due to electricity production.

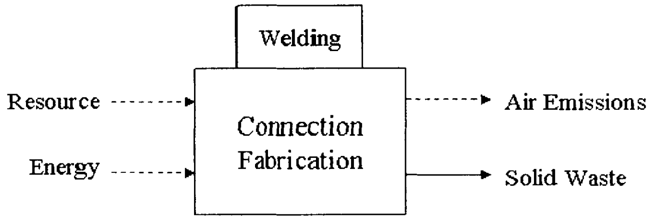
5) Solid Waste. Based on industry research. Solid waste delivery to landfill is included in this inventory (assume to be within 40 miles).

6) Primary Output. None. This inventory serves as a throughput process and only the production data carries forward to the next level inventory.

6.6.8 *Connection Fabrication*

The inventory analysis for steel beams fabricated is located in Appendix B-9 and is depicted graphically in Figure 6.17.

Figure 6.17. Steel Connection Fabrication Process Inventory



1) Primary Inputs. The primary input for this throughput unit process is the flow from the welding sub-unit process. There are no other inputs.

a) Production data. The production data for the welding sub-unit process is based on EcoInvent. The quantity of welds is based on industry research into typical fabrication procedures (MWU method).

b) Transportation data. There is no inbound transportation requirement associated with this inventory because the welding is done at the fabrication shop.

2) Energy Usage. Based on industry research. Raw monthly energy consumption rates are converted to rates based on weight of steel fabricated. This was the only means to back into the energy usage at the fabrication shop. This data module was not included in the EcoInvent database. The welding energy data is based on EcoInvent.

3) Natural Resources (Secondary). Based on industry research.

4) Air Emissions. Based on industry research. The fabrication shops did not have specific information on air emission because they do not track them. All of the air emissions in this inventory are due to electricity production.

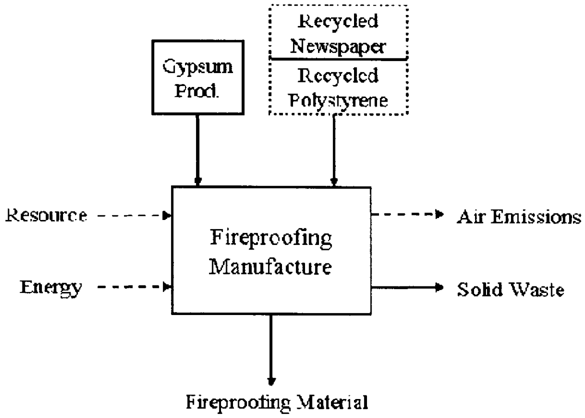
5) Solid Waste. Based on industry research. Solid waste delivery to landfill is included in this inventory.

6) Primary Output. None. This inventory serves as a throughput process and only the production data carries forward to the next level inventory.

6.6.9 *Fireproofing Manufacture*

Information on fireproofing manufacture is not readily available to general public. This inventory assumed the use of Monokote MK-6 type fireproofing, manufactured in Ontario, Canada which met the criteria for the MWU method defined. The inventory analysis for fireproofing manufacture is located in Appendix B-10 and is depicted graphically in Figure 6.18.

Figure 6.18. Fireproofing Manufacture Unit Process Inventory



1) Primary Inputs. The primary inputs for the type of fireproofing used are gypsum, cellulose, and polystyrene.

a) Production data. The main unit process data for manufacture of fireproofing is based on industry research. The gypsum production sub-unit process data is carried forward from the previous level of production and is based solely on EcoInvent. The recycling center operations are outside the scope of the study and production data from the recycling center is not included.

b) Transportation data. The inbound transportation data for the sub-components is included in this inventory. The specific method and relevant locations for transportation is assumed in this case, loosely based on industry research.

2) Energy Usage. Based on industry research and assumptions.

3) Natural Resources (Secondary). There is no information on additional inputs, besides the primary inputs. Based on industry research. The recycled material is not included as a natural resource for tracking purposes.

4) Air Emissions. No data available for emissions related to the manufacture of fire-proofing. This is primarily due to proprietary issues discovered during industry research.

5) Solid Waste. Not available.

6) Primary Output. The finish product for this unit process is spray-on fireproofing measured in kilograms. The production data carries forward to the next level inventory.

6.6.10 *Concrete Production (for Floor Slabs)*

The related inventory analysis matrices for concrete production as part of the overall steel-frame process flow are located in Appendix B-11 through B-15. Because it is assumed that MWU method would be the same between cast-in-place concrete frame construction and floor slab construction the relevant flows and inventory assumptions made in the concrete related section are relevant here. Refer to Sections 6.6.2 through Section 6.6.6 for a description and discussion of the inventory matrix procedures and assumptions. In the case of the floor slabs as it relates to steel-frame construction only the production of concrete is inventoried.

7 *Interpretation of Results*

7.1 Introduction

The purpose of this LCA study is to compare the environmental impacts of steel and concrete when used as building materials. The comparison is made primarily through interpretation of raw data results. Normally, in the LCA methodology the next analytical step is to conduct an impact assessment. Impact assessment serves as a "tool for relating [multiple outcomes] of an inventory analysis to environmental problems." (UNEP, 1996. p. 68). The impact assessment displays results base on weighted values of contributing factors to the environmental hazards. The impact assessment step is used later in this chapter as an analytical tool to compare multiple air emissions, but for the most part, this study will discuss un-weighted results only and not proceed with impact assessment. This is due to the fact that this thesis is a comparison of two materials and the raw results are a sufficient enough tool to interpret the inventory analysis results for our targeted environmental impacts. The raw results equate directly to the environmental costs of erecting concrete and steel frames for our defined functional unit.

The outline of the result discussion is fairly straightforward. The general results are discussed based on a broad overall comparison of the three target areas, followed by a more detailed interpretation of each individual environmental impact areas in separate sections. Discussion of each impact area and potential solutions are presented in the individual section, followed by an overall discussion of results.

7.2 General Results

From a broad perspective, the LCA shows that steel- and concrete-frame buildings have relatively similar impacts on the environment in terms of the three targeted areas defined in Section 1.3. A side by side comparison of the overall raw results is shown in Figure 7.1. These results are total raw emissions of carbon dioxide (in kg), total energy requirement (in MJ), and total amount of natural resources depleted (in 100·kg).[17]

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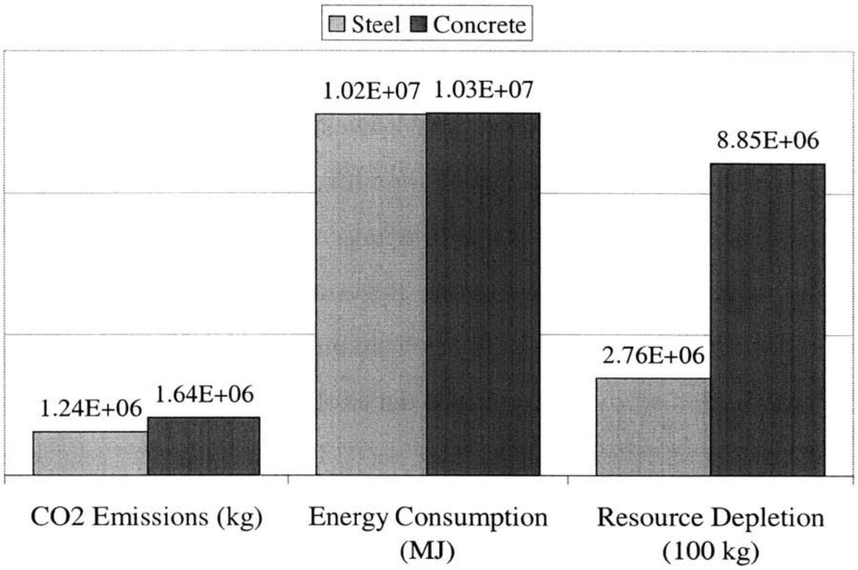
[17] The unit for resource depletion amount is adjusted to (100·kg) to make the result comparable on the side by side chart in Figure 30. The results were tracked during the analysis in kilograms.

Figure 7.1. Overall Comparison of Raw Results



The comparison shows that for each environmental impact area the results are on the same order of magnitude with the difference in total energy requirement being less than 1%. The largest separation is in the resource depletion comparison, with a difference of 70%. The detailed comparisons of the individual environmental impacts are discussed later in the next three sections of this chapter.

The quantities shown in Figure 7.1 are the total raw results for the defined functional unit (100,000 square foot (SF) office building). In order to analyze them on a more tangible level and compare to existing studies the raw results are normalized per square foot (of building floor area). The normalized results are listed in Table 7.1, with direct comparisons to existing studies (Guggemos et al, 2005; Bjorklund et al, 1996; Junnila et al, 2003).

The first two studies, one American and the other Swedish, are similar to the current study in that they compare steel and concrete-frame structures in the pre-use phase. Compared to the Swedish study (Bjorklund et al, 1996) the results of the current study are similar in respect to concrete having a greater impact in both CO_2 emissions and embodied energy. The normalized results are within 7-35%. The American study (Guggemos,et al 2005) is just the opposites, showing that steel has a larger impact in both areas and normalized results are nearly five times of the current study. The difference, most likely, is that (Guggemos et al, 2005) is more comprehensive, including foundation slab and exterior cladding, that is not included in the functional unit building of the current study. The data is also based on the Midwest United States, opposed to this study based on the metro-Boston area, which accounts for some of the difference. The foundation requirements, most likely, play the larger role in affecting the result, based on the fact that they add considerable amount of material and construction time to the raw results without affecting the square footage of the building type being compared. Key assumptions made in this study, for instance the exclusion of mining data may also account for the difference.

The third study (Junnila et al, 2003) is a life cycle study of a cast-in-place concrete office building in Finland. The study makes reference to total materials used in the building material and construction stages. The results are included in Table 7.1 for comparison purposes. Excluding the consumption of water in the current study, the results, in terms of resource depletion, are similar and on the same order of magnitude.

Table 7.1. Comparison of Normalized Environmental Impact Values

	CO_2 emissions (kg/SF)		Energy Consumption (MJ/SF)		Resource Depletion (million·kg)	
	Steel	Concrete	Steel	Concrete	Steel	Concrete
Current Study	12.4	16.4	102.1	102.5	270 27.7*	885 89.3*
Bjorklund et al., 1996	8.1	11.9	84.7	110.6	-	-
Guggemos et al., 2005	57.6	51.1	882.6	771.1	-	-
Junnila et al, 2003	-	-	-	-	-	20.4

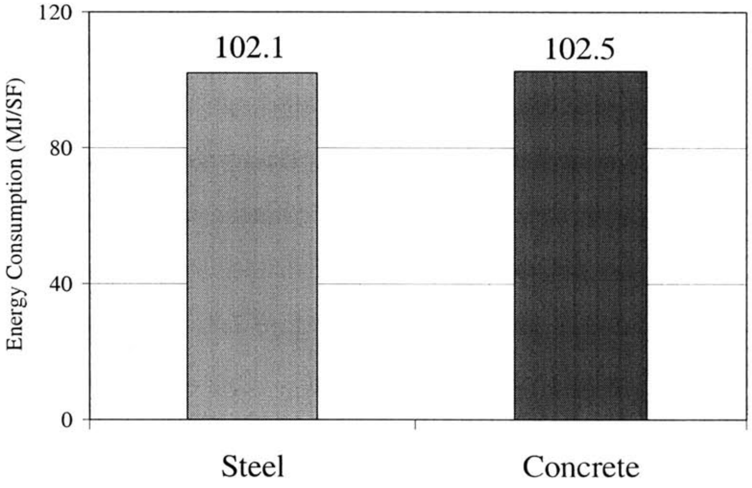
* total results (in million·kg) without water resource included

7.3 **Energy Consumption**

7.3.1 *Raw Results*

In terms of total energy consumption, steel and concrete (as primary building materials) have equivalent energy requirements in the pre-use phase, considering the uncertainty with the input data. The total energy consumption defined in this study equates directly to the embodied energy of the specific building type defined by the functional unit. The total embodied energy for both materials is just over 10 Tera-Joules (TJ) per total structure with a comparable difference of less than 1%. The comparison of the two building material types, normalized per square foot, is depicted in Figure 7.2.

Figure 7.2. Energy Consumption Comparison (Normalized Values)



Total energy consumption is a combination of energy requirements for all production facilities, transportation assets, and construction site demands across the overall process flow of steel and concrete. While some unit processes require a single source of energy, for instance the transportation assets only require the use of diesel energy;[18] most unit processes require several energy sources in their production steps. An example of this multiple energy source requirement is the cement production facility which requires coal

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[18] The transportation assets, in fact, may have additional energy requirements (i.e. for maintenance operations, etc.) but they are outside the system boundaries established in this LCA.

to heat the kiln and electricity to rotate the kiln and power other production machinery.[19] The five types of energy inputs tracked in the LCA are listed in Table 7.2.

Table 7.2. Energy Input Types

Energy Source	Unit	Use
Coal	MJ	Production steps, Electricity production
Diesel	MJ	Transportation assets, Construction site
Natural Gas	MJ	Production steps, Electricity production
Oil Energy	MJ	Production steps, Electricity production
Other*	MJ	Electricity Production

*includes Nuclear, Hydro, Renewable

For the purpose of this study, a combination of all five of these energy sources accounts for the total energy consumption. These energy sources are used directly as the energy inputs required in the production steps of the unit processes or indirectly in the production of electricity. Figure 7.3 shows a breakdown by energy source of the total energy consumption for both steel and concrete. Each material uses a different ratio of energy types in their production steps and transportation requirements.

Figure 7.3. Breakdown of Total Energy Consumption by Energy Type

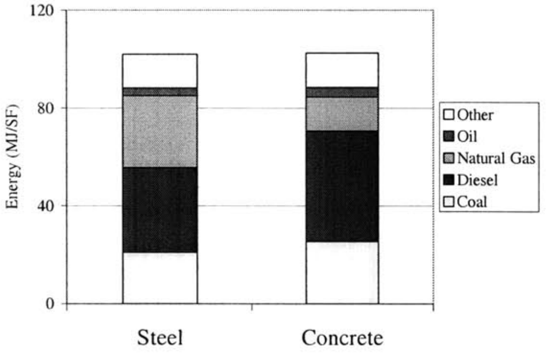
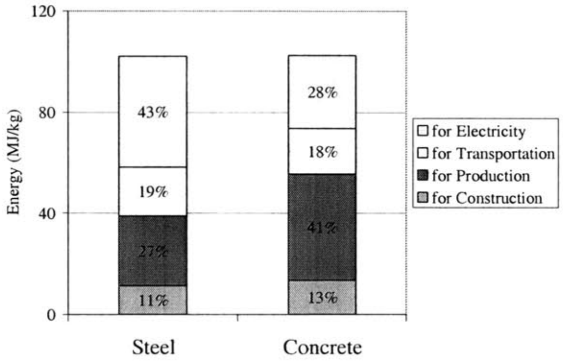


Figure 7.4. Specific End-Users of Total Energy



A large portion of the total energy consumption is the electricity power requirements across the unit processes. Electricity is tracked as an economic input and the production of electricity was analyzed as a separate unit process and inventoried as part of the LCA.

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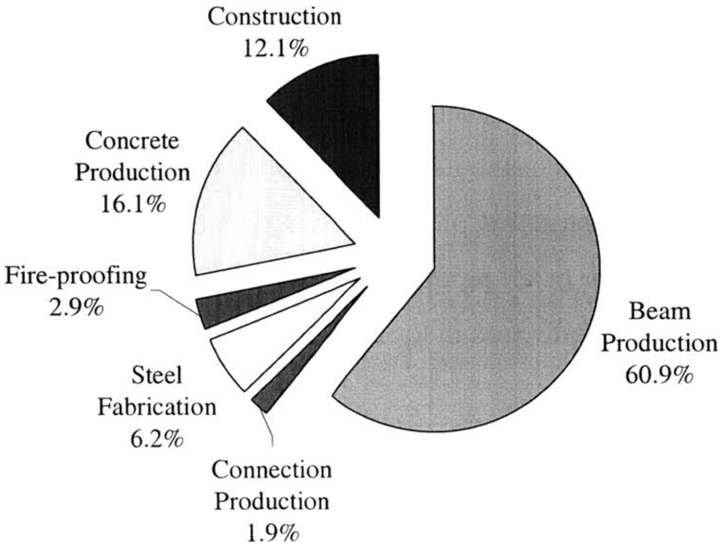
[19] In our case the cement plant in the process flow MWU method uses coal to heat the kiln. This is not the case in every cement production facility.

The production of electricity utilizes a specific production mix of the five energy sources. Electricity production mixes vary widely based on geographical area.[20] The production of electricity accounts for 43% of the total energy requirement for steel and 28% of the total requirements for concrete, see Figure 7.4, and its impact is discussed in greater detail during the material specific result discussions.

7.3.2 *Steel Specific Results*

For the defined functional unit, steel has a total energy requirement of 10.21 TJ. This equates to a normalized value of 10.21 MJ per square foot. Compared to the operational energy determined in a Canadian study (Cole and Kernan, 1996), this is an approximate embodied energy requirement of 2.5%.[21] The percent breakdown of energy consumption by specific product systems is shown in Figure 7.5.

Figure 7.5. Energy Consumption by Product System (Steel-frame)



The production of steel beam is the most energy intensive portion of the overall steel process flow. It accounts for 61% of the total energy requirements when compared against the other five product systems associated with the steel process flow; construction

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[20] For instance, in the mid-west coal plays a major role in electricity production, while in the north-west, hydro-power provides a majority of the electricity production (EPA, 2006).

[21] (Cole and Kernan, 1996) concludes an operational energy for a typical office building in Toronto, Canada at .881GJ/m2/year with a 50 year life span. This equates to total operational energy of roughly 398 TJ/ft2

(12%), steel fabrication (6%), steel connection production (2%), concrete production (16%), and fireproofing (3%).

Figure 7.6. Energy Consumption (Steel) with Transportation Extracted

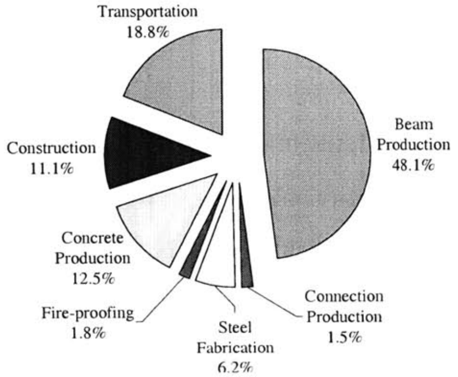
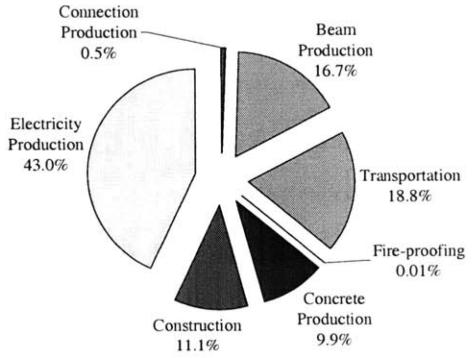
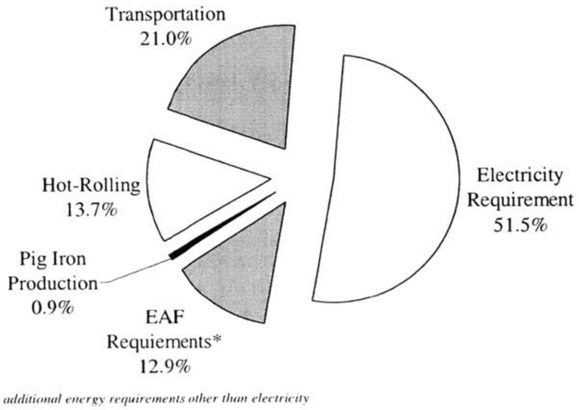


Figure 7.7. Energy Consumption (Steel) with Electricity Extracted



Extracting both the electricity production and transportation requirements from the individual product systems, see Figure 7.6 and Figure 7.7, it becomes evident that the electricity production required during steel beam production is the largest consumer of energy and thereby has the greatest impact on embodied energy of a steel-frame building. The large impact of steel beam production on total energy is an expected result due to the intensive energy requirements of the EAF steel-making process and the large quantity of steel beam required for construction of the functional unit (~600 tons). Over 50% of the total energy requirement for beam production is used in the production of electricity. A breakdown of steel beam production in terms of its energy consumption is depicted in Figure 7.8.

Figure 7.8. Energy Use Breakdown in Steel Beam Production Unit Process



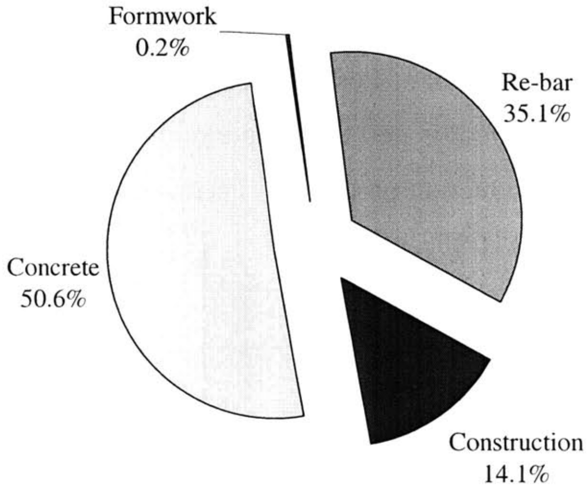
* *additional energy requirements other than electricity*

Because of the large amount of steel beam required to erect the functional unit the electricity requirements for steel beam production are 31% of the total process energy consumption.[22] This equates to 31.7 MJ/SF. Because electricity plays such a predominant role in steel making and the life cycle analysis of steel as a building material, potential solutions to reduce embodied energy need to be looked at from an electricity production standpoint.

7.3.3 *Concrete Specific Results.*

For the defined functional unit, concrete has a total energy requirement of 10.25 TJ. This is only 1% greater than the steel-frame total energy requirement. This equates to roughly 10.25 MJ/SF of building floor area. Again comparing it to the operational energy determined in (Cole and Kernan, 1996) embodied energy of a concrete-frame building is approximately 2.5% of operational energy, the same result in steel-frame construction. The breakdown of total energy consumption by the four main product systems is shown in Figure 7.9.

Figure 7.9. Energy Consumption by Product System (Concrete-Frame)



The concrete production product system accounts for half (51%) of the total energy requirement of cast-in-place concrete-frame construction. Extracting transportation requirements from the product systems (shown in Figure 7.10), concrete production

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[22] By weight, 97% of total steel in structure is steel beam.

remains the largest consumer of energy resources (40%). In the overall concrete process flow, transportation accounts for 18%, while the construction phase requires 13%. As shown in Figure 7.11, the production of electricity has less of an impact on the concrete-frame analysis (28%) and its impact is primarily due to the production of steel re-bar.

Figure 7.10. Energy Consumption (Concrete) with Transportation Extracted

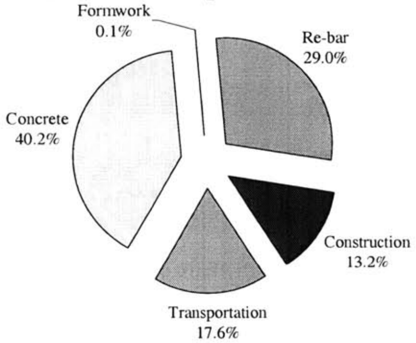
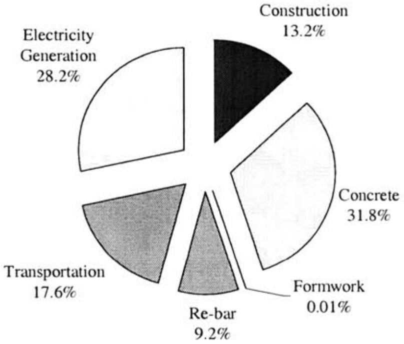
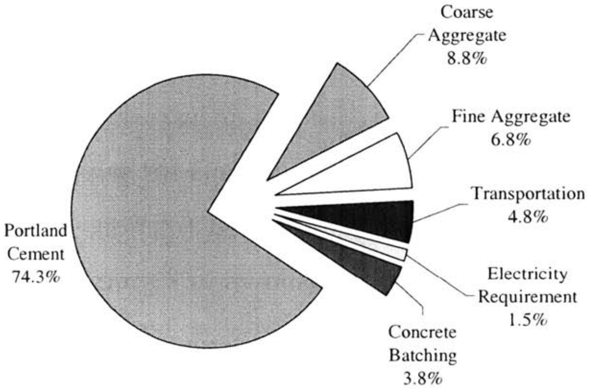


Figure 7.11. Energy Consumption (Concrete) with Electricity Extracted



With concrete production accounting for 40% of the energy consumption in concrete-frame construction, further analysis of that specific flow is required. Figure 7.12 shows the breakdown of energy use in concrete production (batching). The most energy intensive segment of concrete production is the sub-unit process of Portland cement production, which accounts for 74% of energy requirements as shown in Figure 7.12. On a broad perspective the production of Portland cement accounts for 37% of the entire concrete-frame process flow, compared to transportation requirements, constructions steps, and other material production processes. The normalized value of Portland cement production is roughly 37.9 MJ/SF.

Figure 7.12. Energy Use Breakdown in Concrete Production Unit Process



Therefore, because of its relatively large impact on total energy consumption, one of the most effective means to reduce the embodied energy of concrete-framed buildings is to focus on the Portland cement production process. New technologies and production fuels are being used by the concrete industry to reduce the effects of Portland cement energy requirements (Wilson, 2005). These are:

1. Using a recycled scrap material to heat kiln. In some case old tires are now used as an example.
2. Replacing the clinker/cement requirements of concrete with substitutes like fly ash and blast furnace slag.

7.3.4 *Discussion of Energy Consumption Results*

In terms of energy use per the specific process flow stages listed in Table 7.3, the comparison of steel and concrete are again relatively similar. For the most part, this study found that concrete and steel have similar energy requirements during the stages of construction, transport, and material production.

Table 7.3. Comparison of Energy Consumption by Process Flow Stage

Process Flow Stage	Steel	Concrete
Construction	11%	13%
Transportation	19%	18%
Material Production	70%	69%

While looking at the various life cycle (process flow) stages, it is important to conduct a comparison of operational energy (building use phase) to embodied energy (pre-use phase). A 1996 study (Cole and Kernan) referenced earlier, determines that the operational energy for a case study building in Toronto, Canada is approximately 90%.[23] As mentioned in the material specific result paragraphs and in terms of the current study, the significance of operational energy is at 97.5%, with embodied energy only 2.5% of total building energy use (for both steel and concrete). Again this difference is most likely accounted for by the assumptions made in regards to functional unit (excluding the

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[23] The Cole study (1996) is appropriate for comparison to the current study due to the similar climate characteristics between Boston, Massachusetts and Toronto, Canada and its effect on operational energy.

floor slab), MWU method, and system boundary exclusions. With the embodied energy only accounting for 2.5% of total energy, this study determines that embodied energy while important, is negligible, in terms of a sustainable design criteria.

One of the objectives of this study is to determine the relevance of embodied energy on a building life span and determine which material might have less of an impact on pre-use energy requirements. Because the embodied energy is equal, the case for embodied energy in deciding which material to chose (concrete or steel), is even less significant. Operational energy is evidently a more important decision making criteria in sustainable building design.

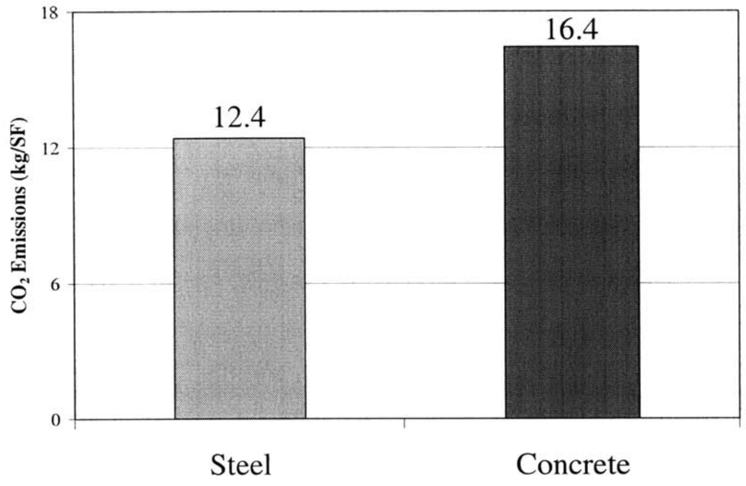
The comparison of total energy results reached in this LCA, while inconclusive in determining which material is more sustainable in terms of embodied energy requirement, is still important because the results do have a significant impact on the environment. This study, in terms of the MWU method, does make a determination that embodied energy between concrete and steel can be ignored as a decision making criteria when deciding between steel or concrete for a given building frame, however the impact of steel- and concrete-frames in terms of total raw energy consumption in the pre-use phase can not be ignored by material manufacturers. The concrete and steel industries, along with the construction industry, need to continue the progress towards reducing energy requirements in the production of their respective materials.

7.4 **Air Emissions**

7.4.1 *Raw Results*

The raw data results indicate that concrete has a 25% greater impact on CO_2 emissions than steel but both are on the same order of magnitude ($x10^6$ kg of CO_2 for the functional unit defined). The normalized results, per square foot, are shown in Figure 7.13.

Figure 7.13. CO_2 Emission Comparison (Normalized Values)

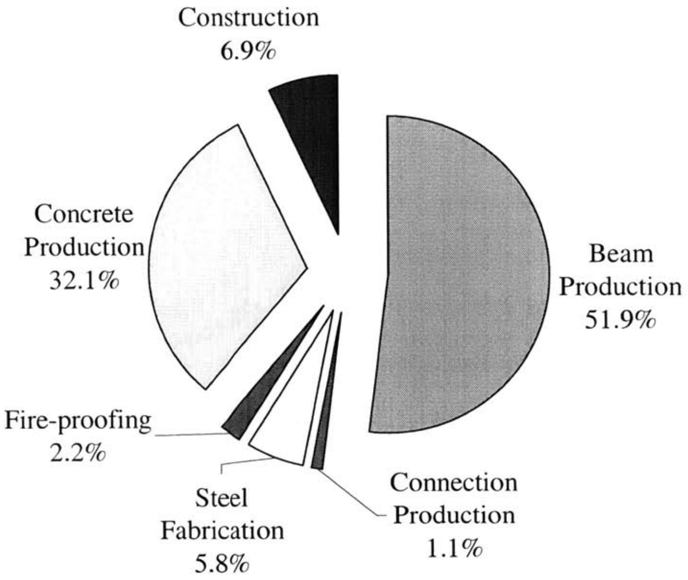


Carbon dioxide (CO_2) is released in almost all unit processes, either directly from a chemical reaction within the productions steps or through the burning of fossil fuels for kiln heating or to provide the electricity required to power the production facility. The process of calcination (discussed in Chapter 3) is integral to the production of Portland cement. It emits CO_2 as a byproduct of the chemical reaction. It is intuitive then to expect that concrete has a greater impact on CO_2 emissions than steel. In that case, the emission results of this study support that assertion.

7.4.2 *Steel Specific Results*

The CO_2 emission rate for steel-frame construction according to this study is 12.4 kg/SF. A breakdown of CO_2 emissions by main product system is depicted in Figure 7.14.

Figure 7.14. CO_2 Emissions by Product Systems (Steel-Frame)



The primary contributors to CO_2 emissions for steel frame buildings are steel beam production at 52% and concrete production (for floor slabs) at 32%. These two main product systems account for nearly 85% of total CO_2 emissions. This is an obvious result because the steel beams and concrete floor slabs account for a vast majority of the material used in steel-frame construction. Even after extracting the transportation requirement from each product systems, steel beam and concrete production, while less, are still the major contributors to CO_2 emissions, see Figure 7.15. Transportation and construction stage CO_2 emissions for the steel process flow remain relatively constant, at 10.7% and 6.9% respectively.

Figure 7.15. CO_2 Emissions (Steel) with Transportation Extracted

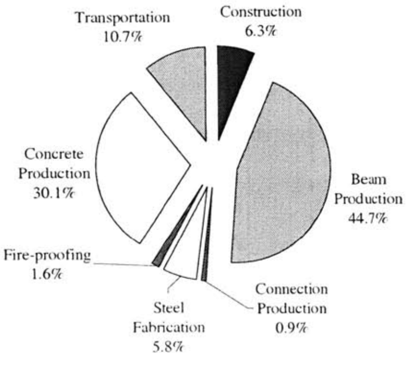
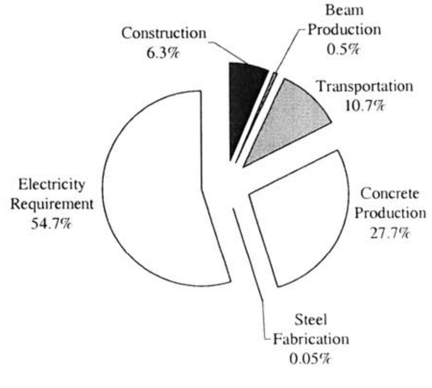
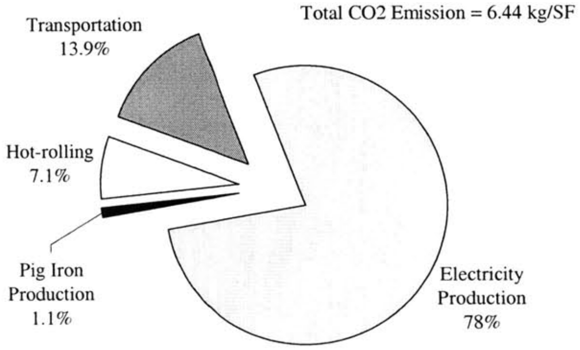


Figure 7.16. CO_2 Emissions (Steel) with Electricity Extracted



As shown in Figure 7.16, once electricity production is removed from the six main product systems their impact on CO_2 emissions is minor and in some cases negligible: steel beam production (.5%), connection fabrication (.05%), connection production (0%), beam fabrication (0%), and fireproofing (0%).[24] The one exception is the production of concrete for the floor slabs, accounting for 27% of the total CO_2 emissions. With extraction of electricity production from the pie chart, the CO_2 emission from concrete production is only reduced by 3%. This is primarily due to the large amount of CO_2 emitted during the calcination process. A more detailed discussion of concrete production's impact on CO_2 emission is included in Section 7.4.3.

Figure 7.17. Breakdown of CO_2 Emissions in Steel Beam Production Unit Process



Focusing on steel beam production as the major contributor, CO_2 is mainly emitted during the production of electricity required to charge the EAF. The production of electricity accounted for over 75% of the steel beam product system's CO_2 emissions, see Figure 7.17. The enormous electricity requirement for beam production accounts for just over 44% of the total CO_2 emissions for steel-frame construction, nearly 5.5kg/SF.

Similar to results shown in the energy consumption result section, the production of electricity in the steel-frame process flow has a similar impact on CO_2 emissions.

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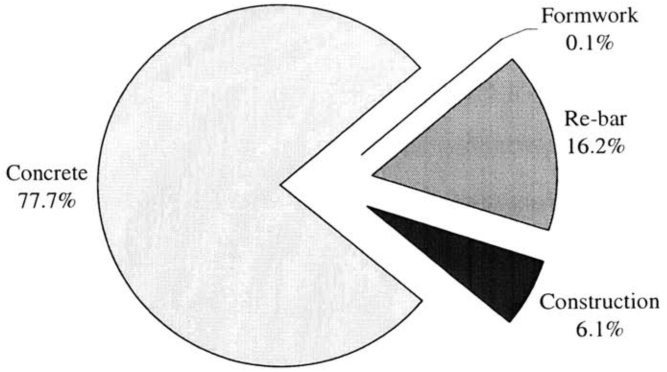
[24] No data available on emissions from fabrication shop and fireproofing manufacture

Potentially cleaner fuels for electricity production could reduce the CO_2 impact of steel. Unfortunately, for the steel producers, this is largely out of their control.

7.4.3 *Concrete Specific Results*

The breakdown of CO_2 emissions by associated product systems are shown in Figure 7.18. The total CO_2 emitted by our functional unit building is 1.64 million kilograms. This equates to 16.4 kilograms per square foot.

Figure 7.18. CO_2 Emissions by Product System (Concrete-Frame)



The primary emitter of CO_2 for the overall concrete-frame process flow is the production of concrete at roughly 78%. Even with transportation and electricity requirements isolated, the concrete product system and its associated unit processes still account for nearly 68% of total CO_2 emissions. See Figures 7.19 and 7.20.

Figure 7.19. CO_2 Emissions (Concrete) with Transportation Extracted

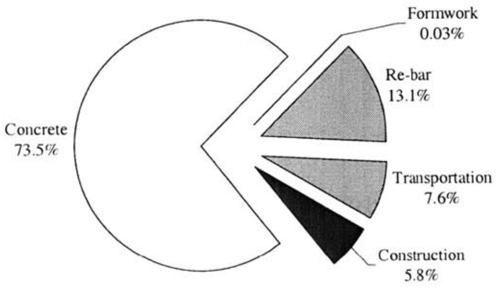
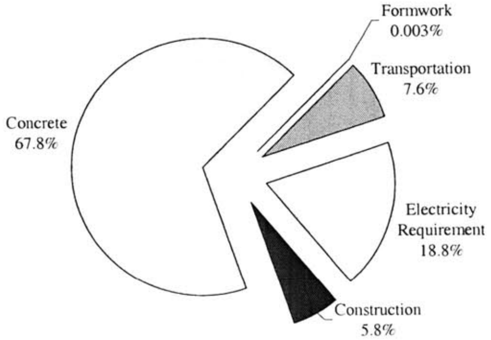


Figure 7.20. CO_2 Emissions (Concrete) with Electricity Extracted



Analyzing the individual unit processes, this study determines that the production of Portland cement accounts for 93% of the total CO_2 emissions in the concrete production unit process, depicted in Figure 7.21. Analyzing further, actual production of Portland cement accounts for 94% of the cement production sub-unit process, with only 6% of CO_2 emissions accounted for by transportation and electricity production to operate the cement production facility. These results are shown in Figure 7.22. This large emission percentage is supported by several research sources citing Portland Cement as the primary source of CO_2 in the concrete industry due to the burning of fossil fuels and the calcination of limestone discussed earlier (Hendricks et al, 2006; Hanle, 2004). Overall, the CO_2 emitted by the cement production sub-unit process accounts for 63% of the total CO_2 release for concrete-framed buildings analyzed within the scope and boundaries of this study.

Figure 7.21. Breakdown of CO_2 Emissions in the Concrete Production Unit Process

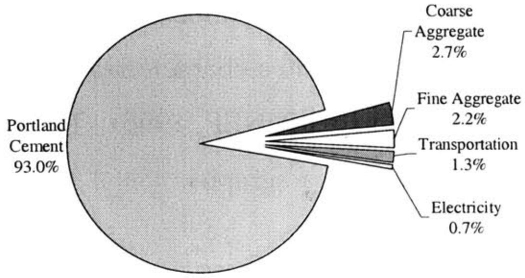
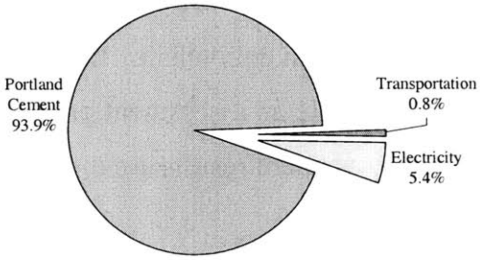


Figure 7.22. Breakdown of CO_2 Emissions in the Cement Production Sub-unit Process



In terms of reducing CO_2 emissions related to cast-in-place concrete, decreasing the amount of Portland cement in the mixture ratio of concrete is the obvious solution. According to this study, for every 10% reduction in the amount of Portland cement in concrete there is a corresponding 7.5% decrease in CO_2 emission per square foot of constructed building. The concrete industry understands this challenge and has started to stress the use of admixtures like mill scale and fly ash to replace the ratio of Portland cement required in today's typical concrete mix ratios (PCA, 2006).

7.4.4 *Additional Air Emissions Results.*

This study, as a secondary objective, tracked and analyzed additional harmful air emissions to include those that lead to acidification and human toxicity. These results, while not as publicized as global warming and CO_2 emissions, are still tools to measure the environmental impacts of steel and concrete as building materials. These were secondary objectives for the study, tracked for information purposes and to highlight the numerous other environmental impact areas that could have been targeted in this study. Some additional environmental impacts include water emissions and soil contamination.

Interpretation of the results for human toxicity and acidification potential used the impact assessment technique outlined in the LCA guidelines (ISO 14042, 2000; UNEP, 1996). As discussed earlier, impact assessment is not used to interpret a majority of the results, because the target areas for the most part, contained only one factor; energy (in MJ) for energy consumption, resources quantity (in kg) for resource depletion, and CO_2 emissions (in kg) for global warming potential.[25] When there are several emission factors, as is the case with human toxicity and acidification potential measurements (refer to Table 5.1), an equivalency factor is added to the raw data and a characterization index is used to make an assessment of a material and then compare (UNEP, 1996). The impact assessment results are discussed in the next two sub-paragraphs.

7.4.4.1 Human Toxicity

Human Toxicity is defined as "exposure to toxic substances—through air, water or the soil-that causes human health problems." (UNEP, 1996, p.68). The relevant emission substances and their respective equivalency factors, along with the characterization matrix are located in Appendix D. The comparison of steel and concrete is shown in Figure 7.23.

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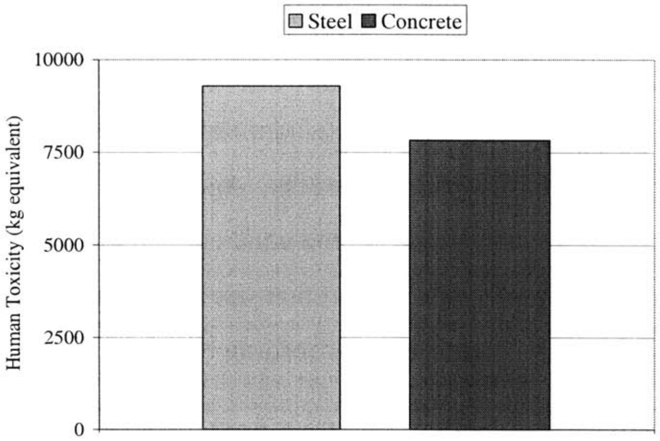
[25] Methane is included in the impact assessment value for Global warming potential, but in this case is ignored because of it lack of impact event with the weighing factor. (UNEP, 1996)

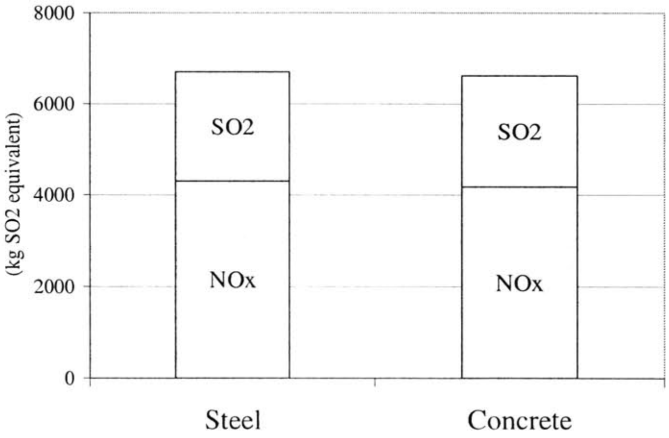
Figure 7.23. Comparison of Human Toxicity Potential



7.4.4.2 Acidification Potential

Acidification is caused by the harmful air emissions of sulphur dioxide (SO_2), Nitrogen oxide (NO_x) and Carbon Monoxide (CO). The United Nations Environment Programme (UNEP) defines acidification potential as the "release of nitrogen and sulphur oxides into the atmosphere, on soil and water [that] can lead to changes in soil and water acidity, which effects both flora and fauna." (1996, p.68). The equivalency factors and characterization matrix results are located in Appendix E. The comparison is shown in Figure 7.24. The results between steel and concrete are comparable.

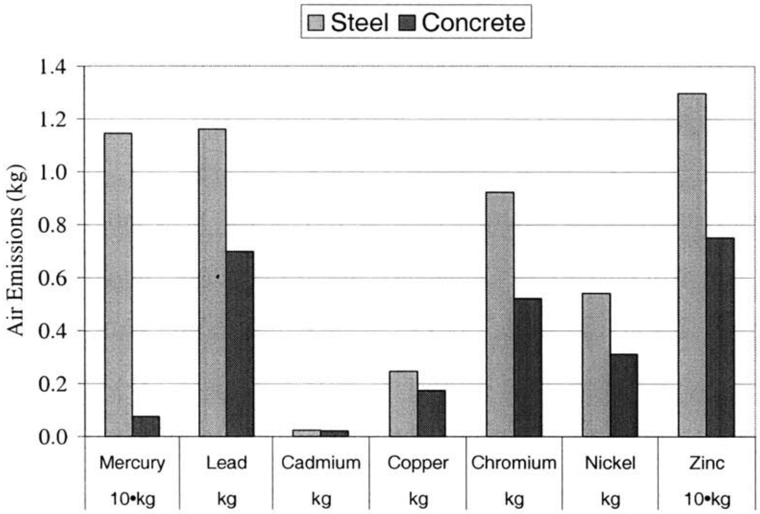
Figure 7.24. Comparison of Acidification Potential



7.4.4.3 Heavy Metal Emissions

Emissions of heavy metal into the atmosphere are also tracked as secondary emissions in the LCA. The raw results comparison is depicted in Figure 7.25. While some of these metals have an impact on Human Toxicity (Cadmium-Cd and Chromium-Cr), the results presented in Figure 7.25 are un-weighted results. Again, this is a tool to show the extent of environmental issues affected by steel- and concrete-frames, especially from a material standpoint. From the figure it is determined that steel has a greater impact in terms of this secondary environmental target area (according to this specific study).

Figure 7.25. Heavy Metal Emissions



7.4.5 *Discussion of Air Emission Results*

Based on the LCA, this study concludes that concrete-frame construction has a greater impact, approximately 25%, on CO_2 emissions than steel-frame construction. The major material product system flows, concrete production in the concrete-frame construction process flow and steel beam production in the steel-frame overall construction process flow are the primary contributors of CO_2 as outlined in the previous sections. So what is causing the difference? This study looked at whether or not the recycled content of steel has an impact on CO_2 emissions, causing the difference in overall CO_2 emissions. The results are listed in Table 7.4.

Table 7.4. CO_2 Emission per Recycled Steel Content in Beam Production

Recycled Content	CO_2 Emission (kg/SF)	% Change
95%*	1.242	
75%	1.273	+ 2.5%
50%	1.311	+3.0%

*current LCA condition

According to the results listed in Table 7.4 the recycled content is not the major issue because reducing the recycled content by 25% only leads to a 2.5% reduction in CO_2 emissions. While the production of increased virgin steel does impact CO_2 emissions, it is not enough to completely account for the difference. Currently, the average recycled content across the United States steel industry is 96% (Steel Recycling Institute, 2005). To reduce the recycled content any lower in the sensitivity analysis, to account for the difference in CO_2 emissions, is not valid.

The CO_2 emissions may be skewed because the production of the fuels that serve as energy sources, such as oil refining, natural gas mining and coal processing are not included in the inventory. This would account for the difference, but as discussed in Section 7.3, the total energy requirement is nearly equivalent so any CO_2 released during fuel production, like oil refining would also be nearly equivalent.

Further analysis of the process stages and their respective CO_2 emission rates are listed in Table 7.5. The CO_2 emitted during transportation and construction for both materials is relatively equal, with transportation accounting for slightly more in steel and the construction stage accounting for slightly more in concrete. The difference in the material production stage is almost 4 MJ/SF. This supports the conclusion that the release of CO_2 during the pyroprocesing of cement is the major cause of the difference in CO_2 emissions. It seems that the solution to CO_2 emission as it relates to the building industry needs to be looked at on the material level.

Table 7.5. Comparison of CO_2 Emission by Process Flow Stage

Process Flow Stage	Steel (MJ/SF)	Concrete (MJ/SF)
Construction	.78	.95
Transportation	1.33	1.25
Material Production	10.30	14.23

Strictly based on the CO_2 emission results as they relate directly to global warming, this LCA finds that steel is the 'better' material for sustainable design. It is important to note that the effects of other harmful air emission, like acidification and human toxicity need to be considered when making a true comparison based on total harmful emissions across a broad environmental impact target area.

7.5 **Resource Depletion**

The study defines resource as the primary natural raw materials used in the individual unit processes of the respective material process flows. The primary materials included in the study are listed in Table 7.6. In order to quantify the total amount of resources used this study tracked the nine natural resources listed in Table 7.6 throughout the inventory analyses.

Table 7.6. List of Primary Natural Resources

Natural Resource	Primary Input for...
Bauxite	Cement Production
Clay	Cement Production
Gravel	Concrete Production
Gypsum	Cement Production Fireproofing Manufacture
Iron Ore	Pig Iron Production
Limestone	Concrete Production Steel Production
Sand	Concrete Production
Water*	Concrete Batching Steel Production Fireproofing Application
Wood*	Formwork Manufacture

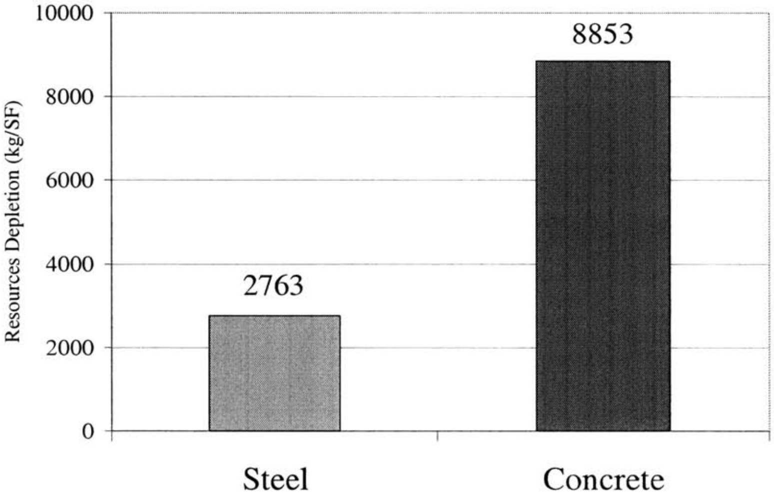
*Indicates a renewable resource

The list includes both renewable and non-renewable raw material types in order to gauge the overall resource depletion corresponding to both steel- and concrete-frame construction. All nine of the natural resources listed are tracked in both the steel and concrete inventory analysis for comparison purposes. The results are discussed in the following sections. While other materials are required for the process flows, only these nine are considered as the major natural resource inputs.

7.5.1 *Raw Results*

Concrete, when used as a building material, has four times the impact on natural resource depletion compared to steel as shown in Figure 7.26. The total resource depletion figure is a combined total amount (in kilograms) of the nine resources tracked in this study and listed in Table 7.6.

Figure 7.26. Resource Depletion Comparison (Normalized Values)



7.5.2 *Steel Specific Results*

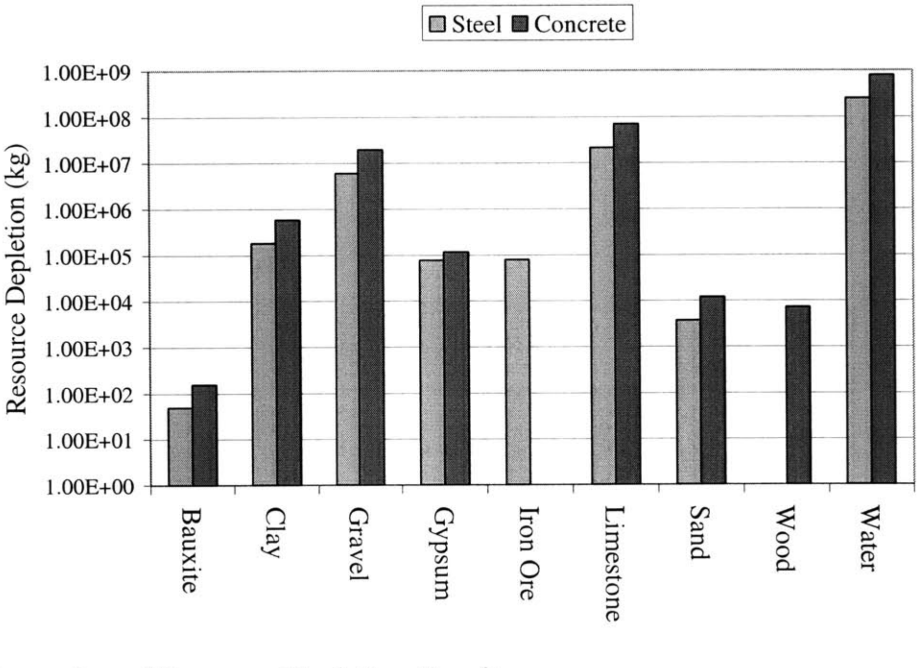
In steel-frame construction total resources consumed is equal to 276 million kilograms. This equates to 2763 kg/SF. The primary natural resources consumed are virgin iron ore required for pig iron production, and gypsum for fireproofing manufacture. The only resource that steel consumes more of compared to concrete is iron ore. See Figure 7.27. The EAF steel-making facilities in the MWU use a very high recycled content (95-

100%). For the purpose of this study the iron scrap content is not included in the inventory because it is a recycled material and thereby its initial production is ignored and potentially counted elsewhere. The amount of raw iron ore it replaces in terms of resource depletion definitely has an effect on the results in this section of the study. The total amount of scrap was tracked for comparison purposes and is equal to approximately. 540,000 kg.

7.5.3 *Concrete Specifics Results*

In terms of overall resource depletion, concrete has nearly a four times greater impact than steel, for the nine primary resources. Total quantity of resources consumed is 885 million kilograms, roughly 8853 kg/SF. In eight out of the nine resource areas in Figure 7.27, the amount in the concrete column exceeds that of the steel column.

Figure 7.27. Comparison of Resource Depletion by Natural Resource Type



7.5.4 *Discussion of Resource Depletion Results*

Concrete and steel construction methods do have a major impact on the limited natural resources on the planet. The conclusion of the study is that concrete construction uses four times the amount of total raw resources than steel. This comparison is based solely on the gross raw resource usage and the difference can be accounted for simply by the different amounts and types of raw materials used by the two very different process flows. The use of scrap iron also accounts for some of the difference, because recycled steel is not counted as one of the raw resources. But what is the future of recycled steel? Is there enough scrap iron to meet demand? This could impact the resource depletion results of this LCA, significantly, especially if recycled steel becomes in short supply.

The important result to note is that both materials, in the construction of a single building require over 10,000 tons (US) of gross raw materials (without water) and consume greater than 100,000 tons of water; these impacts can not be ignored.

7.6 General Discussion of Results

7.6.1 *Verification of Results (Reality Check)*

To ensure accuracy between the two comparisons some measures were taken to ensure compatibility. The following table shows the production and fabrication rates for steel sections used in both concrete- and steel-frame construction. This was done to ensure compatibility and to provide a level of accuracy between the two materials.

Table 7.7. Results of Compatibility Analysis

	Reinforcing Bar	Formwork Bracing	Steel Beam	Steel Connection
Fabrication Rates (MJ/kg of steel)	.524	N/A	1.01	6.27*
Production Rates (MJ/kg of steel)	11.3	10.6	11.0	11.2

* due to welding completed during fabrication process

The minor differences, in Table 7.7, are accounted for by recycling content percentage, outbound shipment distances and electricity production mix for the area the steel is produced in. The results in Table 7.7 highlight the accurate compatibility between the two separate inventory analyses.

7.6.2 *Validity of Assumptions*

The results discussed in the previous sections are based on the coordination between the industry research and database information. The analysis required numerous assumptions to complete the inventories. These assumptions are discussed throughout the report and are listed in the appendices with the individual inventory matrices. These assumptions have an impact on the data, but in most cases are equivalent between the two materials.

The results are comparable to those in other studies, given the specific assumptions that were made (see Section 7.3). The assumptions that had the greatest impact on the study only caused the results to be different compared to existing studies, but for the most part did not impact the intended comparison of steel- and concrete-frames defined by the scope and boundaries of the current LCA study.

The results are purposively based on the geographical area of Boston, and therefore will only apply to Boston. If the relative efficiency of the cement production facility in the MWU method is low, compared to an efficiency of the steel mill, this is part of the intent of this research study and is the nature of the MWU method defined. The potential affect on the results is applicable to the Boston industry and is therefore valid. The intent of this study is not to handpick facilities to develop the process flow, but rely on the actual flow of materials as they relate to how construction is completed in the Boston area.

The limited sensitivity analysis conducted in Section 7.4 shows that recycled content did not have a very large impact on CO_2 emissions or energy requirements, but may have an impact on natural resource depletion. This study did not account for the efficiency ratings of the production facilities in the MWU method, but relied on the database to provide necessary outputs. The MWU method is used primarily to remain unbiased to the materials in question while building the LCA inventory. If a different region was analyzed, the potential differences based on the efficiencies of production facilities and shipment distances (transportation) would certainly effects the results. The results are considered valid for the scope of this study.

8 *Conclusion*

8.1 Summary of Results

The primary objective of this research study and life-cycle assessment was to determine which building material method, steel or cast-in-place concrete is 'better' from a sustainability perspective. A summary of the results is given in Figure 8.1.

Figure 8.1. Overall Results Summary

	CO_2 emissions	Energy Consumption	Resource Depletion
Steel	12.4 kg/SF	102.1 MJ/SF	2.8 Mg/SF
Concrete	16.4 kg/SF	102.5 MJ/SF	8.8 Mg/SF

Based on the three targeted environmental impacts, the study concludes that steel is 'better' and a more sustainable building material in the pre-use phase of building development. This conclusion is based solely on an un-weighted, raw comparison of the two materials in three separate categories. Steel is the clear 'winner' in CO_2 emissions and resource depletion, with 25% less total CO_2 emission and 68% less total natural resources used. This study concludes that energy consumption is equal and therefore does not effect the determination and conclusion of the LCA comparison.

8.2 Conclusions

Without question sustainability is now a decision making tool in the construction and design industry. While the question posed in Chapter 1 of "which material is better?" is answered in this study, the results are fairly close and potentially affected by assumptions made and uncertainty in the data. The conclusion of the study is that steel is 'better', but that conclusion is based on an un-weighted comparison across only three environmental impacts narrowly defined by the functional unit and MWU method. This definitive conclusion can also be made because in the case of this study steel either has less or equivalent impact of concrete in all impact areas. But what if the total energy requirement of steel exceeded concrete, for instance due to the requirement to receive steel from more energy intensive mills overseas; is the conclusion of this study still accurate? Where does it say that impacts of energy consumption are less important than the impact of CO_2 emissions and natural resource consumption?

The politics of environmental policy are such that viewpoints and stances can fluctuate from one that weighs CO_2 emissions as far more important than natural resource depletion to one that advocates just the opposite. Building designers and engineers are now wrapped up in this debate when it comes to sustainable building design. That is why this thesis, for the most part, refers directly to raw data results and avoids the politics of weighing environmental impacts. This allows the reader of this thesis to make his or her own decision on which material they feel is 'better' from their specific standpoint.

Ancillary to defining a 'better' material is the fact that even the 'better' material has a significant impact on the environment. For instance, what is an acceptable threshold of CO_2 emissions? Is choosing steel over concrete going to solve the challenge of global warming? While, this study, and future life cycle assessments may answer the first question of "which is better?" the more important question to answer is "how does industry make both building methods and associate material better?" Again, in the case of steel and concrete-frame construction defined in this study, the 'winner' is steel, but only by a slight margin. Decision makers have to avoid the pitfall of assigning a 'winner' and forgetting the big picture – that both materials, even in only the pre-use phase of a single building – have a significant impact on the global environment.

The author of this study assumes that construction using cast-in-place concrete and steel will continue to dominate the built environment far into the next half-century. From an engineer's perspective, sensitive to environmental issues, the answer to the second question is the future of the built environment and sustainability practice.

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APPENDIX A

APPENDIX A-1. ASSUMPTIONS FOR CONCRETE INVENTORY ANALYSIS

Given Data:

1 ton [metric] =	2204.6	lbs	
1 kg =	2.2046	lbs	
1 m3 =	1.3080	cu yd	
1 m3 =	2.5	metric tons	source: www.concrete.org.uk
1 BTU/hp-hr =	7.3857	MJ/hp-hr	
Average BSFC =	7000		(EPA AP-42, 2003)
Calorific value of diesel =	46	MJ/kg	(NPL, 2006)
Calorific value of coal =	36	MJ/kg	(NPL, 2006)

Assumptions:

Total amount of concrete used to construct functional unit =	**6000**	yd^3	Estimate based on case studies for structure only (Project Manager, Turner Concrete, personal communication.
Concrete			
Concrete placement rate at construction site =	50	yd^3/hr	Based on conversations with concrete contractor (Montero, S., S&F Construction Foreman, personal communication).
Percent of concrete wasted/un-used during placement =	5%		(Montero, S., personal communication).
Formwork			
Number of total forms required per m^3 of concrete placed =	0.07	forms/m^3	Based on assumed number of columns per floor (20) and the amount of concrete per column. In this case a 2' x 2' x 8' column was used as a typical column size. Columns would be formed and poured on alternate days, therefore requiring only enough forms to frame half the columns per floor. Columns account for 50% of total concrete used.
Percent of new forms required =	10%		(Montero, S., personal communication).
Weight of form =	100	lbs	Estimate of form weight based on discussions with concrete contractors and formwork distributors (Sales Representative, AH Harris, 2006).
Density of Douglas Fir: 1 m^3 =	520	kg	The most common wood type used for the production of plywood is the Douglas Fir, (Kline, R., APA Resource desk, personal communication). The density of Douglas fir was found at www.allmeasures.com
Density of Plywood: 1 m^3 =	450	kg	
Reinforcement			
Amount of steel re-bar used per m3 of concrete placed =	62.5	kg/m^3	Based on typical column size and typical re-bar configuration using #10 and #4 steel bar. Amount = weight of rebar per foot/amount of concrete in one foot of column. (Project Manager, Harris Rebar, personal communication)
Percent of re-bar steel wasted during fabrication =	5%		(Project Manager, Harris Re-bar, personal communication)
Percent of re-bar lost during placement =	1%		This is the amount of rebar lost on-site during configuration of re-bar cages. (Montero, s., personal communication).
Re-bar placement rate at construction site =	1000	kg/hr	(Montero, S., personal communication) An estimate of one re-bar cage every 10 minutes.

Energy Source

BSFC for Diesel engine =		0.353971	lb/hp-hr	BSFC = Avg BSFC/Calorific Value
	hp	SFC		SFC = BSFC * hp
Specific fuel consumption rate (generator) =	124	43.9	lb/hr	
Specific fuel consumption rate (mix truck) =	565	200.0	lb/hr	
Specific fuel consumption rate (pump truck) =	300	106.2	lb/hr	
Specific fuel consumption rate (small crane) =	200	70.8	lb/hr	

Matrix C - CONCRETE CONSTRUCTION

This spreadsheet represents the inventory analysis for the entire concrete construction process flow chart.
It is the compilation of all data collected and sub-matrices.
It is based on a construction site in Boston, MA.

Total amount of concrete used to construct functional unit = **6000** cu yds

Distance Data:

	miles	km	
Inbound Mileage:	25	40.23	Approximate distance from formwork storage to construction site [via Truck]
Outbound Mileage:	40	64.37	Approximate distance to waste disposal site [via Truck]

		Processes		Place Concrete	Batch Concrete	Place Formwork	Fabricate Formwork	Remove Formwork	Place Rebar	Fabricate Re-Bar	Rebar Production	Transport by 16T Truck	Transport by 28T Truck	On-Site Equipment Operation	On-Site Energy Generation	Totals
			source:	Industry Research	from M-C1	Industry Research	from M-C2	Industry Research	Industry Research	from M-C3a	from M-C3b	from M-X	from M-X	EPA AP-42 Table 3.3-1	EPA AP-42 Table 3.3-1	
Economic Output			unit:	m3	m3	form	form	form	kg	kg	kg	tkm	tkm	MJ	MJ	
		Placed Concrete	m3	1 4.6E+03	1 4.8E+03	1 3.2E+02	1 3.2E+01	1 2.9E+02	1 2.9E+05	1 2.9E+05	1 3.0E+05	1 2.0E+03	1 7.4E+04	1 1.2E+06	1 1.6E+05	
Economic Inputs																
	2	Batched Concrete	m3	1.1E+00 4.8E+03												4.82E+03 m3
	3	Old Forms	forms			9.0E-01 2.9E+02										2.88E+02 forms
	4	New Forms	forms			1.0E-01 3.2E+01										3.20E+01 forms
	5	Placed Forms	forms	7.0E-02 3.2E+02												3.20E+02 forms
	6	Placed Steel Re-Bar	kg	6.3E+01 2.9E+05												2.87E+05 kg
	7	Steel Re-Bar	kg						1.0E+00 2.9E+05	1.1E+00 3.0E+05						5.94E+05 kg
	8	Formwork Transpo	tkm			3.3E+00 1.1E+03		3.3E+00 9.5E+02								2.00E+03 tkm
	9	Waste Transpo	tkm	1.6E+01 7.4E+04				5.3E-01 1.5E+02	6.4E-04 1.8E+02							7.42E+04 tkm
	10	Mix/Pump Truck Opns	MJ	1.7E+02 7.7E+05												7.67E+05 MJ
	11	Crane Operations	MJ						1.5E+00 4.2E+05							4.24E+05 MJ
	12	On-site Generator Opns	MJ	6.0E+00 2.7E+04					4.6E-01 1.3E+05							1.59E+05 MJ
Environmental Outputs					from M-C1		from M-C2			from M-C3a	from M-C3b	from M-X	from M-X			
Emissions	1	CO2	kg		2.7E+02 1.3E+06		4.1E+01 1.3E+03			5.4E-02 1.6E+04	8.2E-01 2.5E+05	8.5E-02 1.7E+02	6.6E-02 4.9E+03	7.1E-02 8.4E+04	7.1E-02 1.1E+04	1.64E+06 kg
	2	CO	kg		1.6E-01 7.9E+02		4.6E-02 1.5E+00			2.0E-05 5.7E+00	2.8E-03 8.4E+02	1.8E-04 3.7E-01	9.8E-05 7.3E+00	4.1E-04 4.9E+02	4.1E-04 6.5E+01	2.19E+03 kg
	3	NOx	kg		4.9E-01 2.3E+03		2.6E-01 8.5E+00			2.0E-04 5.7E+01	3.1E-03 9.4E+02	8.1E-04 1.6E+00	6.5E-04 4.8E+01	1.9E-03 2.3E+03	1.9E-03 3.0E+02	5.96E+03 kg
	4	SO2	kg		2.0E-01 9.8E+02		4.9E-02 1.6E+00			1.7E-04 5.1E+01	4.1E-03 1.2E+03	1.6E-05 3.3E-02	1.3E-05 9.5E-01	1.2E-04 1.5E+02	1.2E-04 2.0E+01	2.44E+03 kg
	5	Methane	kg		2.8E-03 1.4E+01		5.8E-04 1.8E-02			3.2E-07 9.3E-02	3.8E-06 1.1E+00	3.2E-06 6.4E-03	1.6E-06 1.2E-01			1.51E+01 kg
	6	Hydrocarbons	kg		1.5E-02 7.1E+01		1.5E-03 4.8E-02			1.2E-09 3.4E-04	3.7E-04 1.1E+02	7.4E-09 1.5E-05	5.8E-09 4.3E-04	1.5E-04 1.8E+02	1.5E-04 2.5E+01	3.92E+02 kg
	7	Dust	kg		2.3E+02 1.1E+06		1.9E-03 6.1E-02				4.7E-04 1.4E+02					1.11E+06 kg
	8	Particulates	kg		2.1E-02 9.9E+01		2.5E-02 7.9E-01			1.4E-05 3.9E+00	1.8E-04 5.4E+01	1.2E-04 2.3E-01	6.8E-05 5.1E+00	1.3E-04 1.6E+02	1.3E-04 2.1E+01	3.43E+02 kg
	9	Mercury	kg		9.3E-06 4.5E-02		9.7E-06 3.1E-04			7.6E-10 2.2E-04	2.4E-06 7.2E-01	2.3E-10 4.7E-07	1.8E-10 1.4E-05			7.63E-01 kg
	10	Lead	kg		2.4E-05 1.1E-01		8.6E-06 2.8E-04			4.4E-10 1.3E-04	1.9E-06 5.8E-01	3.6E-09 7.1E-06	2.2E-09 1.7E-04			6.99E-01 kg
	11	Cadmium	kg		2.0E-06 9.6E-03		3.2E-07 1.0E-05			9.3E-11 2.7E-05	3.9E-08 1.2E-02	7.4E-10 1.5E-06	4.7E-10 3.5E-05			2.16E-02 kg
	12	Copper	kg		1.1E-05 5.2E-02		1.3E-05 4.0E-04			6.3E-09 1.8E-03	3.9E-07 1.2E-01	4.2E-08 8.4E-05	3.1E-08 2.3E-03			1.75E-01 kg
	13	Chromium	kg		1.3E-06 6.2E-03		8.2E-06 2.6E-04			7.4E-10 2.1E-04	1.7E-06 5.2E-01	6.0E-09 1.2E-05	3.7E-09 2.8E-04			5.22E-01 kg
	14	Nickel	kg		2.1E-06 1.0E-02		5.3E-06 1.7E-04			7.3E-10 2.1E-04	9.9E-07 3.0E-01	5.8E-09 1.2E-05	3.6E-09 2.7E-04			3.11E-01 kg
	15	Zinc	kg		3.1E-05 1.5E-01		1.2E-04 3.8E-03			1.2E-08 3.4E-03	2.4E-05 7.4E+00	1.7E-07 3.3E-04	6.0E-08 4.4E-03			7.51E+00 kg
	16	Dioxins	kg		7.0E-10 3.4E-06		4.7E-10 1.5E-08			2.5E-13 7.3E-08	7.7E-12 2.4E-06	1.6E-12 3.2E-09	1.3E-12 9.4E-08			5.90E-06 kg
Waste	17	Waste heat	MJ		1.4E+03 6.8E+06		4.8E+02 1.5E+04			2.0E-01 5.9E+04	1.0E+01 3.1E+06	1.2E+00 2.5E+03	9.6E-01 7.2E+04			1.00E+07 MJ
	18	Waste (landfill)	kg	1.3E+02 5.7E+05	1.7E+01 8.2E+04		5.1E-01 1.6E+01	4.1E+00 1.2E+03			1.3E-01 3.8E+04					6.94E+05 kg
	19	Waste (recycle)	kg				2.0E-01 6.5E+00		1.0E-02 2.9E+03	5.0E-02 1.4E+04	5.0E-02 1.5E+04					3.26E+04 kg
	20	Waste (incinerator)	kg		1.3E-01 6.0E+02		8.7E-04 2.8E-02				2.1E-04 6.5E+01					6.68E+02 kg
Environmental Inputs					from M-C1		from M-C2			from M-C3a	from M-C3b	from M-X	from M-X			
Primary Resources	1	Bauxite	kg		3.3E-02 1.6E+02											1.57E+02 kg
	2	Clay	kg		1.2E+02 5.8E+05											5.84E+05 kg
	3	Gravel (in ground)	kg		4.0E+03 1.9E+07											1.94E+07 kg
	4	Gypsum (resource)	kg		2.4E+01 1.2E+05											1.16E+05 kg
	5	Iron Ore (resource)	kg													kg
	6	Limestone	kg		1.4E+04 6.9E+07											6.91E+07 kg
	7	Sand	kg		2.5E+00 1.2E+04											1.21E+04 kg
	8	Water	kg		1.6E+05 7.9E+08		4.2E+02 1.3E+04				5.5E+00 1.7E+06					7.96E+08 kg
	9	Wood (in forest)	kg				2.2E+02 7.2E+03									7.19E+03 kg
Energy	10	Coal Energy	MJ		3.9E+02 1.9E+06		4.9E+01 1.6E+03			6.2E-02 1.8E+04	2.2E+00 6.6E+05					2.54E+06 MJ
	11	Diesel Fuel Energy	MJ		4.9E+02 2.4E+06		3.6E+02 1.2E+04			1.9E-01 5.5E+04	2.2E+00 6.8E+05	1.2E+00 2.4E+03	9.5E-01 7.1E+04	1.0E+00 1.2E+06	1.0E+00 1.6E+05	4.53E+06 MJ
	12	Natural Gas Energy	MJ		3.9E+01 1.9E+05		3.8E+01 1.2E+03			7.6E-02 2.2E+04	3.8E+00 1.2E+06					1.38E+06 MJ
	13	Oil Energy	MJ		5.9E+01 2.8E+05					5.8E-02 1.7E+04	3.2E-01 9.6E+04					3.96E+05 MJ
	14	Other Energy	MJ		8.6E+01 4.1E+05		7.3E+01 2.3E+03			1.6E-01 4.7E+04	3.1E+00 9.4E+05					1.40E+06 MJ

Total Energy Input	Total Energy Input	1.03E+07 MJ
Total Nat'l Resource Input	Nat'l Resource Input	8.85E+08 kg

Matrix C1 - CONCRETE PRODUCTION

This spreadsheet represents the inventory analysis for concrete production at the RMC batch plant.
It includes flows from cement production (M-C1a) and aggregate (coarse/fine) production (M-C1b/M-C1c).

Distance Data:

	miles	km	
Outbound Mileage:	5	8.05	Approximate distance from concrete batching facility to construction site (via Mix Truck)
	40	64.37	Approximate distance to waste disposal site [via Truck]

			Processes:	Concrete Batching		Portland Cement Production		Aggregate Production		Aggregate Production		Transport by 16T Truck		Transport by 28T Truck		Electricity Production		
			source:	EcoInvent-report #7 part III pg33		from M-C1a		from M-C1b		from M-C1c		from M-X		from M-X		EPA Power Profile (02129 zip code)		
Economic Output			unit:	m3		kg		kg		kg		tkm		tkm		kWh		
		Batched Concrete	m3	1	1	1	3.00E+02	1	1.16E+03	1	7.33E+02	1	4.02E+01	1	2.19E+00	1	4.36E+00	
Economic Inputs																		Totals
	2	Portland Cement	kg	3.00E+02	3.00E+02													3.00E+02 kg
	3	Coarse Aggregate (Gravel)	kg	1.16E+03	1.16E+03													1.16E+03 kg
	4	Fine Aggregate (Sand)	kg	7.33E+02	7.33E+02													7.33E+02 kg
	5	Outbound Concrete Transpo	tkm	4.02E+01	4.02E+01													4.02E+01 tkm
	6	Waste Transpo	tkm	2.19E+00	2.19E+00													2.19E+00 tkm
	7	Electricity	kWh	4.36E+00	4.36E+00													4.36E+00 kWh
Environmental Outputs						from M-C1a		from M-C1b		from M-C1c		from M-X		from M-X				
Emissions	1	CO2	kg			8.22E-01	2.47E+02	6.25E-03	7.23E+00	8.05E-03	5.90E+00	8.45E-02	3.40E+00	6.62E-02	1.45E-01	4.07E-01	1.77E+00	2.65E+02 kg
	2	CO	kg			4.37E-04	1.31E-01	6.63E-06	7.66E-03	2.29E-05	1.68E-02	1.84E-04	7.39E-03	9.79E-05	2.15E-04			1.63E-01 kg
	3	NOx	kg			1.11E-03	3.33E-01	4.71E-05	5.45E-02	8.64E-05	6.34E-02	8.13E-04	3.27E-02	6.46E-04	1.42E-03	6.81E-04	2.97E-03	4.87E-01 kg
	4	SO2	kg			5.84E-04	1.75E-01	8.10E-06	9.37E-03	1.43E-05	1.05E-02	1.64E-05	6.59E-04	1.29E-05	2.82E-05	1.72E-03	7.52E-03	2.03E-01 kg
	5	Methane	kg			8.16E-06	2.45E-03	1.09E-07	1.26E-04	1.91E-07	1.40E-04	3.23E-06	1.30E-04	1.61E-06	3.53E-06			2.85E-03 kg
	6	HydroCarbons	kg			4.93E-05	1.48E-02	3.98E-10	4.61E-07	4.55E-10	3.34E-07	7.39E-09	2.97E-07	5.80E-09	1.27E-08			1.48E-02 kg
	7	Dust	kg			7.66E-01	2.30E+02											2.30E+02 kg
	8	Particulates	kg			5.75E-06	1.73E-03	4.63E-06	5.35E-03	1.17E-05	8.59E-03	1.17E-04	4.69E-03	6.83E-05	1.50E-04			2.05E-02 kg
	9	Mercury	kg			3.05E-08	9.15E-06	4.33E-11	5.01E-08	7.14E-11	5.24E-08	2.34E-10	9.40E-09	1.83E-10	4.01E-10	7.35E-09	3.20E-08	9.29E-06 kg
	10	Lead	kg			7.72E-08	2.32E-05	1.52E-10	1.76E-07	6.53E-11	4.79E-08	3.55E-09	1.43E-07	2.23E-09	4.89E-09			2.35E-05 kg
	11	Cadmium	kg			6.36E-09	1.91E-06	3.19E-11	3.69E-08	1.76E-11	1.29E-08	7.39E-10	2.97E-08	4.67E-10	1.03E-09			1.99E-06 kg
	12	Copper	kg			1.55E-08	4.66E-06	2.16E-09	2.49E-06	2.60E-09	1.91E-06	4.23E-08	1.70E-06	3.14E-08	6.90E-08			1.08E-05 kg
	13	Chromium	kg			2.20E-09	6.61E-07	2.53E-10	2.93E-07	1.10E-10	8.04E-08	6.03E-09	2.42E-07	3.71E-09	8.15E-09			1.29E-06 kg
	14	Nickel	kg			4.87E-09	1.46E-06	2.49E-10	2.87E-07	1.30E-10	9.57E-08	5.79E-09	2.33E-07	3.64E-09	7.99E-09			2.09E-06 kg
	15	Zinc	kg			5.92E-08	1.77E-05	4.00E-09	4.63E-06	1.83E-09	1.34E-06	1.68E-07	6.74E-06	5.96E-08	1.31E-07			3.06E-05 kg
	16	Dioxins	kg			1.52E-12	4.56E-10	8.73E-14	1.01E-10	9.94E-14	7.29E-11	1.61E-12	6.49E-11	1.27E-12	2.79E-12			6.97E-10 kg
Waste	17	Waste heat	MJ	1.57E+01	1.57E+01	3.94E+00	1.18E+03	8.13E-02	9.40E+01	9.90E-02	7.26E+01	1.23E+00	4.94E+01	9.64E-01	2.12E+00			1.42E+03 MJ
	18	Waste (landfill)	kg	1.69E+01	1.69E+01	7.22E-05	2.17E-02											1.69E+01 kg
	19	Waste (recycle)	kg															kg
	20	Waste (incinerator)	kg	9.51E-02	9.51E-02	4.06E-05	1.22E-02	7.11E-06	8.22E-03	1.32E-05	9.68E-03							1.25E-01 kg
Environmental Inputs						from M-C1a		from M-C1b		from M-C1c		from M-X		from M-X				
Primary Resources	1	Bauxite	kg			1.08E-04	3.25E-02											3.25E-02 kg
	2	Clay	kg			4.04E-01	1.21E+02											1.21E+02 kg
	3	Gravel (in ground)	kg					1.60E+00	1.85E+03	2.97E+00	2.18E+03							4.03E+03 kg
	4	Gypsum (resource)	kg			8.00E-02	2.40E+01											2.40E+01 kg
	5	Iron Ore (resource)	kg															kg
	6	Limestone	kg			4.78E+01	1.44E+04											1.44E+04 kg
	7	Sand	kg			8.36E-03	2.51E+00											2.51E+00 kg
	8	Water	kg	1.86E+02	1.86E+02	5.31E+02	1.59E+05	2.12E+00	2.46E+03	3.94E+00	2.89E+03							1.65E+05 kg
	9	Wood	kg															kg
Energy	10	Coal Energy	MJ			1.26E+00	3.78E+02	2.58E-03	2.98E+00	4.78E-03	3.51E+00					6.15E-01	2.68E+00	3.87E+02 MJ
	11	Diesel Fuel Energy	MJ	2.27E+01	2.27E+01	9.62E-01	2.88E+02	6.55E-02	7.57E+01	7.10E-02	5.21E+01	1.21E+00	4.88E+01	9.53E-01	2.09E+00			4.90E+02 MJ
	12	Natural Gas Energy	MJ	1.16E+00	1.16E+00	8.98E-02	2.69E+01	3.18E-03	3.68E+00	5.91E-03	4.33E+00					7.60E-01	3.31E+00	3.94E+01 MJ
	13	Oil Energy	MJ	1.64E+01	1.64E+01	1.12E-01	3.37E+01	2.42E-03	2.80E+00	4.50E-03	3.30E+00					5.79E-01	2.53E+00	5.88E+01 MJ
	14	Other Energy	MJ			2.05E-01	6.15E+01	6.82E-03	7.88E+00	1.27E-02	9.28E+00					1.63E+00	7.10E+00	8.57E+01 MJ

Total Energy Input	1.06E+03 MJ
Total Nat'l Resource Input	1.83E+05 kg

APPENDIX A-4. CEMENT PRODUCTION INVENTORY

Matrix C1a - CEMENT PRODUCTION

This matrix represents the inventory analysis for the production of Type I/II Portland Cement following the MWU outlined in the report.
It includes flows from clinker (M-C1a1) and gypsum production facilities to shipment to cement storage facilities in and around Boston.

Distance data:

	miles	km	
Inbound Mileage:		5500.00	Approximate distance traveled for gypsum delivery (from Spain) [via Cargo Ship]
	5	8.05	Approximate distance from ocean port (Albany) to cement production facility (Ravena, NY) [via Truck]
	3	4.83	Distance from cement storage facility (Boston) to batching facility (Boston) [via Truck]
Outbound Mileage:	5	8.05	Distance from cement production facility (Ravena, NY) to barge port (Albany) [via Truck]
	500	804.63	Approximate distance of travel from barge port (Albany) to storage facility (Boston) [via Barge]

		Processes:		Portland Cement Production		Gypsum Production		Clinker Production		Transport by Barge		Transport by 28T Truck		Transport by Cargo Ship		Electricity Production		
			source:	EcoInvent-report #7 part II pg 46		EcoInvent-report #7 part VIII pgs11-12		from M-C1a1		from M-X		from M-X		from M-X		EPA Power Profile (12414 zip code)		
Economic Output			units:	kg		kg		kg		tkm		tkm		tkm		kWh		
		Portland Cement	kg	1	1	0.65	5.20E-02	1	9.03E-01	1	8.05E-01	1	2.66E-02	1	2.86E-01	1	2.93E-02	
Economic Inputs																		**Totals**
	2	Clinker	kg	9.03E-01	9.03E-01													9.03E-01 kg
	3	Gypsum	kg	5.20E-02	5.20E-02													5.20E-02 kg
	4	Outbound Cement Transpo	tkm	8.05E-01	8.05E-01													8.05E-01 tkm
	5	In- Gypsum/Out- Cement Transpo	tkm	2.57E-02	2.57E-02	1.05E-02	8.37E-04											2.66E-02 tkm
	6	Inbound Gypsum Transpo	tkm			3.58E+00	2.86E-01											2.86E-01 tkm
	7	Electricity	kWh	2.92E-02	2.92E-02	9.16E-04	7.33E-05											2.93E-02 kWh
Environmental Outputs								from M-C1a1		from M-X		from M-X		from M-X				
Emissions	1	CO2	kg					8.96E-01	8.09E-01	1.80E-04	1.45E-04	6.62E-02	1.76E-03	4.65E-05	1.33E-05	3.82E-01	1.12E-02	8.22E-01 kg
	2	CO	kg					4.77E-04	4.31E-04	3.25E-06	2.62E-06	9.79E-05	2.60E-06	8.39E-07	2.40E-07			4.37E-04 kg
	3	NOx	kg					1.18E-03	1.07E-03	4.02E-06	3.23E-06	6.46E-04	1.72E-05	1.05E-06	3.00E-07	6.35E-04	1.86E-05	1.11E-03 kg
	4	SO2	kg					5.73E-04	5.17E-04	1.48E-07	1.19E-07	1.29E-05	3.42E-07	3.80E-08	1.09E-08	2.27E-03	6.64E-05	5.84E-04 kg
	5	Methane	kg					8.97E-06	8.10E-06	2.08E-08	1.67E-08	1.61E-06	4.27E-08	5.15E-09	1.47E-09			8.16E-06 kg
	6	Hydrocarbons	kg					5.46E-05	4.93E-05	2.80E-09	2.25E-09	5.80E-09	1.54E-10	7.24E-10	2.07E-10			4.93E-05 kg
	7	Dust	kg			1.60E-03	1.28E-04	8.48E-01	7.66E-01									7.66E-01 kg
	8	Particulates	kg					3.87E-06	3.49E-06	5.03E-07	4.05E-07	6.83E-05	1.82E-06	1.31E-07	3.74E-08			5.75E-06 kg
	9	Mercury	kg					3.35E-08	3.03E-08	8.77E-11	7.06E-11	1.83E-10	4.86E-12	2.27E-11	6.49E-12	5.26E-09	1.54E-10	3.05E-08 kg
	10	Lead	kg					8.51E-08	7.69E-08	3.38E-10	2.72E-10	2.23E-09	5.92E-11	8.62E-11	2.47E-11			7.72E-08 kg
	11	Cadmium	kg					7.03E-09	6.35E-09	3.53E-12	2.84E-12	4.67E-10	1.24E-11	9.11E-13	2.61E-13			6.36E-09 kg
	12	Copper	kg					1.62E-08	1.46E-08	8.86E-11	7.13E-11	3.14E-08	8.36E-10	2.31E-11	6.61E-12			1.55E-08 kg
	13	Chromium	kg					2.23E-09	2.02E-09	1.01E-10	8.13E-11	3.71E-09	9.87E-11	2.61E-11	7.46E-12			2.20E-09 kg
	14	Nickel	kg					5.23E-09	4.72E-09	5.68E-11	4.57E-11	3.64E-09	9.68E-11	1.47E-11	4.20E-12			4.87E-09 kg
	15	Zinc	kg					6.28E-08	5.67E-08	9.94E-10	8.00E-10	5.96E-08	1.58E-09	2.56E-10	7.32E-11			5.92E-08 kg
	16	Dioxins	kg					1.05E-12	9.49E-13	6.11E-13	4.92E-13	1.27E-12	3.38E-14	1.58E-13	4.52E-14			1.52E-12 kg
Waste	17	Waste heat	MJ	1.05E-01	1.05E-01	3.30E-03	2.64E-04	3.82E+00	3.45E+00	4.08E-01	3.28E-01	9.64E-01	2.56E-02	1.02E-01	2.92E-02			3.94E+00 MJ
	18	Waste (landfill)	kg					8.00E-05	7.22E-05									7.22E-05 kg
	19	Waste (recycle)	kg															kg
	20	Waste (incinerator)	kg					4.50E-05	4.06E-05									4.06E-05 kg
Environmental Inputs								from M-C1a1		from M-X		from M-X		from M-X				
Primary Resources	1	Bauxite	kg					1.20E-04	1.08E-04									1.08E-04 kg
	2	Clay	kg					4.48E-01	4.04E-01									4.04E-01 kg
	3	Gravel (in ground)	kg															kg
	4	Gypsum (resource)	kg			1.00E+00	8.00E-02											8.00E-02 kg
	5	Iron Ore (resource)	kg															kg
	6	Limestone	kg					5.30E+01	4.78E+01									4.78E+01 kg
	7	Sand	kg					9.26E-03	8.36E-03									8.36E-03 kg
	8	Water	kg					5.88E+02	5.31E+02									5.31E+02 kg
	9	Wood	kg															kg
Energy	10	Coal Energy	MJ					1.36E+00	1.23E+00							9.41E-01	2.76E-02	1.26E+00 MJ
	11	Diesel Fuel Energy	MJ			1.80E-02	1.44E-03	1.04E+00	9.35E-01			9.53E-01	2.53E-02					9.62E-01 MJ
	12	Natural Gas Energy	MJ					7.60E-02	6.86E-02							7.24E-01	2.12E-02	8.98E-02 MJ
	13	Oil Energy	MJ					1.19E-01	1.07E-01							1.81E-01	5.30E-03	1.12E-01 MJ
	14	Other Energy	MJ					1.69E-01	1.53E-01							1.77E+00	5.19E-02	2.05E-01 MJ

Total Energy Input	2.63E+00 MJ
Total Nat'l Resource Input	5.80E+02 kg

Matrix C1a1 - CLINKER PRODUCTION

This matrix represents the inventory analysis for the production of clinker (co-located with cement production).
It includes flows from delivery of limestone to production of clinker.
It is based solely on EcoInvent reports.

Distance data:

	miles	km	
Inbound Mileage:	0.5	0.80	Distance from limestone quarry to primary crusher (Co-located) [via HD Dump]

		Processes:		Clinker Production		Limestone Milling		Primary Crushing (for mill)		Marl Production		Crushing and Washing (for kiln)		Limestone Mining		Transport by HD Dump Truck		Electricity Production		
			source:	EcoInvent-report #7 part II pgs19-25		EcoInvent-report #7 part VII pg 32		EcoInvent-report #7 part VII pg31		EcoInvent-report #7 part II pg37		EcoInvent-report #7 part VII pg30		EcoInvent-report #7 part VII pg20		from M-X		EPA Power Profile (12414 zip code)		
		Economic Output	units:	kg		kg		kg		kg		kg		kg		tkm		kWh		
		Clinker	kg	1	1	1	8.41E-01	0.042	8.41E-01	1	4.66E-01	0.67	3.50E-01	0.38 0.51	2.00E+01 5.19E-01	1	8.52E-02	1	9.55E-02	
		Economic Inputs																		**Totals**
	2	Milled Limestone	kg	8.41E-01	8.41E-01															8.41E-01 kg
	3	Marl	kg	4.66E-01	4.66E-01															4.66E-01 kg
	4	Limestone, crushed	kg			1.00E+00	8.41E-01													8.41E-01 kg
	5	Limestone,crushed & washed	kg							7.50E-01	3.50E-01									3.50E-01 kg
	6	Limestone at mine, to mill	kg					1.00E+00	2.00E+01											2.00E+01 kg
	7	Limestone at mine, to kiln	kg									1.00E+00	5.19E-01							5.19E-01 kg
	8	In- Raw Material Transpo	tkm											1.61E-03	8.52E-02					8.52E-02 tkm
	9	Electricity	kWh	5.80E-02	5.80E-02	3.20E-02	2.69E-02	5.10E-04	1.02E-02			7.20E-04	3.74E-04							9.55E-02 kWh
		Environmental Outputs														from M-X				
Emissions	1	CO2	kg	8.55E-01	8.55E-01											5.60E-02	4.77E-03	3.82E-01	3.65E-02	8.96E-01 kg
	2	CO	kg	4.72E-04	4.72E-04											6.35E-05	5.41E-06			4.77E-04 kg
	3	NOx	kg	1.08E-03	1.08E-03											5.10E-04	4.35E-05	6.35E-04	6.07E-05	1.18E-03 kg
	4	SO2	kg	3.55E-04	3.55E-04											1.08E-05	9.21E-07	2.27E-03	2.17E-04	5.73E-04 kg
	5	Methane	kg	8.88E-06	8.88E-06											1.04E-06	8.87E-08			8.97E-06 kg
	6	HydroCarbons	kg	5.46E-05	5.46E-05											4.88E-09	4.16E-10			5.46E-05 kg
	7	Dust	kg	3.77E-05	3.77E-05			1.74E-05	3.49E-04			1.74E-05	9.05E-06	1.60E-02	8.48E-01					8.48E-01 kg
	8	Particulates	kg													4.54E-05	3.87E-06			3.87E-06 kg
	9	Mercury	kg	3.30E-08	3.30E-08											1.54E-10	1.31E-11	5.26E-09	5.03E-10	3.35E-08 kg
	10	Lead	kg	8.50E-08	8.50E-08											1.66E-09	1.42E-10			8.51E-08 kg
	11	Cadmium	kg	7.00E-09	7.00E-09											3.51E-10	2.99E-11			7.03E-09 kg
	12	Copper	kg	1.40E-08	1.40E-08											2.58E-08	2.20E-09			1.62E-08 kg
	13	Chromium	kg	2.00E-09	2.00E-09											2.75E-09	2.34E-10			2.23E-09 kg
	14	Nickel	kg	5.00E-09	5.00E-09											2.72E-09	2.32E-10			5.23E-09 kg
	15	Zinc	kg	6.00E-08	6.00E-08											3.27E-08	2.79E-09			6.28E-08 kg
	16	Dioxins	kg	9.60E-13	9.60E-13											1.07E-12	9.08E-14			1.05E-12 kg
Waste	17	Waste heat	MJ	3.62E+00	3.62E+00	1.15E-01	9.67E-02	1.84E-03	3.68E-02			2.59E-03	1.35E-03			8.10E-01	6.91E-02			3.82E+00 MJ
	18	Waste (landfill)	kg	8.00E-05	8.00E-05															8.00E-05 kg
	19	Waste (recycle)	kg																	kg
	20	Waste (incinerator)	kg	4.50E-05	4.50E-05															4.50E-05 kg
		Environmental Inputs														from M-X				
Primary Resources	1	Bauxite	kg	1.20E-04	1.20E-04															1.20E-04 kg
	2	Clay	kg	3.31E-01	3.31E-01					2.50E-01	1.17E-01									4.48E-01 kg
	3	Gravel (in ground)	kg																	kg
	4	Gypsum (resource)	kg																	kg
	5	Iron Ore (resource)	kg																	kg
	6	Limestone	kg											1.00E+00	5.30E+01					5.30E+01 kg
	7	Sand	kg	9.26E-03	9.26E-03															9.26E-03 kg
	8	Water	kg	1.62E+00	1.62E+00			2.93E+01	5.87E+02			2.18E-02	1.13E-02							5.88E+02 kg
	9	Wood	kg																	kg
Energy	10	Coal Energy	MJ	1.27E+00	1.27E+00													9.41E-01	8.99E-02	1.36E+00 MJ
	11	Diesel Fuel Energy	MJ	1.34E-02	1.34E-02									1.80E-02	9.54E-01	8.00E-01	6.82E-02			1.04E+00 MJ
	12	Natural Gas Energy	MJ	6.81E-03	6.81E-03													7.24E-01	6.91E-02	7.60E-02 MJ
	13	Oil Energy	MJ	2.59E-02	2.59E-02	8.98E-02	7.55E-02											1.81E-01	1.73E-02	1.19E-01 MJ
	14	Other Energy	MJ															1.77E+00	1.69E-01	1.69E-01 MJ

Total Energy Input	2.76E+00 MJ
Total Nat'l Resource Input	6.42E+02 kg

APPENDIX A-6. COURSE AGGREGATE PRODUCTION INVENTORY

Matrix C1b - COARSE AGGREGATE PRODUCTION

This matrix represents the inventory analysis for the production of coarse aggregate following the MWU outlined in the report.
It includes flows from transport to primary crusher to shipment to concrete batching facilities in and around Boston
In this case the quarry and primary crusher are colocated and the aggregate is crushed on site

Distance Data:

	miles	km	
Inbound Mileage:	1	1.61	Approximate distance from gravel quarry to primary crusher (within same facility) [via HD Dump]
Outbound Mileage:	20	32.19	Distance from gravel quarry to concrete batching facility [via Truck]

		Processes		Aggregate Production		Transport by 28T Truck		Transport by HD Dump Truck		Electricity Production		
			source:	EcoInvnet Report #7 part I pg15-16		from M-X		from M-X		EPA Power Profile (01907 zip code)		
Economic Output			unit:	kg		tkm		tkm		kWh		
		Aggregate (Gravel, round)	kg	0.650	1	1	6.44E-02	1	5.15E-03	1	4.18E-03	
Economic Inputs												**Totals**
	2	Outbound Transpo	tkm	4.18E-02	6.44E-02							6.44E-02 tkm
	3	Inbound Transpo	tkm	3.35E-03	5.15E-03							5.15E-03 tkm
	4	Electricity	kWh	2.72E-03	4.18E-03							4.18E-03 kWh
Environmental Outputs						from M-X		from M-X				
Emissions	1	CO2	kg			6.62E-02	4.26E-03	5.60E-02	2.88E-04	4.07E-01	1.70E-03	6.25E-03 kg
	2	CO	kg			9.79E-05	6.30E-06	6.35E-05	3.27E-07			6.63E-06 kg
	3	NOx	kg			6.46E-04	4.16E-05	5.10E-04	2.63E-06	6.81E-04	2.85E-06	4.71E-05 kg
	4	SO2	kg			1.29E-05	8.28E-07	1.08E-05	5.56E-08	1.72E-03	7.21E-06	8.10E-06 kg
	5	Methane	kg			1.61E-06	1.03E-07	1.04E-06	5.36E-09			1.09E-07 kg
	6	HydroCarbons	kg			5.80E-09	3.73E-10	4.88E-09	2.51E-11			3.98E-10 kg
	7	Dust	kg									kg
	8	Particulates	kg			6.83E-05	4.40E-06	4.54E-05	2.34E-07			4.63E-06 kg
	9	Mercury	kg			1.83E-10	1.18E-11	1.54E-10	7.93E-13	7.35E-09	3.08E-11	4.33E-11 kg
	10	Lead	kg			2.23E-09	1.43E-10	1.66E-09	8.55E-12			1.52E-10 kg
	11	Cadmium	kg			4.67E-10	3.01E-11	3.51E-10	1.81E-12			3.19E-11 kg
	12	Copper	kg			3.14E-08	2.02E-09	2.58E-08	1.33E-10			2.16E-09 kg
	13	Chromium	kg			3.71E-09	2.39E-10	2.75E-09	1.41E-11			2.53E-10 kg
	14	Nickel	kg			3.64E-09	2.34E-10	2.72E-09	1.40E-11			2.49E-10 kg
	15	Zinc	kg			5.96E-08	3.83E-09	3.27E-08	1.68E-10			4.00E-09 kg
	16	Dioxins	kg			1.27E-12	8.18E-14	1.07E-12	5.48E-15			8.73E-14 kg
Waste	17	Waste heat	MJ	9.77E-03	1.50E-02	9.64E-01	6.21E-02	8.10E-01	4.17E-03			8.13E-02 MJ
	18	Waste (landfill)	kg									kg
	19	Waste (recycle)	kg									kg
	20	Waste (incinerator)	kg	4.62E-06	7.11E-06							7.11E-06 kg
Environmental Inputs						from M-X		from M-X				
Primary Resources	1	Bauxite	kg									kg
	2	Clay	kg									kg
	3	Gravel (in ground)	kg	1.04E+00	1.60E+00							1.60E+00 kg
	4	Gypsum (resource)	kg									kg
	5	Iron Ore (resource)	kg									kg
	6	Limestone	kg									kg
	7	Sand	kg									kg
	8	Water	kg	1.38E+00	2.12E+00							2.12E+00 kg
	9	Wood	kg									kg
Energy	10	Coal Energy	MJ							6.15E-01	2.58E-03	2.58E-03 MJ
	11	Diesel Fuel Energy	MJ			9.53E-01	6.13E-02	8.00E-01	4.12E-03			6.55E-02 MJ
	12	Natural Gas Energy	MJ							7.60E-01	3.18E-03	3.18E-03 MJ
	13	Oil Energy	MJ							5.79E-01	2.42E-03	2.42E-03 MJ
	14	Other Energy	MJ							1.63E+00	6.82E-03	6.82E-03 MJ

Total Energy Input	8.05E-02 MJ
Total Nat'l Resource Input	3.72E+00 kg

APPENDIX A-7. FINE AGGREGATE PRODUCTION INVENTORY

Matrix C1c - FINE AGGREGATE PRODUCTION

This matrix represents the inventory analysis for the production of concrete aggregate following the MWU outlined in the report.
It includes flows from transport to primary crusher to shipment to concrete batching facilities in and around Boston
In this case the quarry and primary crusher are colocated and the aggregate is crushed on site

Ditance data:

	miles	km	
Inbound Mileage:	1	1.61	Approximate distance from quarry to primary crusher (within same facility) [via HD Dump]
Outbound Mileage:	40	64.37	Distance from quarry to concrete batching facility [via Rail]

		Processes		**Aggregate Production**		**Transport by Rail**		**Transport by HD Dump Truck**		**Electricity Production**		
			source:	EcoInvnet Report #7 part I pg15-16		from M-X		from M-X		EPA Power Profile (01907 zip code)		
Economic Output			unit:	kg		tkm		tkm		kWh		
		Fine Aggregate (Sand)	kg	0.350	1	1	1.29E-01	1	9.56E-03	1	7.77E-03	
Economic Inputs												**Totals**
	2	Outbound Transpo	tkm	4.51E-02	1.29E-01							1.29E-01 tkm
	3	Inbound Transpo	tkm	3.35E-03	9.56E-03							9.56E-03 tkm
	4	Electricity	kWh	2.72E-03	7.77E-03							7.77E-03 kWh
Environmental Outputs						from M-X		from M-X				
Emissions	1	CO2	kg			3.38E-02	4.35E-03	5.60E-02	5.36E-04	4.07E-01	3.16E-03	8.05E-03 kg
	2	CO	kg			1.73E-04	2.23E-05	6.35E-05	6.07E-07			2.29E-05 kg
	3	NOx	kg			5.92E-04	7.62E-05	5.10E-04	4.88E-06	6.81E-04	5.29E-06	8.64E-05 kg
	4	SO2	kg			6.58E-06	8.47E-07	1.08E-05	1.03E-07	1.72E-03	1.34E-05	1.43E-05 kg
	5	Methane	kg			1.41E-06	1.82E-07	1.04E-06	9.95E-09			1.91E-07 kg
	6	HydroCarbons	kg			3.17E-09	4.08E-10	4.88E-09	4.66E-11			4.55E-10 kg
	7	Dust	kg									kg
	8	Particulates	kg			8.76E-05	1.13E-05	4.54E-05	4.34E-07			1.17E-05 kg
	9	Mercury	kg			9.97E-11	1.28E-11	1.54E-10	1.47E-12	7.35E-09	5.71E-11	7.14E-11 kg
	10	Lead	kg			3.84E-10	4.94E-11	1.66E-09	1.59E-11			6.53E-11 kg
	11	Cadmium	kg			1.11E-10	1.43E-11	3.51E-10	3.36E-12			1.76E-11 kg
	12	Copper	kg			1.83E-08	2.36E-09	2.58E-08	2.46E-10			2.60E-09 kg
	13	Chromium	kg			6.48E-10	8.34E-11	2.75E-09	2.63E-11			1.10E-10 kg
	14	Nickel	kg			8.11E-10	1.04E-10	2.72E-09	2.60E-11			1.30E-10 kg
	15	Zinc	kg			1.18E-08	1.52E-09	3.27E-08	3.13E-10			1.83E-09 kg
	16	Dioxins	kg			6.93E-13	8.92E-14	1.07E-12	1.02E-14			9.94E-14 kg
Waste	17	Waste heat	MJ	9.77E-03	2.79E-02	4.92E-01	6.33E-02	8.10E-01	7.75E-03			9.90E-02 MJ
	18	Waste (landfill)	kg									kg
	19	Waste (recycle)	kg									kg
	20	Waste (incinerator)	kg	4.62E-06	1.32E-05							1.32E-05 kg
Environmental Inputs						from M-X		from M-X				
Primary Resources	1	Bauxite	kg									kg
	2	Clay	kg									kg
	3	Gravel (in ground)	kg	1.04E+00	2.97E+00							2.97E+00 kg
	4	Gypsum (resource)	kg									kg
	5	Iron Ore (resource)	kg									kg
	6	Limestone	kg									kg
	7	Sand	kg									kg
	8	Water	kg	1.38E+00	3.94E+00							3.94E+00 kg
	9	Wood	kg									kg
Energy	10	Coal Energy	MJ							6.15E-01	4.78E-03	4.78E-03 MJ
	11	Diesel Fuel Energy	MJ			4.92E-01	6.34E-02	8.00E-01	7.65E-03			7.10E-02 MJ
	12	Natural Gas Energy	MJ							7.60E-01	5.91E-03	5.91E-03 MJ
	13	Oil Energy	MJ							5.79E-01	4.50E-03	4.50E-03 MJ
	14	Other Energy	MJ							1.63E+00	1.27E-02	1.27E-02 MJ

Total Energy Input	9.89E-02 MJ
Total Nat'l Resource Input	6.91E+00 kg

APPENDIX A-8. FORMWORK PRODUCTION INVENTORY

Matrix C2 - FORMWORK PRODUCTION

This matrix represents the inventory analysis for the production of concrete formwork.
It includes the flows from plywood (M-C2a) and steel (M-C2b) production to delivery to formwork distributors.
The location of the formwork manufacture is Illinois

Assumptions:

Weight of form =	40.82	kg
Percent of wood in form (by weight) =	90%	

Distance Data:

	miles	km	
Outbound Mileage:	1500	2413.90	Distance from form fabricator to formwork storage [via Truck]
	40	64.37	Approximate distance to waste disposal site

		Processes		**Fabricate Formwork**		**Plywood Production**		**Steel Production**		**Transport by 28T Truck**		**Electricity Production**		
			source:	Industry Research		from M-C2a		from M-C2b		from M-X		EPA Power Profiler Illinois		
Economic Output			unit:	form		kg		kg		tkm		kWh		
		New Forms	form	1	1	1	3.67E+01	1	4.08E+00	1	1.97E+02	1	1.00E+00	
Economic Inputs														**Totals**
	2	Plywood	kg	3.67E+01	3.67E+01									3.67E+01 kg
	3	Steel	kg	4.08E+00	4.08E+00									4.08E+00 kg
	4	Out- Form Transpo	tkm	1.97E+02	1.97E+02									1.97E+02 tkm
	5	Waste Transpo	tkm	9.25E-02	9.25E-02									9.25E-02 tkm
	6	Electricity	kWh	1.00E+00	1.00E+00									1.00E+00 kWh
Environmental Outputs						from M-C2a		from M-C2b		from M-X				
Emissions	1	CO2	kg			5.62E-01	2.06E+01	1.63E+00	6.67E+00	6.62E-02	1.31E+01	5.61E-01	5.61E-01	4.09E+01 kg
	2	CO	kg			4.04E-04	1.49E-02	2.84E-03	1.16E-02	9.79E-05	1.93E-02			4.58E-02 kg
	3	NOx	kg			3.10E-03	1.14E-01	5.38E-03	2.20E-02	6.46E-04	1.27E-01	1.23E-03	1.23E-03	2.65E-01 kg
	4	SO2	kg			7.46E-04	2.74E-02	4.16E-03	1.70E-02	1.29E-05	2.54E-03	2.36E-03	2.36E-03	4.93E-02 kg
	5	Methane	kg			6.59E-06	2.42E-04	4.12E-06	1.68E-05	1.61E-06	3.17E-04			5.76E-04 kg
	6	HydroCarbons	kg			2.38E-08	8.74E-07	3.69E-04	1.51E-03	5.80E-09	1.14E-06			1.51E-03 kg
	7	Dust	kg					4.67E-04	1.91E-03					1.91E-03 kg
	8	Particulates	kg			2.80E-04	1.03E-02	2.16E-04	8.82E-04	6.83E-05	1.35E-02			2.46E-02 kg
	9	Mercury	kg			1.99E-09	7.31E-08	2.35E-06	9.60E-06	1.83E-10	3.61E-08			9.71E-06 kg
	10	Lead	kg			9.14E-09	3.36E-07	1.92E-06	7.85E-06	2.23E-09	4.39E-07			8.62E-06 kg
	11	Cadmium	kg			1.92E-09	7.04E-08	3.93E-08	1.60E-07	4.67E-10	9.21E-08			3.23E-07 kg
	12	Copper	kg			1.29E-07	4.74E-06	3.87E-07	1.58E-06	3.14E-08	6.20E-06			1.25E-05 kg
	13	Chromium	kg			1.52E-08	5.60E-07	1.69E-06	6.92E-06	3.71E-09	7.32E-07			8.21E-06 kg
	14	Nickel	kg			1.49E-08	5.49E-07	9.87E-07	4.03E-06	3.64E-09	7.18E-07			5.30E-06 kg
	15	Zinc	kg			2.44E-07	8.98E-06	2.42E-05	9.87E-05	5.96E-08	1.17E-05			1.19E-04 kg
	16	Dioxins	kg			5.22E-12	1.92E-10	7.69E-12	3.14E-11	1.27E-12	2.51E-10			4.74E-10 kg
Waste	17	Waste heat	MJ			6.85E+00	2.52E+02	1.00E+01	4.09E+01	9.64E-01	1.90E+02			4.83E+02 MJ
	18	Waste (landfill)	kg					1.26E-01	5.14E-01					5.14E-01 kg
	19	Waste (recycle)	kg					5.00E-02	2.04E-01					2.04E-01 kg
	20	Waste (incinerator)	kg			6.16E-09	2.26E-07	2.13E-04	8.70E-04					8.70E-04 kg
Environmental Inputs						from M-C2a		from M-C2b		from M-X				
Primary Resources	1	Bauxite	kg											kg
	2	Clay	kg											kg
	3	Gravel (in ground)	kg											kg
	4	Gypsum (resource)	kg											kg
	5	Iron Ore (resource)	kg											kg
	6	Limestone	kg											kg
	7	Sand	kg											kg
	8	Water	kg			1.07E+01	3.95E+02	5.50E+00	2.25E+01					4.17E+02 kg
	9	Wood	kg			6.12E+00	2.25E+02							2.25E+02 kg
Energy	10	Coal Energy	MJ			6.70E-01	2.46E+01	5.42E+00	2.21E+01			1.88E+00	1.88E+00	4.86E+01 MJ
	11	Diesel Fuel Energy	MJ			4.45E+00	1.63E+02	2.17E+00	8.85E+00	9.53E-01	1.88E+02			3.60E+02 MJ
	12	Natural Gas Energy	MJ			7.30E-01	2.68E+01	2.65E+00	1.08E+01			7.24E-02	7.24E-02	3.77E+01 MJ
	13	Oil Energy	MJ											MJ
	14	Other Energy	MJ			1.78E+00	6.53E+01	1.42E+00	5.78E+00			1.59E+00	1.59E+00	7.26E+01 MJ

Total Energy Input	5.19E+02 MJ
Total Nat'l Resource Input	6.42E+02 kg

Matrix C2a - PLYWOOD PRODUCTION

This matrix represents the inventory analysis for the production of plywood used in concrete formwork IAW the MWU outlined in the report.
It includes all process flows from wood harvesting to delivery to formwork manufacturer.
Location of plywood production is the Pacific Northwest

Distance Data:

	miles	km	
Inbound Mileage:	50	80.46	Distance from forest to plywood production facility [via Truck]
	100	160.93	Approximate distance from resin production facility to plywood production facility [via Truck]
Outbound Mileage:	1100	1770.20	Approximate distance from plywood production facility to form fabrication location [via Truck]

		Processes		Plywood Production		Wood harvesting		Phenolic Resin Production		Formaldehyde Production		Phenol Production		Transport by 28T Truck		Electricity Production		Electricity Production (Resin)		
			source:	EcoInvent Report #9 Pg80-81		EcoInvent Report #9 Pg 26		EcoInvent Report #8 Pg 510		EcoInvent Report #8 pg 342		EcoInvent Report #8 pg502		from M-X		EPA Power Profiler Oregon		EPA Power Profiler Oregon		
		Economic Output	unit:	kg		kg		kg		kg		kg		tkm		kWh		kWh		
		Plywood	kg	450	1	265	3.12E+00	1	1.85E-01	1	2.81E-02	1	1.76E-01	1	4.10E+00	1	6.80E-01	1	1.24E-01	
		Economic Inputs																		**Totals**
	2	Wood (at forest road)	kg	1.40E+03	3.12E+00															3.12E+00 kg
	3	Resin	kg	8.32E+01	1.85E-01															1.85E-01 kg
	4	Formaldehyde	kg					1.52E-01	2.81E-02											2.81E-02 kg
	5	Phenol	kg					9.50E-01	1.76E-01											1.76E-01 kg
	6	In-/Out- Transpo	tkm	1.59E+03	3.54E+00	4.27E+01	5.02E-01	3.22E-01	5.95E-02											4.10E+00 tkm
	7	Electricity	kWh	3.06E+02	6.80E-01															6.80E-01 kWh
	8	Electricity (Resin)	kWh					3.33E-01	6.16E-02	1.50E-01	4.22E-03	3.33E-01	5.85E-02							1.24E-01 kWh
		Environmental Outputs												from M-X						
Emissions	1	CO2	kg					4.68E-02	8.65E-03	1.10E-01	3.09E-03	1.91E-01	3.35E-02	6.62E-02	2.72E-01	3.04E-01	2.07E-01	3.04E-01	3.78E-02	5.62E-01 kg
	2	CO	kg							1.00E-04	2.81E-06			9.79E-05	4.01E-04					4.04E-04 kg
	3	NOx	kg							3.80E-04	1.07E-05			6.46E-04	2.65E-03	5.44E-04	3.70E-04	5.44E-04	6.77E-05	3.10E-03 kg
	4	SO2	kg											1.29E-05	5.27E-05	8.62E-04	5.86E-04	8.62E-04	1.07E-04	7.46E-04 kg
	5	Methane	kg											1.61E-06	6.59E-06					6.59E-06 kg
	6	HydroCarbons	kg											5.80E-09	2.38E-08					2.38E-08 kg
	7	Dust	kg																	kg
	8	Particulates	kg							5.00E-06	1.41E-07			6.83E-05	2.80E-04					2.80E-04 kg
	9	Mercury	kg											1.83E-10	7.50E-10	1.54E-09	1.05E-09	1.54E-09	1.92E-10	1.99E-09 kg
	10	Lead	kg											2.23E-09	9.14E-09					9.14E-09 kg
	11	Cadmium	kg											4.67E-10	1.92E-09					1.92E-09 kg
	12	Copper	kg											3.14E-08	1.29E-07					1.29E-07 kg
	13	Chromium	kg											3.71E-09	1.52E-08					1.52E-08 kg
	14	Nickel	kg											3.64E-09	1.49E-08					1.49E-08 kg
	15	Zinc	kg											5.96E-08	2.44E-07					2.44E-07 kg
	16	Dioxins	kg											1.27E-12	5.22E-12					5.22E-12 kg
Waste	17	Waste heat	MJ	1.10E+03	2.44E+00			1.20E+00	2.22E-01	5.40E-01	1.52E-02	1.20E+00	2.11E-01	9.64E-01	3.96E+00					6.85E+00 MJ
	18	Waste (landfill)	kg																	kg
	19	Waste (recycle)	kg																	kg
	20	Waste (incinerator)	kg	2.77E-06	6.16E-09															6.16E-09 kg
		Environmental Inputs												from M-X						
Primary Resources	1	Bauxite	kg																	kg
	2	Clay	kg																	kg
	3	Gravel (in ground)	kg																	kg
	4	Gypsum (resource)	kg																	kg
	5	Iron Ore (resource)	kg																	kg
	6	Limestone	kg																	kg
	7	Sand	kg																	kg
	8	Water	kg	1.84E+03	4.09E+00			3.60E+01	6.66E+00											1.07E+01 kg
	9	Wood	kg			5.20E+02	6.12E+00													6.12E+00 kg
Energy	10	Coal Energy	MJ													8.33E-01	5.66E-01	8.33E-01	1.03E-01	6.70E-01 MJ
	11	Diesel Fuel Energy	MJ	3.20E+00	7.11E-03	4.54E+01	5.34E-01							9.53E-01	3.91E+00					4.45E+00 MJ
	12	Natural Gas Energy	MJ									2.00E+00	3.51E-01			4.71E-01	3.20E-01	4.71E-01	5.85E-02	7.30E-01 MJ
	13	Oil Energy	MJ																	MJ
	14	Other Energy	MJ													2.21E+00	1.50E+00	2.21E+00	2.74E-01	1.78E+00 MJ

Total Energy Input	7.63E+00 MJ
Total Nat'l Resource Input	1.69E+01 kg

APPENDIX A-10. STEEL PRODUCTION INVENTORY (for Formwork Bracing)

Matrix C2b - STEEL SECTION PRODUCTION (for Formwork)

This matrix is the inventory analysis for steel section production for use in formwork.
It is based on EAF process using 100% recycled steel and covers transportation of scrap iron to shipment of steel sections to formwork fabricator.
It includes the flows from Steel Rolling (M-C2b1).
The location of steel production is a regional steel producer. For the purpose of this study a steel bar mill in Nebraska was used.

Distance Data:

	miles	km	
Inbound Mileage:	500	804.63	Average radius of scrap iron collection to steel mill [via Truck]
Outbound mileage:	500	804.63	Approximate distance from steel mill to formwork fabricator [via Truck]

		Processes		Steel Forming (Channel)		EAF, 100% Recycled Steel Production		28T Truck Transportation		Rail Transportation		Electricity Production		Totals
			source:	Inudstry Research		EcoInvent Report #10 Part II pgs57-59		from M-X		from M-X		EPA Power Profile (Nebraska)		
		Economic Output	unit:	kg		kg		tkm		tkm		kWh		
		Steel	kg	1	1	1	1.05E+00	1	1.86E+00	1	8.05E-01	1	1.64E+00	
		Economic Inputs												
	2	Steel (pre-formed)	kg	1.05E+00	1.05E+00									1.05E+00 kg
	3	Recycled Scrap Iron	kg			1.10E+00	1.16E+00							1.16E+00 kg
	4	In- Scrap Transpo	tkm			1.77E+00	1.86E+00							1.86E+00 tkm
	5	Out- Steel Transpo	tkm	8.05E-01	8.05E-01									8.05E-01 tkm
	6	Electricity	kWh			1.53E+00	1.61E+00			3.96E-02	3.19E-02			1.64E+00 kWh
		Environmental Outputs		from M-C2b1				from M-X		from M-X				
Emissions	1	CO2	kg	1.17E-01	1.17E-01			6.62E-02	1.23E-01	3.38E-02	2.72E-02	8.34E-01	1.37E+00	1.63E+00 kg
	2	CO	kg	8.76E-05	8.76E-05	2.32E-03	2.44E-03	9.79E-05	1.82E-04	1.73E-04	1.39E-04			2.84E-03 kg
	3	NOx	kg	5.41E-04	5.41E-04	1.80E-04	1.89E-04	6.46E-04	1.20E-03	5.92E-04	4.76E-04	1.81E-03	2.97E-03	5.38E-03 kg
	4	SO2	kg	3.31E-04	3.31E-04	7.70E-05	8.09E-05	1.29E-05	2.39E-05	6.58E-06	5.29E-06	2.27E-03	3.72E-03	4.16E-03 kg
	5	Methane	kg					1.61E-06	2.99E-06	1.41E-06	1.13E-06			4.12E-06 kg
	6	Hydrocarbons	kg	2.86E-04	2.86E-04	7.93E-05	8.33E-05	5.80E-09	1.08E-08	3.17E-09	2.55E-09			3.69E-04 kg
	7	Dust	kg	5.69E-05	5.69E-05	3.91E-04	4.10E-04							4.67E-04 kg
	8	Particulates	kg	1.86E-05	1.86E-05			6.83E-05	1.27E-04	8.76E-05	7.05E-05			2.16E-04 kg
	9	Mercury	kg			2.24E-06	2.35E-06	1.83E-10	3.40E-10	9.97E-11	8.02E-11			2.35E-06 kg
	10	Lead	kg	1.77E-08	1.77E-08	1.81E-06	1.90E-06	2.23E-09	4.14E-09	3.84E-10	3.09E-10			1.92E-06 kg
	11	Cadmium	kg			3.65E-08	3.83E-08	4.67E-10	8.68E-10	1.11E-10	8.93E-11			3.93E-08 kg
	12	Copper	kg	7.18E-08	7.18E-08	2.31E-07	2.43E-07	3.14E-08	5.84E-08	1.83E-08	1.47E-08			3.87E-07 kg
	13	Chromium	kg	3.74E-07	3.74E-07	1.25E-06	1.31E-06	3.71E-09	6.90E-09	6.48E-10	5.21E-10			1.69E-06 kg
	14	Nickel	kg	2.44E-07	2.44E-07	7.01E-07	7.36E-07	3.64E-09	6.77E-09	8.11E-10	6.53E-10			9.87E-07 kg
	15	Zinc	kg			2.29E-05	2.40E-05	5.96E-08	1.11E-07	1.18E-08	9.49E-09			2.42E-05 kg
	16	Dioxins	kg			4.54E-12	4.77E-12	1.27E-12	2.36E-12	6.93E-13	5.58E-13			7.69E-12 kg
Waste	17	Waste heat	MJ	5.04E-01	5.04E-01	6.98E+00	7.33E+00	9.64E-01	1.79E+00	4.92E-01	3.96E-01			1.00E+01 MJ
	18	Waste (landfill)	kg	1.83E-02	1.83E-02	1.02E-01	1.08E-01							1.26E-01 kg
	19	Waste (recycle)	kg	5.00E-02	5.00E-02									5.00E-02 kg
	20	Waste (incinerator)	kg	2.13E-04	2.13E-04									2.13E-04 kg
		Environmental Inputs		from M-C2b1				from M-X		from M-X				
Primary Resources	1	Bauxite	kg											kg
	2	Clay	kg											kg
	3	Gravel (in ground)	kg											kg
	4	Gypsum (resource)	kg											kg
	5	Iron Ore (resource)	kg											kg
	6	Limestone	kg											kg
	7	Sand	kg											kg
	8	Water	kg	5.50E+00	5.50E+00									5.50E+00 kg
	9	Wood	kg											kg
Energy	10	Coal Energy	MJ	3.85E-01	3.85E-01	5.04E-01	5.29E-01					2.75E+00	4.51E+00	5.42E+00 MJ
	11	Diesel Energy	MJ					9.53E-01	1.77E+00	4.92E-01	3.96E-01			2.17E+00 MJ
	12	Natural Gas Energy	MJ	1.57E+00	1.57E+00	9.75E-01	1.02E+00					3.62E-02	5.93E-02	2.65E+00 MJ
	13	Oil Energy	MJ											MJ
	14	Other Energy	MJ	1.11E-01	1.11E-01							7.96E-01	1.30E+00	1.42E+00 MJ

Total Energy Inputs	1.17E+01 MJ
Total Nat'l Resource Inputs	5.50E+00 kg

APPENDIX A-11. HOT ROLLING PROCESS INVENTORY (for Formwork Steel)

Matrix C2b1 - HOT ROLLING, STEEL

This matrix is the inventory analysis for the hot rolling of steel.
It is solely based on data received from the EcoInvent Reports.

		Processes		Overall		Waste water treatment		Hot Rolling		Descaling		Reheat Furnace		Grinding		Scarfing		Electricity Production		Total	
			source:	EcoInvnet Report #10 part X pgs9-14		EcoInvnet Report #10 part X pgs9-14		EcoInvnet Report #10 part X pgs9-14		EcoInvnet Report #10 part X pgs9-14		EcoInvnet Report #10 part X pgs9-14		EcoInvnet Report #10 part X pgs9-14		EcoInvnet Report #10 part X pgs9-14		EPA Power Profile Nebraska			
Economic Outputs			unit:	kg														kWh			
		Rolled Steel Member	kg	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.14		
Economic Inputs																					
	2	Electricity	kWh	0.14	0.14															0.14	kWh
Environmental Outputs																					
Emissions	1	CO2	kg															8.34E-01	1.17E-01	1.17E-01	kg
	2	CO	kg									6.52E-05	6.52E-05			2.24E-05	2.24E-05			8.76E-05	kg
	3	NOx	kg									2.74E-04	2.74E-04			1.31E-05	1.31E-05	1.81E-03	2.54E-04	5.41E-04	kg
	4	SO2	kg									1.34E-05	1.34E-05					2.27E-03	3.18E-04	3.31E-04	kg
	5	Methane	kg																		kg
	6	Hydrocarbons	kg					2.83E-04	2.83E-04			2.50E-06	2.50E-06							2.86E-04	kg
	7	Dust	kg					5.37E-05	5.37E-05			3.16E-06	3.16E-06							5.69E-05	kg
	8	Particulates	kg											9.64E-06	9.64E-06	8.94E-06	8.94E-06			1.86E-05	kg
	9	Mercury	kg																		kg
	10	Lead	kg													1.77E-08	1.77E-08			1.77E-08	kg
	11	Cadmium	kg																		kg
	12	Copper	kg													7.18E-08	7.18E-08			7.18E-08	kg
	13	Chromium	kg											3.54E-07	3.54E-07	2.00E-08	2.00E-08			3.74E-07	kg
	14	Nickel	kg											2.24E-07	2.24E-07	2.00E-08	2.00E-08			2.44E-07	kg
	15	Zinc	kg																		kg
	16	Dioxins	kg																		kg
Waste	17	Waste heat	MJ	5.04E-01	5.04E-01															5.04E-01	MJ
	18	Waste (landfill)	kg			1.63E-02	1.63E-02	8.72E-04	8.72E-04	4.83E-04	4.83E-04	2.23E-04	2.23E-04			4.42E-04	4.42E-04			1.83E-02	kg
	19	Waste (recycle)	kg	5.00E-02	5.00E-02															5.00E-02	kg
	20	Waste (incinerator)	kg							2.13E-04	2.13E-04									2.13E-04	kg
Environmental Inputs																					
Primary Resources	1	Bauxite	kg																		kg
	2	Clay	kg																		kg
	3	Gravel (in ground)	kg																		kg
	4	Gypsum (resource)	kg																		kg
	5	Iron Ore (resource)	kg																		kg
	6	Limestone	kg																		kg
	7	Sand	kg																		kg
	8	Water	kg			5.50E+00	5.50E+00													5.50E+00	kg
	9	Wood	kg																		kg
Energy	10	Coal Energy	MJ															2.75E+00	3.85E-01	3.85E-01	MJ
	11	Diesel Energy	MJ																		MJ
	12	Natural Gas Energy	MJ									1.56E+00	1.56E+00					3.62E-02	5.07E-03	1.57E+00	MJ
	13	Oil Energy	MJ																		MJ
	14	Other Energy	MJ																	7.96E-01	1.11E-01	1.11E-01	MJ

Total Energy Inputs	2.06E+00	MJ
Total Nat'l Resource Inputs	5.50E+00	kg

APPENDIX A-12. STEEL RE-BAR FABRICATION INVENTORY

Matrix C3a - STEEL RE-BAR FABRICATION

This matrix represents the inventory analysis for the process of cutting and fabricating steel reinforcing bar.
It includes the cutting, fitting, caging and finishing steps of the fabrication process.
Given data and assumptions are based on information gained from fabricators for the Boston/New England market

Distance data:

miles	km	
60	96.56	Approximate distance from Re-bar fabricator to construction site
40	64.37	Approx. distance to waste site [via Truck]

		Processes		**Re-bar Fabrication**		**Transport by 28T**		**Electricity Production**		
			source:	Industry Research		from M-X		EPA Power Profile 02770 zip code		
Economic Output			units:	kg		tkm		kWh		
		Fabricated Steel Re-bar	kg	1	1	1	2.00E-01	1	1.00E-01	
Economic Inputs										**Totals**
	2	Outbound Steel Transpo	tkm	1.93E-01	1.93E-01					1.93E-01 tkm
	3	Waste Transpo	tkm	6.44E-03	6.44E-03					6.44E-03 tkm
	4	Electricity	kWh	1.00E-01	1.00E-01					1.00E-01 kWh
Environmental Outputs						from M-X				
Emissions	1	CO2	kg			6.62E-02	1.32E-02	4.07E-01	4.07E-02	5.39E-02 kg
	2	CO	kg			9.79E-05	1.95E-05			1.95E-05 kg
	3	NOx	kg			6.46E-04	1.29E-04	6.81E-04	6.81E-05	1.97E-04 kg
	4	SO2	kg			1.29E-05	2.57E-06	1.72E-03	1.72E-04	1.75E-04 kg
	5	Methane	kg			1.61E-06	3.21E-07			3.21E-07 kg
	6	HydroCarbons	kg			5.80E-09	1.16E-09			1.16E-09 kg
	7	Dust	kg							kg
	8	Particulates	kg			6.83E-05	1.36E-05			1.36E-05 kg
	9	Mercury	kg			1.83E-10	3.65E-11	7.26E-09	7.26E-10	7.62E-10 kg
	10	Lead	kg			2.23E-09	4.45E-10			4.45E-10 kg
	11	Cadmium	kg			4.67E-10	9.32E-11			9.32E-11 kg
	12	Copper	kg			3.14E-08	6.27E-09			6.27E-09 kg
	13	Chromium	kg			3.71E-09	7.41E-10			7.41E-10 kg
	14	Nickel	kg			3.64E-09	7.27E-10			7.27E-10 kg
	15	Zinc	kg			5.96E-08	1.19E-08			1.19E-08 kg
	16	Dioxins	kg			1.27E-12	2.54E-13			2.54E-13 kg
Waste	17	Waste heat	MJ	1.05E-02	1.05E-02	9.64E-01	1.92E-01			2.03E-01 MJ
	18	Waste (landfill)	kg							kg
	19	Waste (recycle)	kg	5.00E-02	5.00E-02					5.00E-02 kg
	20	Waste (incinerator)	kg							kg
Environmental Inputs						from M-X				
Resource Depletion	1	Bauxite	kg							kg
	2	Clay	kg							kg
	3	Gravel (in ground)	kg							kg
	4	Gypsum (resource)	kg							kg
	5	Iron Ore (resource)	kg							kg
	6	Limestone	kg							kg
	7	Sand	kg							kg
	8	Water	kg							kg
	9	Wood	kg							kg
Energy	10	Coal Energy	MJ					6.15E-01	6.15E-02	6.15E-02 MJ
	11	Diesel Fuel Energy	MJ			9.53E-01	1.90E-01			1.90E-01 MJ
	12	Natural Gas Energy	MJ					7.60E-01	7.60E-02	7.60E-02 MJ
	13	Oil Energy	MJ					5.79E-01	5.79E-02	5.79E-02 MJ
	14	Other Energy	MJ					1.63E+00	1.63E-01	1.63E-01 MJ

Total Energy Input	5.49E-01 MJ
Total Nat'l Resource Input	kg

APPENDIX A-13. STEEL RE-BAR PRODUCTION INVENTORY

Matrix C3b - STEEL REINFORCING BAR PRODUCTION

This matrix is the inventory analysis for the process of steel re-bar production.
It is based on EAF process using 100% recycled steel and covers transportation of scrap iron to shipment of finished re-bar to local re-bar warehouse.
It includes the flows from Steel Rolling (M-C3a1).

Given Data:

	miles	km	
Inbound Mileage:	300	482.78	Average radius of scrap iron collection to steel mill [via Truck]
Outbound Mileage:	375	603.48	Approximate distance from steel mill to re-bar fabricator [via Truck]
	40	64.37	Distance to disposal site

Recycled waste is steel lost during the forming phase and is re-used on site without transportation requirements.

		Processes		Steel Forming (Re-Bar)		EAF, 100% Recycled Steel Production		28T Truck Transportation		Electricity Production		
			source:	Industry Research		EcoInvent Report #10 Part II pgs57-59		from M-X		EPA Power Profile (13021 zip code)		
Economic Output			unit:	kg		kg		tkm		kWh		
		Steel Rebar	kg	1	1	1	1.05E+00	1	2.34E+00	1	1.61E+00	
Economic Inputs												**Totals**
	2	Steel (pre-formed)	kg	1.05E+00	1.05E+00							1.05E+00 kg
	3	Recycled Scrap Iron	kg			1.10E+00	1.16E+00					1.16E+00 kg
	4	Truck Transpo	tkm	1.21E+00	1.21E+00	1.06E+00	1.12E+00					2.32E+00 tkm
	5	Waste Transpo	tkm	1.62E-02	1.62E-02							1.62E-02 tkm
	6	Electricity	kWh			1.53E+00	1.61E+00					1.61E+00 kWh
Environmental Outputs				from M-C3b1				from M-X				
Emissions	1	CO2	kg	5.35E-02	5.35E-02			6.62E-02	1.55E-01	3.82E-01	6.14E-01	8.23E-01 kg
	2	CO	kg	8.76E-05	8.76E-05	2.32E-03	2.44E-03	9.79E-05	2.29E-04			2.75E-03 kg
	3	NOx	kg	3.76E-04	3.76E-04	1.80E-04	1.89E-04	6.46E-04	1.51E-03	6.35E-04	1.02E-03	3.10E-03 kg
	4	SO2	kg	3.31E-04	3.31E-04	7.70E-05	8.09E-05	1.29E-05	3.01E-05	2.27E-03	3.64E-03	4.09E-03 kg
	5	Methane	kg					1.61E-06	3.76E-06			3.76E-06 kg
	6	Hydrocarbons	kg	2.86E-04	2.86E-04	7.93E-05	8.33E-05	5.80E-09	1.36E-08			3.69E-04 kg
	7	Dust	kg	5.69E-05	5.69E-05	3.91E-04	4.10E-04					4.67E-04 kg
	8	Particulates	kg	1.86E-05	1.86E-05			6.83E-05	1.60E-04			1.78E-04 kg
	9	Mercury	kg	7.37E-10	7.37E-10	2.24E-06	2.35E-06	1.83E-10	4.28E-10	5.26E-09	8.46E-09	2.36E-06 kg
	10	Lead	kg	1.77E-08	1.77E-08	1.81E-06	1.90E-06	2.23E-09	5.21E-09			1.92E-06 kg
	11	Cadmium	kg			3.65E-08	3.83E-08	4.67E-10	1.09E-09			3.94E-08 kg
	12	Copper	kg	7.18E-08	7.18E-08	2.31E-07	2.43E-07	3.14E-08	7.35E-08			3.88E-07 kg
	13	Chromium	kg	3.74E-07	3.74E-07	1.25E-06	1.31E-06	3.71E-09	8.69E-09			1.70E-06 kg
	14	Nickel	kg	2.44E-07	2.44E-07	7.01E-07	7.36E-07	3.64E-09	8.52E-09			9.89E-07 kg
	15	Zinc	kg			2.29E-05	2.40E-05	5.96E-08	1.39E-07			2.42E-05 kg
	16	Dioxins	kg			4.54E-12	4.77E-12	1.27E-12	2.97E-12			7.74E-12 kg
Waste	17	Waste heat	MJ	5.04E-01	5.04E-01	6.98E+00	7.33E+00	9.64E-01	2.25E+00			1.01E+01 MJ
	18	Waste (landfill)	kg	1.83E-02	1.83E-02	1.02E-01	1.08E-01					1.26E-01 kg
	19	Waste (recycle)	kg	5.00E-02	5.00E-02							5.00E-02 kg
	20	Waste (incinerator)	kg	2.13E-04	2.13E-04							2.13E-04 kg
Environmental Inputs				from M-C3b1				from M-X				
Primary Resources	1	Bauxite	kg									kg
	2	Clay	kg									kg
	3	Gravel (in ground)	kg									kg
	4	Gypsum (resource)	kg									kg
	5	Iron Ore (resource)	kg									kg
	6	Limestone	kg									kg
	7	Sand	kg									kg
	8	Water	kg	5.50E+00	5.50E+00							5.50E+00 kg
	9	Wood	kg									kg
Energy	10	Coal Energy	MJ	1.32E-01	1.32E-01	5.04E-01	5.29E-01			9.41E-01	1.51E+00	2.17E+00 MJ
	11	Diesel Energy	MJ					9.53E-01	2.23E+00			2.23E+00 MJ
	12	Natural Gas Energy	MJ	1.66E+00	1.66E+00	9.75E-01	1.02E+00			7.24E-01	1.16E+00	3.85E+00 MJ
	13	Oil Energy	MJ	2.53E-02	2.53E-02					1.81E-01	2.91E-01	3.16E-01 MJ
	14	Other Energy	MJ	2.48E-01	2.48E-01					1.77E+00	2.85E+00	3.10E+00 MJ

Total Energy Inputs	1.17E+01 MJ
Total Nat'l Resource Inputs	5.50E+00 kg

APPENDIX A-14. HOT ROLLING PROCESS INVENTORY (for Steel Re-bar)

Matrix C3b1 - HOT ROLLING, STEEL

This matrix is the inventory analysis for the forming of steel rebar. This process is colocated with the steel production facility.
It is solely based on data received from the EcoInvent Reports.

		Processes		Overall		Waste water treatment		Hot Rolling		Descaling		Reheat Furnace		Grinding		Scarfing		Electricity Production		Total	
			source	EcoInvnet Report #10 part X pgs9-14		EcoInvnet Report #10 part X pgs9-14		EcoInvnet Report #10 part X pgs9-14		EcoInvnet Report #10 part X pgs9-14		EcoInvnet Report #10 part X pgs9-14		EcoInvnet Report #10 part X pgs9-14		EcoInvnet Report #10 part X pgs9-14		EPA Power Profile (13021 zip code)			
Economic Outputs			unit:	kg														kWh			
		Rolled Steel Member	kg	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.14		
Economic Inputs																					
	2	Electricity	kWh	0.14	0.14															0.14	kWh
Environmental Outputs																					
Emissions	1	CO2	kg															3.82E-01	5.35E-02	5.35E-02	kg
	2	CO	kg									6.52E-05	6.52E-05			2.24E-05	2.24E-05			8.76E-05	kg
	3	NOx	kg									2.74E-04	2.74E-04			1.31E-05	1.31E-05	6.35E-04	8.89E-05	3.76E-04	kg
	4	SO2	kg									1.34E-05	1.34E-05					2.27E-03	3.18E-04	3.31E-04	kg
	5	Methane	kg																		kg
	6	Hydrocarbons	kg					2.83E-04	2.83E-04			2.50E-06	2.50E-06							2.86E-04	kg
	7	Dust	kg					5.37E-05	5.37E-05			3.16E-06	3.16E-06							5.69E-05	kg
	8	Particulates	kg											9.64E-06	9.64E-06	8.94E-06	8.94E-06			1.86E-05	kg
	9	Mercury	kg															5.26E-09	7.37E-10	7.37E-10	kg
	10	Lead	kg													1.77E-08	1.77E-08			1.77E-08	kg
	11	Cadmium	kg																		kg
	12	Copper	kg													7.18E-08	7.18E-08			7.18E-08	kg
	13	Chromium	kg											3.54E-07	3.54E-07	2.00E-08	2.00E-08			3.74E-07	kg
	14	Nickel	kg											2.24E-07	2.24E-07	2.00E-08	2.00E-08			2.44E-07	kg
	15	Zinc	kg																		kg
	16	Dioxins	kg																		kg
Waste	17	Waste heat	MJ	5.04E-01	5.04E-01															5.04E-01	MJ
	18	Waste (landfill)	kg			1.63E-02	1.63E-02	8.72E-04	8.72E-04	4.83E-04	4.83E-04	2.23E-04	2.23E-04			4.42E-04	4.42E-04			1.83E-02	kg
	19	Waste (recycle)	kg	5.00E-02	5.00E-02															5.00E-02	kg
	20	Waste (incinerator)	kg							2.13E-04	2.13E-04									2.13E-04	kg
Environmental Inputs																					
Primary Resources	1	Bauxite	kg																		kg
	2	Clay	kg																		kg
	3	Gravel (in ground)	kg																		kg
	4	Gypsum (resource)	kg																		kg
	5	Iron Ore (resource)	kg																		kg
	6	Limestone	kg																		kg
	7	Sand	kg																		kg
	8	Water	kg			5.50E+00	5.50E+00													5.50E+00	kg
	9	Wood	kg																		kg
Energy	10	Coal Energy	MJ															9.41E-01	1.32E-01	1.32E-01	MJ
	11	Diesel Energy	MJ																		MJ
	12	Natural Gas Energy	MJ									1.56E+00	1.56E+00					7.24E-01	1.01E-01	1.66E+00	MJ
	13	Oil Energy	MJ															1.81E-01	2.53E-02	2.53E-02	MJ
	14	Other Energy	MJ															1.77E+00	2.48E-01	2.48E-01	MJ

Total Energy Inputs	2.07E+00	MJ
Total Nat'l Resource Inputs	5.50E+00	kg

APPENDIX B

APPENDIX B-1. ASSUMPTIONS FOR STEEL INVENTORY ANALYSIS

Given Data:

1 kg =	2.2046	lbs	
1 metric ton =	2204.62	lbs	
1 ton [US] =	0.9072	tons [metric]	
1 m^3 =	1.3080	yd^3	
1 m^3 =	2.5	tons [metric]	source: www.concrete.org.uk
1 BTU/hp-hr =	7.3857	MJ/hp-hr	
Average BSFC =	7000		(EPA AP-42, 2003)
Calorific value of diesel =	46	MJ/kg	(NPL, 2006)
Calorific value of coal =	36	MJ/kg	(NPL, 2006)

Assumptions:

Total amount of steel used to construct functional unit =	**600**	tons(US)	Based on estimate of steel construction at 12 lb (steel) per square foot (building). (Taylor, T., Suffolk Construction estimator, personal communication).
Total amount of concrete used in floor slabs =	**50000**	ft3	Based on calculation shown in Section 6.6. Amount of Concrete = # of floors x Slab Height x Floor Area.

Steel

Percent of steel wasted during beam fabrication =	7.5%		Based on conversations with steel fabricators who gave a range between 1-15% (Coates, S., Novel Iron Works Engineering Department, April 28, 2006; Willard, W., Cives Northern Division, March 16, 2006; Huber, C., Cives New England Division, March 16, 2006).
Typical beam size (W18x35) =	35	lb/ft	Based on a 100,000sf case study: A W18x35 was used 23.7% of the time. Case study provided by Novel Iron Works (Coates, personal communication)
Typical beam length =	30	ft	This is an estimate of the typical span length of a bay in the steel frame
Percent of steel wasted during connection fabrication =	3.0%		Based on conversations with steel fabricator (Coates, personal communication). Assumed to be slighlty less than beams because of common angle size use.
Typical connection size (L4x3-1/2x5/16) =	7.7	lb/ft	Based on conversation with steel fabricators concerning common used angle sections (Coates, personal communication).
Typical connection length =	1	ft	Assumption based on W18x35 flange height.
Weight of Combined Member =	490.24	kg	Combined member is defined as beam section with two connections attached on both ends. Value based on weight of four typical connection sections plus one typical beam section. The purpose of the combined member is to provide a link, based on steel weight to the next higher inventory analysis.
Percent (by weight) of steel beam on combined steel member =	97.2%		Based on weight of 30ft W18x35 section compared to entire combined member.
Steel Erection rate (per combined member) at construction site =	0.20	hrs/ member	Based on personal communication with steel erectors who gave an estimate of 4-5 members per hour for an erection rate (Marr, D., Vice President Daniel Marr, Inc., personal communication).

Fire-proofing

Fireproofing application rate =	1375	lbf/hr	Application rate varies widely across industry (Littlejohn, S., Century Drywall, personal communication). Based on a typical pump (Big Blue 2750 lb/hr), operating at 50% full capacity.
Percent of fireproofing wasted during application =	10.0%		Based on conversation with sub-contractors (Colby, J., Grace Construction Sales, personal communication; Neuwirth, F., personal communication)
Thickness of fireproofing coating =	0.50	in	Varies based on code requirement. Typical application thickness is .5 inches.
Density of Fireproofing (Dry) =	15	lb/ft^3	MSDS of Monokote Mk-6 (Grace, 2006)
Surface length of W18x35 =	58.9	in	Calculation based on beam measurements.
Weight of FP (per Linear Board Feet [lbf]) =	1.39	kg/lbf	Perimeter x thickness x density of fireproofing

Welds

Number of welds per combined steel member =	4		
Weld length per connection =	0.5	m	Estimate based on connection length
Percent of welded connections on typical job site =	9%		Based on conversation with steel erectors giving an estimate of 8-10% welds done on site (Marr D., personal communication).

Concrete

Concrete placement rate at construction site =	50	yd^3/hr	Based on conversations with concrete contractor (Montero, S., S&F Construction Foreman, personal communication).
Percent of concrete wasted/un-used during placement =	5%		(Montero, S., personal communication).

Construction Equipment

BSFC for Diesel engine =		0.353971	lb/hp-hr	BSFC = Avg BSFC/Calorific Value
	hp	SFC		SFC = BSFC x hp
Specific fuel consumption rate (crane) =	450	159.29	lb/hr	
Specific fuel consumption rate (air comp) =	124	43.89	lb/hr	
Specific fuel consumption rate (pump truck) =	300	106.19	lb/hr	
Specific fuel consumption rate (mix truck) =	565	199.99	lb/hr	

Matrix S - STEEL CONSTRUCTION

This spreadsheet represents the inventory analysis for the entire steel construction process flow chart.
It is the combination of collected data and all other matrices.
It is based on a construction site in Boston, MA.

Assumptions:

Total amount of steel used to construct functional unit = **600** tons (US)
Total amount of concrete used in floor slabs = **50000** ft3

Distance Data:

miles	km	
50	80.46	Distance from fabricator to Construction Site [via Truck]
40	64.37	Approximate distance to waste disposal location [via Truck]

		Processes		Steel Erection	Welding	Steel Beam Fabrication	Steel Connection Fabrication	Steel Beam Production	Steel Connection Production	Fireproofing Application	Fireproofing Manufacture	Concrete Floor Slab Placement	Concrete Production	Transport by 28T Truck	On-Site Equipment Operation	On-Site Energy Generation	Totals
		source:		Industry Research	EcoInvent Report #10 part X pg 112	from M-S3a	from M-S3b	from M-S1	from M-S2	Industry Research	from M-S4		from M-S5	from M-X	EPA AP-42 Table 3.3-1	EPA AP-42 Table 3.3-1	
Economic Output			unit:	kg	m	kg	kg	kg	kg	kg	kg	m3	m3	tkm	MJ	MJ	
		Erected Steel	kg	490.24 5.4E+05	1 2.0E+02	1 5.3E+05	1 1.6E+04	1 5.4E+05	1 1.7E+04	1 4.6E+04	1 5.1E+04	1 1.4E+03	1 1.5E+03	1 1.1E+05	1 9.7E+05	1 1.3E+05	
Economic Inputs																	
	2	Welds	m	1.8E-01 2.0E+02													2.00E+02 m
	3	Fabricated Steel Beams	kg	4.8E+02 5.3E+05													5.29E+05 kg
	4	Steel Beams (pre-fab)	kg			1.0E+00 5.4E+05											5.45E+05 kg
	5	Fabricated Connections	kg	1.4E+01 1.6E+04													1.55E+04 kg
	6	Steel Connections (pre-fab)	kg				1.1E+00 1.7E+04										1.67E+04 kg
	7	Fireproofing	kg	4.2E+01 4.6E+04						1.1E+00 5.1E+04							9.73E+04 kg
	8	Batched Concrete	m3									1.1E+00 1.5E+03					1.49E+03 m3
	9	Fabricated Steel Transpo	tkm	7.9E+01 8.8E+04													8.76E+04 tkm
	10	Solid Waste Transpo	tkm							1.3E-02 6.0E+02		1.6E+01 2.3E+04					2.34E+04 tkm
	11	Crane Operations	MJ	6.6E+02 7.4E+05													7.38E+05 MJ
	12	Pump/Mix Truck Operations	MJ									1.7E+02 2.4E+05					2.37E+05 MJ
	13	Air Comp/Generator Use	MJ	9.2E+01 1.0E+05	9.9E-02 2.0E+01					4.8E-01 2.2E+04		6.0E+00 8.5E+03					1.32E+05 MJ
Environmental Outputs						from M-S3a	from M-S3b	from M-S1	from M-S2		from M-S4		from M-S5	from M-X			
Emissions	1	CO2	kg		5.0E-02 1.0E+01	1.1E-01 6.1E+04	7.2E-01 1.1E+04	1.2E+00 6.4E+05	8.2E-01 1.4E+04		5.3E-01 2.7E+04		2.7E+02 4.0E+05	6.6E-02 7.3E+03	7.1E-02 6.9E+04	7.1E-02 9.3E+03	1.24E+06 kg
	2	CO	kg		6.7E-05 1.3E-02	3.8E-07 2.0E-01	1.1E-05 1.6E-01	4.7E-03 2.5E+03	2.7E-03 4.6E+01		2.1E-04 1.1E+01		1.6E-01 2.3E+02	9.8E-05 1.1E+01	4.1E-04 4.0E+02	4.1E-04 5.4E+01	3.30E+03 kg
	3	NOx	kg		2.0E-06 4.0E-04	1.9E-04 1.0E+02	1.2E-03 1.9E+01	5.5E-03 3.0E+03	3.0E-03 5.1E+01		2.1E-03 1.0E+02		4.9E-01 7.3E+02	6.5E-04 7.2E+01	1.9E-03 1.8E+03	1.9E-03 2.5E+02	6.15E+03 kg
	4	SO2	kg			4.9E-04 2.6E+02	3.0E-03 4.7E+01	2.7E-03 1.5E+03	4.1E-03 6.8E+01		2.3E-03 1.2E+02		2.0E-01 3.0E+02	1.3E-05 1.4E+00	1.2E-04 1.2E+02	1.2E-04 1.7E+01	2.40E+03 kg
	5	Methane	kg			6.2E-09 3.3E-03	1.7E-08 2.6E-04	6.6E-06 3.6E+00	3.6E-06 6.1E-02		3.5E-06 1.8E-01		2.9E-03 4.3E+00	1.6E-06 1.8E-01			8.26E+00 kg
	6	Hydrocarbons	m3			2.2E-11 1.2E-05	6.1E-11 9.4E-07	6.5E-04 3.5E+02	3.7E-04 6.1E+00		1.3E-08 6.5E-04		1.5E-02 2.2E+01	5.8E-09 6.4E-04	1.5E-04 1.5E+02	1.5E-04 2.0E+01	5.53E+02 m3
	7	Dust	kg					4.6E-04 2.5E+02	4.8E-04 7.9E+00		1.3E-03 6.5E+01		2.3E+02 3.4E+05				3.42E+05 kg
	8	Particulates	kg		1.4E-04 2.8E-02	2.6E-07 1.4E-01	2.1E-05 3.2E-01	8.4E-04 4.6E+02	1.6E-04 2.7E+00		1.5E-04 7.6E+00		1.9E-02 2.8E+01	6.8E-05 7.6E+00	1.3E-04 1.3E+02	1.3E-04 1.8E+01	6.53E+02 kg
	9	Mercury	kg			4.3E-07 2.3E-01	2.7E-06 4.2E-02	2.0E-05 1.1E+01	1.2E-05 1.9E-01		5.7E-09 2.9E-04		9.3E-06 1.4E-02	1.8E-10 2.0E-05			1.15E+01 kg
	10	Lead	kg			8.6E-12 4.6E-06		2.0E-06 1.1E+00	1.9E-06 3.2E-02		4.9E-09 2.5E-04		2.4E-05 3.5E-02	2.2E-09 2.5E-04			1.16E+00 kg
	11	Cadmium	kg			1.8E-12 9.5E-07		3.8E-08 2.1E-02	3.9E-08 6.6E-04		1.0E-09 5.2E-05		2.0E-06 3.0E-03	4.7E-10 5.2E-05			2.45E-02 kg
	12	Copper	m3		2.1E-07 4.2E-05	1.2E-10 6.4E-05		3.9E-07 2.1E-01	3.9E-07 6.4E-03		6.9E-08 3.5E-03		1.2E-05 1.8E-02	3.1E-08 3.5E-03			2.46E-01 m3
	13	Chromium	kg		2.8E-05 5.6E-03	1.4E-11 7.6E-06		1.6E-06 8.9E-01	1.7E-06 2.8E-02		8.2E-09 4.2E-04		1.6E-06 2.3E-03	3.7E-09 4.1E-04			9.23E-01 kg
	14	Nickel	kg		1.1E-05 2.3E-03	1.4E-11 7.4E-06		9.5E-07 5.2E-01	9.9E-07 1.6E-02		8.0E-09 4.1E-04		2.4E-06 3.5E-03	3.6E-09 4.0E-04			5.40E-01 kg
	15	Zinc	kg		4.2E-07 8.4E-05	2.3E-10 1.2E-04		2.3E-05 1.3E+01	2.4E-05 4.0E-01		1.3E-07 6.7E-03		3.5E-05 5.2E-02	6.0E-08 6.6E-03			1.30E+01 kg
	16	Dioxins	kg			4.9E-15 2.6E-09	1.3E-14 2.1E-10	5.1E-10 2.8E-04	7.6E-12 1.3E-07		2.8E-12 1.4E-07		7.5E-10 1.1E-06	1.3E-12 1.4E-07			2.81E-04 kg
Waste	17	Waste heat	MJ		9.9E-02 2.0E+01	1.4E-02 7.5E+03	2.7E-02 4.2E+02	1.0E+01 5.5E+06	1.0E+01 1.7E+05		2.1E+00 1.1E+05		1.5E+03 2.2E+06	9.6E-01 1.1E+05			8.01E+06 MJ
	18	Waste (landfill)	kg					1.2E-01 6.6E+04	1.3E-01 2.1E+03	1.0E-01 4.6E+03		1.3E+02 1.8E+05	1.7E+01 2.5E+04				2.75E+05 kg
	19	Waste (recycle)	kg			3.0E-02 1.6E+04	8.1E-02 1.3E+03	5.0E-02 2.7E+04	5.0E-02 8.3E+02								4.52E+04 kg
	20	Waste (incinerator)	kg					2.1E-04 1.2E+02	2.1E-04 3.6E+00				1.3E-01 1.9E+02				3.06E+02 kg
Environmental Inputs						from M-S3a	from M-S3b	from M-S1	from M-S2		from M-S4		from M-S5	from M-X			
Resource Depletion	1	Bauxite	kg										3.3E-02 4.8E+01				4.83E+01 kg
	2	Clay	kg										1.2E+02 1.8E+05				1.80E+05 kg
	3	Gravel (in ground)	kg										4.0E+03 6.0E+06				5.99E+06 kg
	4	Gypsum (resource)	kg								8.0E-01 4.1E+04		2.4E+01 3.6E+04				7.64E+04 kg
	5	Iron Ore (resource)	kg					1.5E-01 7.9E+04									7.94E+04 kg
	6	Limestone	kg					5.3E-04 2.9E+02					1.4E+04 2.1E+07				2.13E+07 kg
	7	Sand	kg										2.5E+00 3.7E+03				3.73E+03 kg
	8	Water	kg					6.0E+00 3.3E+06	5.5E+00 9.2E+04	1.9E+00 8.8E+04			1.6E+05 2.5E+08				2.49E+08 kg
	9	Wood	kg														kg
Energy	10	Coal Energy	MJ			1.7E-01 9.2E+04	1.1E+00 1.7E+04	2.4E+00 1.3E+06	2.2E+00 3.6E+04		9.4E-01 4.8E+04		3.9E+02 5.8E+05				2.09E+06 MJ
	11	Diesel Fuel Energy	MJ			3.7E-03 1.9E+03	9.9E-03 1.5E+02	2.4E+00 1.3E+06	2.2E+00 3.6E+04	4.8E-01 2.2E+04	2.1E+00 1.1E+05		5.3E+02 7.9E+05	9.5E-01 1.1E+05	1.0E+00 9.7E+05	1.0E+00 1.3E+05	3.48E+06 MJ
	12	Natural Gas Energy	MJ			2.1E-01 1.1E+05	1.3E+00 2.1E+04	4.9E+00 2.7E+06	2.8E+00 4.7E+04		7.2E-01 3.7E+04		3.9E+01 5.9E+04				2.94E+06 MJ
	13	Oil Energy	MJ			1.6E-01 8.6E+04	1.0E+00 1.6E+04	1.8E-01 9.9E+04	1.3E+00 2.2E+04		1.8E-01 9.2E+03		5.9E+01 8.7E+04				3.20E+05 MJ
	14	Other Energy	MJ			4.6E-01 2.4E+05	2.8E+00 4.4E+04	1.5E+00 8.2E+05	3.1E+00 5.2E+04		1.8E+00 9.0E+04		8.6E+01 1.3E+05				1.38E+06 MJ

Total Energy Input	1.02E+07 MJ
Total Nat'l Resource Input	2.76E+08 kg

Matrix S1 - STEEL BEAM PRODUCTION

This matrix is the inventory analysis of the production of steel members using the EAF steel-making process
It includes flows from the production of pig iron/iron scrap collection to delivery to local NE steel fabricators via rail.
The information was mainly gained from EcoInvent Reports and interviews with industry players.
The assumptions and given data were based on Steel Production at Nucor Yamato Steel in Arkansas.

Assumptions:

95% Recycled steel content IAW environmental letter of NYS.
5% Amount of steel lost during hot rolling, cutting.
Steel is automatically recycled on site and there is no transportation requirement.

Distance Data:

	miles	km	
Inbound Mileages:	1000	1609.27	Average radius of scrap iron collection to steel mill [via Rail]
	50	80.46	Approximate distance from local scrap heap to rail head [via Truck]
	1975	3178.31	Distance from Venezuela to U.S. Port (Mobile,AL) [via Ocean Cargo Ship]
	460	740.26	Approximate distance from port to steel mill [via Rail]
Outbound Mileages:	1500	2413.90	Approximate distance from steel mill to New England railhead [via Rail]
	20	32.19	Approximate distance from NE railhead to steel fabricator [via Truck]
	40	64.37	Approximate distance to waste disposal location [via Truck]

		Processes		Steel, Section Rolling		Steel Mill Production Mix 95% recycled/5% pig iron		EAF Steel-making Process, 100% Recycled		Pig Iron Production (Foreign Source)		Cargo Ship Transportation		28T Truck Transportation		Rail Transportation		Electricity Production		Totals
		source:		from M-S1b		Environmental certification from mill		EcoInvent Report #10 Part II pg57-59		from M-S1a		from M-X		from M-X		from M-X		EPA Power Profile (72310 zip code)		
Economic Output		unit:		kg		kg		kg		kg		tkm		tkm		tkm		kWh		
		Steel Beam	kg	1	1	1	1.05E+00	1	9.98E-01	1	5.25E-02	1	1.67E-01	1	2.60E-01	1	4.34E+00	1	1.53E+00	
Economic Inputs																				
	2	Steel (pre-rolled)	kg	1.05E+00	1.05E+00															1.05E+00 kg
	3	Pig Iron	kg			5.00E-02	5.25E-02													5.25E-02 kg
	4	Recycled Scrap Iron	kg			9.50E-01	9.98E-01	1.10E+00	1.10E+00											2.09E+00 kg
	5	Transport by Cargo Ship	tkm			1.59E-01	1.67E-01													1.67E-01 tkm
	6	Transport by Truck	tkm	6.76E-02	6.76E-02			1.77E-01	1.77E-01											2.44E-01 tkm
	7	Transport by rail	tkm	2.53E+00	2.53E+00	3.70E-02	3.89E-02	1.77E+00	1.77E+00											4.34E+00 tkm
	8	Waste Transpo	tkm	1.56E-02	1.56E-02															1.56E-02 tkm
	9	Electricity	kWh					1.53E+00	1.53E+00											1.53E+00 kWh
Environmental Outputs				from M-S1b						from M-S1a		from M-X		from M-X		from M-X				
Emissions	1	CO2	kg	8.45E-02	8.45E-02					2.42E-01	1.27E-02	4.65E-05	7.76E-06	6.62E-02	1.72E-02	3.38E-02	1.47E-01	6.04E-01	9.22E-01	1.18E+00 kg
	2	CO	kg	8.76E-05	8.76E-05			2.32E-03	2.31E-03	2.85E-02	1.50E-03	8.39E-07	1.40E-07	9.79E-05	2.54E-05	1.73E-04	7.51E-04			4.67E-03 kg
	3	NOx	kg	4.71E-04	4.71E-04			1.80E-04	1.80E-04	1.07E-03	5.64E-05	1.05E-06	1.75E-07	6.46E-04	1.68E-04	5.92E-04	2.57E-03	1.32E-03	2.01E-03	5.45E-03 kg
	4	SO2	kg	2.23E-04	2.23E-04			7.70E-05	7.68E-05	1.51E-03	7.94E-05	3.80E-08	6.34E-09	1.29E-05	3.34E-06	6.58E-06	2.86E-05	1.50E-03	2.28E-03	2.70E-03 kg
	5	Methane	kg							7.44E-07	3.90E-08	5.15E-09	8.59E-10	1.61E-06	4.18E-07	1.41E-06	6.12E-06			6.58E-06 kg
	6	Hydrocarbons	kg	2.86E-04	2.86E-04			7.93E-05	7.91E-05	5.40E-03	2.84E-04	7.24E-10	1.21E-10	5.80E-09	1.51E-09	3.17E-09	1.38E-08			6.48E-04 kg
	7	Dust	kg	6.65E-05	6.65E-05			3.91E-04	3.90E-04	3.19E-05	1.67E-06									4.58E-04 kg
	8	Particulates	kg	8.94E-06	8.94E-06					8.30E-03	4.36E-04	1.31E-07	2.18E-08	6.83E-05	1.77E-05	8.76E-05	3.80E-04			8.43E-04 kg
	9	Mercury	kg	1.51E-06	1.51E-06			2.24E-06	2.23E-06	7.97E-08	4.18E-09	2.27E-11	3.79E-12	1.83E-10	4.75E-11	9.97E-11	4.33E-10	1.08E-05	1.64E-05	2.02E-05 kg
	10	Lead	kg	1.77E-08	1.77E-08			1.81E-06	1.81E-06	3.49E-06	1.83E-07	8.62E-11	1.44E-11	2.23E-09	5.79E-10	3.84E-10	1.67E-09			2.01E-06 kg
	11	Cadmium	kg					3.65E-08	3.64E-08	2.04E-08	1.07E-09	9.11E-13	1.52E-13	4.67E-10	1.21E-10	1.11E-10	4.82E-10			3.81E-08 kg
	12	Copper	kg	7.18E-08	7.18E-08			2.31E-07	2.30E-07	9.20E-08	4.83E-09	2.31E-11	3.85E-12	3.14E-08	8.16E-09	1.83E-08	7.94E-08			3.95E-07 kg
	13	Chromium	kg	3.74E-07	3.74E-07			1.25E-06	1.25E-06	2.79E-08	1.46E-09	2.61E-11	4.36E-12	3.71E-09	9.65E-10	6.48E-10	2.81E-09			1.63E-06 kg
	14	Nickel	kg	2.44E-07	2.44E-07			7.01E-07	6.99E-07	4.27E-08	2.24E-09	1.47E-11	2.45E-12	3.64E-09	9.46E-10	8.11E-10	3.52E-09			9.50E-07 kg
	15	Zinc	kg					2.29E-05	2.28E-05	8.96E-07	4.71E-08	2.56E-10	4.27E-11	5.96E-08	1.55E-08	1.18E-08	5.12E-08			2.30E-05 kg
	16	Dioxins	kg					4.54E-12	4.53E-12	9.63E-09	5.06E-10	1.58E-13	2.64E-14	1.27E-12	3.30E-13	6.93E-13	3.01E-12			5.13E-10 kg
Waste	17	Waste heat	MJ	5.04E-01	5.04E-01			6.98E+00	6.96E+00	2.71E+00	1.42E-01	1.02E-01	1.70E-02	9.64E-01	2.51E-01	4.92E-01	2.13E+00			1.00E+01 MJ
	18	Waste (landfill)	kg	1.88E-02	1.88E-02			1.02E-01	1.02E-01	4.26E-03	2.24E-04									1.21E-01 kg
	19	Waste (recycle)	kg	5.00E-02	5.00E-02															5.00E-02 kg
	20	Waste (incinerator)	kg	2.13E-04	2.13E-04															2.13E-04 kg
Environmental Inputs				from M-S1b						from M-S1a		from M-X		from M-X		from M-X				
Resource Depletion	1	Bauxite	kg																	kg
	2	Clay	kg																	kg
	3	Gravel (in ground)	kg																	kg
	4	Gypsum (resource)	kg																	kg
	5	Iron Ore (resource)	kg							2.78E+00	1.46E-01									1.46E-01 kg
	6	Limestone	kg							1.00E-02	5.25E-04									5.25E-04 kg
	7	Sand	kg																	kg
	8	Water	kg	5.50E+00	5.50E+00					9.14E+00	4.80E-01									5.98E+00 kg
	9	Wood	kg																	kg
Energy	10	Coal Energy	MJ	1.52E-01	1.52E-01			5.04E-01	5.03E-01	2.27E+00	1.19E-01							1.09E+00	1.66E+00	2.43E+00 MJ
	11	Diesel Energy	MJ							3.33E-01	1.75E-02			9.53E-01	2.48E-01	4.92E-01	2.14E+00			2.40E+00 MJ
	12	Natural Gas Energy	MJ	1.76E+00	1.76E+00			9.75E-01	9.73E-01	8.30E-02	4.36E-03							1.41E+00	2.15E+00	4.89E+00 MJ
	13	Oil Energy	MJ	1.52E-02	1.52E-02					8.17E-03	4.29E-04							1.09E-01	1.66E-01	1.81E-01 MJ
	14	Other Enrgy	MJ	1.27E-01	1.27E-01													9.05E-01	1.38E+00	1.51E+00 MJ

Total Energy Inputs	1.14E+01 MJ
Total Nat'l Resource Inputs	6.13E+00 kg

APPENDIX B-4. PIG IRON PRODUCTION INVENTORY

Matrix S1a - PIG IRON PRODUCTION

This matrix is the inventory analysis for the production of pig iron.
It includes all flows from extraction of natural resource to ready for shipment.
It is solely based on data received from the EcoInvent Reports.

Assumptions: Location of pig iron production is assumed to be from overseas. In this case S. America was used based on interviews conducted.
EcoInvent data based on European information was assumed to be relevant for S. America, including all transportation requirements.

		Processes		**Pig Iron Production**		**Sinter Production**		**Pellets Production**		**Refined Iron Ore Production**		**Iron Ore Mining**		**28T Truck Transportation**		**40T Truck Transportation**		**Rail Transportation**		**Electricity Production**		**Total**	
			source:	EcoInvent Report #10 part II pgs28-29		EcoInvent Report #10 part II pgs19-20		EcoInvent Report #10 part II pgs21-22		EcoInvent Report #10 part II pgs13-14		EcoInvent Report #10 part II pg10		from M-X		from M-X		from M-X		Overseas Electricity Production EcoInvent			
		Economic Outputs	unit:	kg		kg		kg		kg		kg		tkm		tkm		tkm		kWh			
		Pig Iron	kg	1	1	1	1.05E+00	1	4.00E-01	1	1.67E+00	1	2.78E+00	1	5.58E-03	1	1.60E-03	1	5.20E-01	1	5.57E-02		
		Economic Inputs																					
	2	Refined Iron Ore	kg	1.50E-01	1.50E-01	1.05E+00	1.10E+00	1.05E+00	4.20E-01													1.67E+00	kg
	3	Sinter	kg	1.05E+00	1.05E+00																	1.05E+00	kg
	3	Pellets	kg	4.00E-01	4.00E-01																	4.00E-01	kg
	4	Unrefined Iron Ore	kg							1.66E+00	2.78E+00											2.78E+00	kg
	5	Truck Transpo	tkm	3.48E-03	3.48E-03	2.00E-03	2.10E-03															5.58E-03	tkm
	6	Heavy Truck Transpo	tkm					4.01E-03	1.60E-03													1.60E-03	tkm
	7	Rail Transpo	tkm	1.86E-01	1.86E-01	3.09E-01	3.24E-01	2.41E-02	9.64E-03													5.20E-01	tkm
	8	Electricity	kWh			1.00E-02	1.05E-02	2.50E-02	1.00E-02	1.87E-02	3.13E-02	1.42E-03	3.94E-03									5.57E-02	kWh
		Environmental Outputs												from M-X		from M-X		from M-X					
Emissions	1	CO2	kg	4.15E-04	4.15E-04	2.04E-01	2.14E-01	2.37E-02	9.48E-03					6.62E-02	3.69E-04	5.60E-02	8.98E-05	3.38E-02	1.76E-02	2.20E-03	1.23E-04	2.42E-01	kg
	2	CO	kg	1.34E-03	1.34E-03	2.57E-02	2.70E-02	2.10E-04	8.40E-05					9.79E-05	5.46E-07	6.35E-05	1.02E-07	1.73E-04	8.99E-05			2.85E-02	kg
	3	NOx	kg	7.98E-05	7.98E-05	5.27E-04	5.53E-04	3.15E-04	1.26E-04					6.46E-04	3.61E-06	5.10E-04	8.18E-07	5.92E-04	3.08E-04	3.89E-05	2.17E-06	1.07E-03	kg
	4	SO2	kg	1.33E-04	1.33E-04	1.26E-03	1.32E-03	1.34E-04	5.36E-05					1.29E-05	7.17E-08	1.08E-05	1.73E-08	6.58E-06	3.42E-06	1.79E-06	9.97E-08	1.51E-03	kg
	5	Methane	kg											1.61E-06	8.97E-09	1.04E-06	1.67E-09	1.41E-06	7.33E-07			7.44E-07	kg
	6	Hydrocarbons	kg			1.37E-04	1.44E-04	2.25E-05	9.00E-06	3.14E-03	5.25E-03			5.80E-09	3.24E-11	4.88E-09	7.82E-12	3.17E-09	1.65E-09			5.40E-03	kg
	7	Dust	kg	3.19E-05	3.19E-05																	3.19E-05	kg
	8	Particulates	kg			2.06E-04	2.16E-04	7.50E-05	3.00E-05			2.88E-03	8.01E-03	6.83E-05	3.81E-07	4.54E-05	7.28E-08	8.76E-05	4.55E-05			8.30E-03	kg
	9	Mercury	kg			7.57E-08	7.95E-08	2.50E-10	1.00E-10					1.83E-10	1.02E-12	1.54E-10	2.47E-13	9.97E-11	5.18E-11	5.60E-10	3.12E-11	7.97E-08	kg
	10	Lead	kg	6.91E-08	6.91E-08	3.23E-06	3.39E-06	6.65E-08	2.66E-08					2.23E-09	1.24E-11	1.66E-09	2.66E-12	3.84E-10	2.00E-10			3.49E-06	kg
	11	Cadmium	kg			1.93E-08	2.03E-08	2.10E-10	8.40E-11					4.67E-10	2.61E-12	3.51E-10	5.63E-13	1.11E-10	5.77E-11			2.04E-08	kg
	12	Copper	kg			7.66E-08	8.04E-08	4.60E-09	1.84E-09					3.14E-08	1.75E-10	2.58E-08	4.13E-11	1.83E-08	9.51E-09			9.20E-08	kg
	13	Chromium	kg			2.52E-08	2.65E-08	2.70E-09	1.08E-09					3.71E-09	2.07E-11	2.75E-09	4.40E-12	6.48E-10	3.37E-10			2.79E-08	kg
	14	Nickel	kg	1.60E-08	1.60E-08	1.93E-08	2.03E-08	1.50E-08	6.00E-09					3.64E-09	2.03E-11	2.72E-09	4.36E-12	8.11E-10	4.22E-10			4.27E-08	kg
	15	Zinc	kg			8.26E-07	8.67E-07	5.62E-08	2.25E-08					5.96E-08	3.32E-10	3.27E-08	5.25E-11	1.18E-08	6.13E-09			8.96E-07	kg
	16	Dioxins	kg	2.66E-12		7.00E-09	7.35E-09	5.70E-09	2.28E-09					1.27E-12	7.09E-15	1.07E-12	1.71E-15	6.93E-13	3.60E-13			9.63E-09	kg
Waste	17	Waste heat	MJ	4.90E-01	4.90E-01	1.54E+00	1.62E+00	5.31E-01	2.12E-01	6.74E-02	1.13E-01	5.13E-03	1.42E-02	9.64E-01	5.38E-03	8.10E-01	1.30E-03	4.92E-01	2.56E-01			2.71E+00	MJ
	18	Waste (landfill)	kg	4.26E-03	4.26E-03																	4.26E-03	kg
	19	Waste (recycle)	kg																				kg
	20	Waste (incinerator)	kg																				kg
		Environmental Inputs												from M-X		from M-X		from M-X					
Resource Depletion	1	Bauxite	kg																				kg
	2	Clay	kg																				kg
	3	Gravel (in ground)	kg																				kg
	4	Gypsum (resource)	kg																				kg
	5	Iron Ore (resource)	kg									1.00E+00	2.78E+00									2.78E+00	kg
	6	Limestone	kg	1.00E-02	1.00E-02																	1.00E-02	kg
	7	Sand	kg																				kg
	8	Water	kg	6.00E+00	6.00E+00	5.00E-01	5.25E-01	9.00E-02	3.60E-02	1.52E+00	2.54E+00	1.15E-02	3.19E-02									9.14E+00	kg
	9	Wood	kg																				kg
Energy	10	Coal Energy	MJ	3.40E-01	3.40E-01	1.43E+00	1.50E+00													7.75E+00	4.32E-01	2.27E+00	MJ
	11	Diesel Energy	MJ									2.55E-02	7.08E-02	9.53E-01	5.32E-03	8.00E-01	1.28E-03	4.92E-01	2.56E-01			3.33E-01	MJ
	12	Natural Gas Energy	MJ			3.63E-02	3.81E-02	6.90E-02	2.76E-02											3.10E-01	1.73E-02	8.30E-02	MJ
	13	Oil Energy	MJ																	1.47E-01	8.17E-03	8.17E-03	MJ
	14	Other Energy	MJ																				MJ

Total Energy Inputs	2.70E+00	MJ
Total Nat'l Resource Inputs	1.19E+01	kg

APPENDIX B-5. HOT ROLLING PROCESS INVENTORY (for Steel Beam)

Matrix S1b - HOT ROLLING, STEEL (for beam production)

This matrix is the inventory analysis for the hot rolling of steel.
It is solely based on data received from the EcoInvent Reports.
The hot rolling is assumed to be a continuous (throughput) process of EAF steel production.

Assumptions: This inventory assumes the same location as the beam production steel mill in M-S1
The wasted steel is immediately returned to the loop. There is no transportation requirement for this steel.

		Processes		Overall		Waste water treatment		Hot Rolling		Descaling		Reheat Furnace		Grinding		Scarfing		Electricity Production		Total	
		source:		EcoInvent Report #10 part X pgs9-14		EcoInvent Report #10 part X pgs9-14		EcoInvent Report #10 part X pgs9-14		EcoInvent Report #10 part X pgs9-14		EcoInvent Report #10 part X pgs9-14		EcoInvent Report #10 part X pgs9-14		EcoInvent Report #10 part X pgs9-14		EPA Power Profile (72310 zip code)			
Economic Outputs			unit:	kg														kWh			
		Rolled Steel Member	kg	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.14		
Economic Inputs																					
	1	Electricity	kWh	0.14	0.14															0.14	kWh
Environmental Outputs																					
Emissions	1	CO2	kg															6.04E-01	8.45E-02	8.45E-02	kg
	2	CO	kg									6.52E-05	6.52E-05			2.24E-05	2.24E-05			8.76E-05	kg
	3	NOx	kg									2.74E-04	2.74E-04			1.31E-05	1.31E-05	1.32E-03	1.84E-04	4.71E-04	kg
	4	SO2	kg									1.34E-05	1.34E-05					1.50E-03	2.10E-04	2.23E-04	kg
	5	Methane	kg																		kg
	6	Hydrocarbons	kg					2.83E-04	2.83E-04			2.50E-06	2.50E-06							2.86E-04	kg
	7	Dust	kg					5.37E-05	5.37E-05			3.16E-06	3.16E-06	9.64E-06	9.64E-06					6.65E-05	kg
	8	Particulates	kg													8.94E-06	8.94E-06			8.94E-06	kg
	9	Mercury	kg															1.08E-05	1.51E-06	1.51E-06	kg
	10	Lead	kg													1.77E-08	1.77E-08			1.77E-08	kg
	11	Cadmium	kg																		kg
	12	Copper	kg													7.18E-08	7.18E-08			7.18E-08	kg
	13	Chromium	kg											3.54E-07	3.54E-07	2.00E-08	2.00E-08			3.74E-07	kg
	14	Nickel	kg											2.24E-07	2.24E-07	2.00E-08	2.00E-08			2.44E-07	kg
	15	Zinc	kg																		kg
	16	Dioxins	kg																		kg
Waste	17	Waste heat	MJ	5.04E-01	5.04E-01															5.04E-01	MJ
	18	Waste (landfill)	kg			1.63E-02	1.63E-02	8.72E-04	8.72E-04	4.83E-04	4.83E-04	2.23E-04	2.23E-04	4.42E-04	4.42E-04	4.42E-04	4.42E-04			1.88E-02	kg
	19	Waste (recycle)	kg	5.00E-02	5.00E-02															5.00E-02	kg
	20	Waste (incinerator)	kg							2.13E-04	2.13E-04									2.13E-04	kg
Environmental Inputs																					
Resource Depletion	1	Bauxite	kg																		kg
	2	Clay	kg																		kg
	3	Gravel (in ground)	kg																		kg
	4	Gypsum (resource)	kg																		kg
	5	Iron Ore (resource)	kg																		kg
	6	Limestone	kg																		kg
	7	Sand	kg																		kg
	8	Water	kg			5.50E+00	5.50E+00													5.50E+00	kg
	9	Wood	kg																		kg
Energy	10	Coal Energy	MJ															1.09E+00	1.52E-01	1.52E-01	MJ
	11	Diesel Energy	MJ																		MJ
	12	Natural Gas Energy	MJ									1.56E+00	1.56E+00					1.41E+00	1.98E-01	1.76E+00	MJ
	13	Oil Energy	MJ															1.09E-01	1.52E-02	1.52E-02	MJ
	14	Other Energy	MJ															9.05E-01	1.27E-01	1.27E-01	MJ

Total Energy Inputs 2.05E+00 MJ
Total Nat'l Resource Inputs 5.50E+00 kg

APPENDIX B-6. STEEL CONNECTION PRODUCTION INVENTORY

Matrix S2 - STEEL CONNECTION PRODUCTION

This matrix is the inventory analysis of the production of steel angle used for structural steel connections using EAF process.
It includes flows from the delivery of iron scrap to delivery to local NE steel fabricators.
The information was mainly gained from EcoInvent Reports and interviews with industry players.
The assumptions and given data are based on angle sections produced at Nucor-Auburn, New York in accordance with the MWU method.

Assumptions:

100%	Recycled Steel Content
5%	Amount of steel lost during hot rolling, cutting

Steel is automatically recycled on site and there is no transportation requirement

Distance Data:

	miles	km	
Inbound Mileages:	300	482.78	Average radius of scrap iron collection to ste
Outbound Mileages:	350	563.24	Approximate distance from steel mill to steel
	40	64.37	Approximate distance to disposal location [vi

		Processes		Steel, Forming		Steel Mill Production Mix 100% recycled content		EAF Steel-making Process, 100% Recycled		28T Truck Transportation		Electricity Production		Totals
			source:	from M-S2a		Steel Mill Environmental Certification		EcoInvent Report #10 Part II pg57-59		from M-X		EPA Power Profile (13021 zip code)		
Economic Output			unit:	kg		kg		kg		tkm		kWh		
		Steel Connections	kg	1	1	1	1.05E+00	1	1.05E+00	1	2.26E+00	1	1.61E+00	
Economic Inputs														
	2	Steel (pre-rolled)	kg	1.05E+00	1.05E+00									1.05E+00 kg
	3	Recycled Scrap Iron	kg			1.00E+00	1.05E+00	1.10E+00	1.16E+00					2.21E+00 kg
	4	Transport by Truck	tkm	1.13E+00	1.13E+00			1.06E+00	1.12E+00					2.24E+00 tkm
	5	Waste Transpo	tkm	1.63E-02	1.63E-02									1.63E-02 tkm
	6	Electricity	kWh					1.53E+00	1.61E+00					1.61E+00 kWh
Environmental Outputs				from M-S2a						from M-X				
Emissions	1	CO2	kg	5.35E-02	5.35E-02					6.62E-02	1.50E-01	3.82E-01	6.14E-01	8.18E-01 kg
	2	CO	kg	8.76E-05	8.76E-05			2.32E-03	2.44E-03	9.79E-05	2.21E-04			2.74E-03 kg
	3	NOx	kg	3.76E-04	3.76E-04			1.80E-04	1.89E-04	6.46E-04	1.46E-03	6.35E-04	1.02E-03	3.04E-03 kg
	4	SO2	kg	3.31E-04	3.31E-04			7.70E-05	8.09E-05	1.29E-05	2.90E-05	2.27E-03	3.65E-03	4.09E-03 kg
	5	Methane	kg							1.61E-06	3.63E-06			3.63E-06 kg
	6	Hydrocarbons	kg	2.86E-04	2.86E-04			7.93E-05	8.33E-05	5.80E-09	1.31E-08			3.69E-04 kg
	7	Dust	kg	6.65E-05	6.65E-05			3.91E-04	4.10E-04					4.77E-04 kg
	8	Particulates	kg	8.94E-06	8.94E-06					6.83E-05	1.54E-04			1.63E-04 kg
	9	Mercury	kg	7.36E-07	7.36E-07			2.24E-06	2.35E-06	1.83E-10	4.13E-10	5.26E-06	8.45E-06	1.15E-05 kg
	10	Lead	kg	1.77E-08	1.77E-08			1.81E-06	1.90E-06	2.23E-09	5.03E-09			1.92E-06 kg
	11	Cadmium	kg					3.65E-08	3.83E-08	4.67E-10	1.05E-09			3.94E-08 kg
	12	Copper	kg	7.18E-08	7.18E-08			2.31E-07	2.43E-07	3.14E-08	7.10E-08			3.85E-07 kg
	13	Chromium	kg	3.74E-07	3.74E-07			1.25E-06	1.31E-06	3.71E-09	8.39E-09			1.69E-06 kg
	14	Nickel	kg	2.44E-07	2.44E-07			7.01E-07	7.36E-07	3.64E-09	8.23E-09			9.88E-07 kg
	15	Zinc	kg					2.29E-05	2.40E-05	5.96E-08	1.35E-07			2.42E-05 kg
	10	Dioxins	kg					4.54E-12	4.77E-12	1.27E-12	2.87E-12			7.64E-12 kg
Waste	11	Waste heat	MJ	5.04E-01	5.04E-01			6.98E+00	7.33E+00	9.64E-01	2.18E+00			1.00E+01 MJ
	12	Waste (landfill)	kg	1.88E-02	1.88E-02			1.02E-01	1.08E-01					1.26E-01 kg
	13	Waste (recycle)	kg	5.00E-02	5.00E-02									5.00E-02 kg
	14	Waste (incinerator)	kg	2.13E-04	2.13E-04									2.13E-04 kg
Environmental Inputs				from M-S2a						from M-X				
Resource Depletion	1	Bauxite	kg											kg
	2	Clay	kg											kg
	3	Gravel (in ground)	kg											kg
	4	Gypsum (resource)	kg											kg
	5	Iron Ore (resource)	kg											kg
	6	Limestone	kg											kg
	7	Sand	kg											kg
	8	Water	kg	5.50E+00	5.50E+00									5.50E+00 kg
	9	Wood	kg											kg
Energy	10	Light Fuel Oil	MJ	1.32E-01	1.32E-01			5.04E-01	5.29E-01			9.41E-01	1.51E+00	2.17E+00 MJ
	11	Heavy Fuel Oil	MJ							9.53E-01	2.15E+00			2.15E+00 MJ
	12	Pet Coke	MJ	1.66E+00	1.66E+00							7.24E-01	1.16E+00	2.82E+00 MJ
	13	Natural Gas Energy	MJ	2.53E-02	2.53E-02			9.75E-01	1.02E+00			1.81E-01	2.91E-01	1.34E+00 MJ
	14	Diesel Energy	MJ	2.48E-01	2.48E-01							1.77E+00	2.85E+00	3.10E+00 MJ

Total Energy Inputs	1.16E+01 MJ
Total Nat'l Resource Inputs	5.50E+00 kg

APPENDIX B-7. HOT ROLLING PROCESS INVENTORY (for Steel Connection)

Matrix S2a - HOT ROLLING, STEEL (for connection production)

This matrix is the inventory analysis for the hot rolling of steel.
It is solely based on data received from the EcoInvent Reports.
The hot rolling is assumed to be a continuous (throughput) process of EAF steel production.

Assumptions: This inventory assumes the same location as the connection production steel mill in M-S2
The wasted steel is immediately returned to the loop. There is no transportation requirement for this invnetory.

		Processes		Overall		Waste water treatment		Hot Rolling		Descaling		Reheat Furnace		Grinding		Scarfing		Electricity Production		Total	
		source:		EcoInvent Report #10 part X pgs9-14		EcoInvent Report #10 part X pgs9-14		EcoInvent Report #10 part X pgs9-14		EcoInvent Report #10 part X pgs9-14		EcoInvent Report #10 part X pgs9-14		EcoInvent Report #10 part X pgs9-14		EcoInvent Report #10 part X pgs9-14		EPA Power Profile (13021 zip code)			
Economic Outputs			unit:	kg														kWh			
		Rolled Steel Member	kg	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.14		
Economic Inputs																					
	1	Electricity	kWh	0.14	0.14															0.14	kWh
Environmental Outputs																					
Emissions	1	CO2	kg															3.825E-01	5.35E-02	5.35E-02	kg
	2	CO	kg									6.52E-05	6.52E-05			2.24E-05	2.24E-05			8.76E-05	kg
	3	NOx	kg									2.74E-04	2.74E-04			1.31E-05	1.31E-05	6.350E-04	8.89E-05	3.76E-04	kg
	4	SO2	kg									1.34E-05	1.34E-05					2.269E-03	3.18E-04	3.31E-04	kg
	5	Methane	kg																		kg
	6	Hydrocarbons	kg					2.83E-04	2.83E-04			2.50E-06	2.50E-06							2.86E-04	kg
	7	Dust	kg					5.37E-05	5.37E-05			3.16E-06	3.16E-06	9.64E-06	9.64E-06					6.65E-05	kg
	8	Particulates	kg													8.94E-06	8.94E-06			8.94E-06	kg
	9	Mercury	kg															5.260E-06	7.36E-07	7.36E-07	kg
	10	Lead	kg													1.77E-08	1.77E-08			1.77E-08	kg
	11	Cadmium	kg																		kg
	12	Copper	kg													7.18E-08	7.18E-08			7.18E-08	kg
	13	Chromium	kg											3.54E-07	3.54E-07	2.00E-08	2.00E-08			3.74E-07	kg
	14	Nickel	kg											2.24E-07	2.24E-07	2.00E-08	2.00E-08			2.44E-07	kg
	15	Zinc	kg																		kg
	16	Dioxins	kg																		kg
Waste	17	Waste heat	MJ	5.04E-01	5.04E-01															5.04E-01	MJ
	18	Waste (landfill)	kg			1.63E-02	1.63E-02	8.72E-04	8.72E-04	4.83E-04	4.83E-04	2.23E-04	2.23E-04	4.42E-04	4.42E-04	4.42E-04	4.42E-04			1.88E-02	kg
	19	Waste (recycle)	kg	5.00E-02	5.00E-02															5.00E-02	kg
	20	Waste (incinerator)	kg							2.13E-04	2.13E-04									2.13E-04	kg
Environmental Inputs																					
Resource Depletion	1	Bauxite	kg																		kg
	2	Clay	kg																		kg
	3	Gravel (in ground)	kg																		kg
	4	Gypsum (resource)	kg																		kg
	5	Iron Ore (resource)	kg																		kg
	6	Limestone	kg																		kg
	7	Sand	kg																		kg
	8	Water	kg			5.50E+00	5.50E+00													5.50E+00	kg
	9	Wood	kg																		kg
Energy	10	Coal Energy	MJ															9.412E-01	1.32E-01	1.32E-01	MJ
	11	Diesel Energy	MJ																		MJ
	12	Natural Gas Energy	MJ									1.56E+00	1.56E+00					7.240E-01	1.01E-01	1.66E+00	MJ
	13	Oil Energy	MJ															1.810E-01	2.53E-02	2.53E-02	MJ
	14	Other Energy	MJ															1.774E+00	2.48E-01	2.48E-01	MJ

Total Energy Inputs	2.07E+00	MJ
Total Nat'l Resource Inputs	5.50E+00	kg

APPENDIX B-8. STEEL BEAM FABRICATION INVENTORY

Matrix S3a - STEEL BEAM FABRICATION

This matrix represents the inventory analysis for the process of cutting and fabricating steel members.
It includes the cutting, drilling and fitting and finishing (welding is not included) steps of the fabrication process.
Given data and assumptions are based on information gained from several major steel fabricators for the Boston/New England market

Assumptions:		
Typical beam size (W18x35) =	35	lb/ft
Typical beam length =	30	ft
Percent of steel wasted during fabrication =	3%	

Distance data:		
miles	km	
40	64.37	Approx. distance to waste site [via Truck]

		Processes		**Steel Cutting**		**Transport by 28T**		**Electricity Production**		
			source:	Industry Research		from M-X		EPA Power Profile 04330 zip code		
		Economic Output	units:	kg		tkm		kWh		
		Fabricated Steel Beam	kg	476.272	1	1	3.86E-03	1	2.81E-01	
		Economic Inputs								**Totals**
	2	Waste Transpo	tkm	1.84E+00	3.86E-03					3.86E-03 tkm
	3	Electricity	kWh	1.34E+02	2.81E-01					2.81E-01 kWh
		Environmental Outputs				from M-X				
Emissions	1	CO2	kg			6.62E-02	2.56E-04	4.07E-01	1.14E-01	1.15E-01 kg
	2	CO	kg			9.79E-05	3.78E-07			3.78E-07 kg
	3	NOx	kg			6.46E-04	2.50E-06	6.81E-04	1.92E-04	1.94E-04 kg
	4	SO2	kg			1.29E-05	4.97E-08	1.72E-03	4.85E-04	4.85E-04 kg
	5	Methane	kg			1.61E-06	6.21E-09			6.21E-09 kg
	6	HydroCarbons	kg			5.80E-09	2.24E-11			2.24E-11 kg
	7	Dust	kg							kg
	8	Particulates	kg			6.83E-05	2.64E-07			2.64E-07 kg
	9	Mercury	kg			1.83E-10	7.06E-13	1.54E-06	4.34E-07	4.34E-07 kg
	10	Lead	kg			2.23E-09	8.61E-12			8.61E-12 kg
	11	Cadmium	kg			4.67E-10	1.80E-12			1.80E-12 kg
	12	Copper	kg			3.14E-08	1.21E-10			1.21E-10 kg
	13	Chromium	kg			3.71E-09	1.43E-11			1.43E-11 kg
	14	Nickel	kg			3.64E-09	1.41E-11			1.41E-11 kg
	15	Zinc	kg			5.96E-08	2.30E-10			2.30E-10 kg
	16	Dioxins	kg			1.27E-12	4.91E-15			4.91E-15 kg
Waste	17	Waste heat	MJ	5.00E+00	1.05E-02	9.64E-01	3.72E-03			1.42E-02 MJ
	18	Waste (landfill)	kg							kg
	19	Waste (recycle)	kg	1.43E+01	3.00E-02					3.00E-02 kg
	20	Waste (incinerator)	kg							kg
		Environmental Inputs				from M-X				
Resource Depletion	1	Bauxite	kg							kg
	2	Clay	kg							kg
	3	Gravel (in ground)	kg							kg
	4	Gypsum (resource)	kg							kg
	5	Iron Ore (resource)	kg							kg
	6	Limestone	kg							kg
	7	Sand	kg							kg
	8	Water	kg							kg
	9	Wood	kg							kg
Energy	10	Coal Energy	MJ					6.15E-01	1.73E-01	1.73E-01 MJ
	11	Diesel Fuel Energy	MJ			9.53E-01	3.68E-03			3.68E-03 MJ
	12	Natural Gas Energy	MJ					7.60E-01	2.14E-01	2.14E-01 MJ
	13	Oil Energy	MJ					5.79E-01	1.63E-01	1.63E-01 MJ
	14	Other Energy	MJ					1.63E+00	4.58E-01	4.58E-01 MJ

Total Energy Input	1.01E+00 MJ
Total Nat'l Resource Input	kg

APPENDIX B-9. STEEL CONNECTION FABRICATION INVENTORY

Matrix S3b - CONNECTION FABRICATION

This matrix is the inventory analysis for the process of fabricating steel connections
It includes the cutting, drilling, fitting, welding, and finishing steps of the fabrication process.
The study assumes that the connection inventory would include the welding analysis.

Assumptions:

Typical connection size (L4x3-1/2x5/16) =	7.7	lb/ft
Typical connection length =	1	ft
Percent of steel wasted during fabrication =	8%	
Weld length per connection =	0.5	m
Percent of welded connections =	15%	

Distance data:

miles	km	
40	64.37	Approximate distance from fabricator to waste site [via Truck]

		Processes		Steel Cutting		Welding		Transport by 28T		Electricity Production		
		source:		Industry Research		EcoInvent Report #10 part X pg 112		from M-X		EPA Power Profile 03840 zip code		
Economic Output			units:	kg		m		tkm		kWh		
		Fabricated Steel Connections	kg	3.493	1	1	1.43E-01	1	1.04E-02	1	1.75E+00	
Economic Inputs												**Totals**
	2	Welds	m	5.00E-01	1.43E-01							1.43E-01 m
	3	Waste Transpo	tkm	3.65E-02	1.04E-02							1.04E-02 tkm
	4	Electricity	kWh	6.09E+00	1.74E+00	2.75E-02	3.94E-03					1.75E+00 kWh
Environmental Flows (Outputs)								from M-X				
Emissions	1	CO2	kg			5.00E-02	7.16E-03	6.62E-02	6.91E-04	4.07E-01	7.11E-01	7.19E-01 kg
Emissions	2	CO	kg			6.67E-05	9.55E-06	9.79E-05	1.02E-06			1.06E-05 kg
Emissions	3	NOx	kg			2.00E-06	2.86E-07	6.46E-04	6.75E-06	6.81E-04	1.19E-03	1.20E-03 kg
Emissions	4	SO2	kg					1.29E-05	1.34E-07	1.72E-03	3.01E-03	3.01E-03 kg
Emissions	5	Methane	kg					1.61E-06	1.68E-08			1.68E-08 kg
Emissions	6	HydroCarbons	kg					5.80E-09	6.05E-11			6.05E-11 kg
Emissions	7	Dust	kg									kg
Emissions	8	Particulates	kg			1.41E-04	2.02E-05	6.83E-05	7.13E-07			2.09E-05 kg
Emissions	9	Mercury	kg					1.83E-10	1.91E-12	1.54E-06	2.70E-06	2.70E-06 kg
Emissions	10	Lead	kg					2.23E-09	2.33E-11			2.33E-11 kg
Emissions	11	Cadmium	kg					4.67E-10	4.88E-12			4.88E-12 kg
Emissions	12	Copper	kg			2.10E-07	3.01E-08	3.14E-08	3.28E-10			3.04E-08 kg
Emissions	13	Chromium	kg			2.81E-05	4.03E-06	3.71E-09	3.88E-11			4.03E-06 kg
Emissions	14	Nickel	kg			1.13E-05	1.62E-06	3.64E-09	3.80E-11			1.62E-06 kg
Emissions	15	Zinc	kg			4.20E-07	6.01E-08	5.96E-08	6.22E-10			6.07E-08 kg
Emissions	16	Dioxins	kg					1.27E-12	1.33E-14			1.33E-14 kg
Waste	17	Waste heat	MJ	1.05E-02	3.01E-03	9.90E-02	1.42E-02	9.64E-01	1.01E-02			2.72E-02 MJ
Waste	18	Waste (landfill)	kg									kg
Waste	19	Waste (recycle)	kg	2.83E-01	8.11E-02							8.11E-02 kg
Waste	20	Waste (incinerator)	kg									kg
Environmental Inputs								from M-X				
Resource Depletion	1	Bauxite	kg									kg
Resource Depletion	2	Clay	kg									kg
Resource Depletion	3	Gravel (in ground)	kg									kg
Resource Depletion	4	Gypsum (resource)	kg									kg
Resource Depletion	5	Iron Ore (resource)	kg									kg
Resource Depletion	6	Limestone	kg									kg
Resource Depletion	7	Sand	kg									kg
Resource Depletion	8	Water	kg									kg
Resource Depletion	9	Wood	kg									kg
Energy	10	Coal Energy	MJ							6.15E-01	1.08E+00	1.08E+00 MJ
Energy	11	Diesel Fuel Energy	MJ					9.53E-01	9.95E-03			9.95E-03 MJ
Energy	12	Natural Gas Energy	MJ							7.60E-01	1.33E+00	1.33E+00 MJ
Energy	13	Oil Energy	MJ							5.79E-01	1.01E+00	1.01E+00 MJ
Energy	14	Other Energy	MJ							1.63E+00	2.85E+00	2.85E+00 MJ
											Total Energy Input	6.27E+00 MJ
											Total Nat'l Resource Input	kg

APPENDIX B-10. FIREPROOFING MANUFACTURE INVENTORY

Matrix S4 - FIREPROOFING MANUFACTURE

This matrix serves as the inventory analysis for the production of low-density cementitious fireproofing (Monokote MK-6).
It includes process flows from delivery of major sub components to delivery of finished fireproofing product to construction site.
The location of fireproofing manufacture is Ontario, Canada.

Assumptions:

75% Gypsum content IAW MSDS
12.5% Cellulose content IAW MSDS
12.5% Polystyrene content IAW MSDS
Electricity production mix of NYS is assumed

Distance Data:

	miles	km	
Inbound Mileages:	50	80.46	Distance from recycling center to FP manufacture [via Truck]
	200	321.85	Distance from gypsum production to FP manufacture [via Truck]
Outbound Mileages:	600	965.56	Distance from FP manufacturer to construction site [via Truck]
	40	64.37	Approximate distance to disposal site [via Truck]

		Processes		**Fireproofing Production**		**Gypsum**		**Polystyrene**		**Cellulose**		**Transport by 28T Truck**		**Electricity Production**		
			source:	Industry Research / MSDS		EcoInvent-report #7 part VII pgs11-12		Recycled Content		Recycled Content		from M-X		EPA Power Profiler (NYS region)		
Economic Output			unit:	kg		tkm		tkm		tkm		tkm		kWh		
		Fire-proofing	kg	1	1	1	8.00E-01	1	5.00E-02	1	5.00E-02	1	2.20E+00	1	1.00E+00	
Economic Inputs																**Totals**
	2	Gypsum	kg	8.00E-01	8.00E-01											8.00E-01 kg
	3	Polystyrene	kg	5.00E-02	5.00E-02											5.00E-02 kg
	4	Cellulose	kg	5.00E-02	5.00E-02											5.00E-02 kg
	5	In-/Out- Transpo	tkm	1.93E+00	1.93E+00	3.22E-01	2.57E-01	8.05E-02	4.02E-03	8.05E-02	4.02E-03					2.20E+00 tkm
	6	Electricity	kWh	1.00E+00	1.00E+00	9.16E-04	7.33E-04									1.00E+00 kWh
Environmental Outputs												from M-X				
Emissions	1	CO2	kg									6.62E-02	1.45E-01	3.82E-01	3.83E-01	5.28E-01 kg
	2	CO	kg									9.79E-05	2.15E-04			2.15E-04 kg
	3	NOx	kg									6.46E-04	1.42E-03	6.35E-04	6.36E-04	2.06E-03 kg
	4	SO2	kg									1.29E-05	2.82E-05	2.27E-03	2.27E-03	2.30E-03 kg
	5	Methane	kg									1.61E-06	3.53E-06			3.53E-06 kg
	6	HydroCarbons	kg									5.80E-09	1.27E-08			1.27E-08 kg
	7	Dust	kg			1.60E-03	1.28E-03									1.28E-03 kg
	8	Particulates	kg									6.83E-05	1.50E-04			1.50E-04 kg
	9	Mercury	kg									1.83E-10	4.02E-10	5.26E-09	5.27E-09	5.67E-09 kg
	10	Lead	kg									2.23E-09	4.90E-09			4.90E-09 kg
	11	Cadmium	kg									4.67E-10	1.03E-09			1.03E-09 kg
	12	Copper	kg									3.14E-08	6.90E-08			6.90E-08 kg
	13	Chromium	kg									3.71E-09	8.16E-09			8.16E-09 kg
	14	Nickel	kg									3.64E-09	8.00E-09			8.00E-09 kg
	15	Zinc	kg									5.96E-08	1.31E-07			1.31E-07 kg
	16	Dioxins	kg									1.27E-12	2.79E-12			2.79E-12 kg
Waste	17	Waste heat	MJ			3.30E-03	2.64E-03					9.64E-01	2.12E+00			2.12E+00 MJ
	18	Waste (landfill)	kg													kg
	19	Waste (recycle)	kg													kg
	20	Waste (incinerator)	kg													kg
Environmental Inputs												from M-X				
Resource Depletion	1	Bauxite	kg													kg
	2	Clay	kg													kg
	3	Gravel (in ground)	kg													kg
	4	Gypsum (resource)	kg			1.00E+00	8.00E-01									8.00E-01 kg
	5	Iron Ore (resource)	kg													kg
	6	Limestone	kg													kg
	7	Sand	kg													kg
	8	Water	kg													kg
	9	Wood	kg													kg
Energy	10	Coal Energy	MJ											9.41E-01	9.42E-01	9.42E-01 MJ
	11	Diesel Fuel Energy	MJ			1.80E-02	1.44E-02					9.53E-01	2.09E+00			2.11E+00 MJ
	12	Natural Gas Energy	MJ											7.24E-01	7.25E-01	7.25E-01 MJ
	13	Oil Energy	MJ											1.81E-01	1.81E-01	1.81E-01 MJ
	14	Other Energy	MJ											1.77E+00	1.78E+00	1.78E+00 MJ

Total Energy Input	5.73E+00 MJ
Total Nat'l Resource Input	8.00E-01 kg

Matrix S5 - CONCRETE PRODUCTION (for floor slabs)

This spreadsheet represents the inventory analysis for concrete production at the RMC batch plant.
It includes flows from cement production (M-S5a1) and aggregate (coarse/fine) production (M-S5a2/M-S5a3).

Given Data:

	miles	km	
Outbound Mileage:	5	8.05	Approximate distance from concrete batching facility to construction site (via Mix Truck)
	40	64.37	Approximate distance to waste disposal site [via Truck]

		Processes:		**Concrete Batching**		**Portland Cement Production**		**Aggregate Production**		**Aggregate Production**		**Transport by 16T Truck**		**Transport by 28T Truck**		**Electricity Production**		
			source:	EcoInvent-report #7 part III pg33		from M-C1a		from M-C1b		from M-C1c		from M-X		from M-X		EPA Power Profile (02129 zip code)		
Economic Output			unit:	m3		kg		kg		kg		tkm		tkm		kWh		
		Batched Concrete	m3	1	1	1	3.00E+02	1	1.16E+03	1	7.33E+02	1	4.02E+01	1	2.19E+00	1	4.36E+00	
Economic Inputs																		**Totals**
	2	Portland Cement	kg	3.00E+02	3.00E+02													3.00E+02 kg
	3	Coarse Aggregate (Gravel)	kg	1.16E+03	1.16E+03													1.16E+03 kg
	4	Fine Aggregate (Sand)	kg	7.33E+02	7.33E+02													7.33E+02 kg
	5	Outbound Concrete Transpo	tkm	4.02E+01	4.02E+01													4.02E+01 tkm
	6	Waste Transpo	tkm	2.19E+00	2.19E+00													2.19E+00 tkm
	7	Electricity	kWh	4.36E+00	4.36E+00													4.36E+00 kWh
Environmental Outputs						from M-S5a		from M-S5b		from M-S5c		from M-X		from M-X				
Emissions	1	CO2	kg			8.22E-01	2.47E+02	6.25E-03	7.23E+00	1.22E-02	8.96E+00	8.45E-02	3.40E+00	6.62E-02	1.45E-01	4.07E-01	1.77E+00	2.68E+02 kg
	2	CO	kg			4.37E-04	1.31E-01	6.63E-06	7.66E-03	1.32E-05	9.68E-03	1.84E-04	7.39E-03	9.79E-05	2.15E-04			1.56E-01 kg
	3	NOx	kg			1.11E-03	3.33E-01	4.71E-05	5.45E-02	9.34E-05	6.85E-02	8.13E-04	3.27E-02	6.46E-04	1.42E-03	6.81E-04	2.97E-03	4.93E-01 kg
	4	SO2	kg			5.84E-04	1.75E-01	8.10E-06	9.37E-03	1.52E-05	1.11E-02	1.64E-05	6.59E-04	1.29E-05	2.82E-05	1.72E-03	7.52E-03	2.04E-01 kg
	5	Methane	kg			8.16E-06	2.45E-03	1.09E-07	1.26E-04	2.17E-07	1.59E-04	3.23E-06	1.30E-04	1.61E-06	3.53E-06			2.87E-03 kg
	6	HydroCarbons	kg			4.93E-05	1.48E-02	3.98E-10	4.61E-07	7.93E-10	5.82E-07	7.39E-09	2.97E-07	5.80E-09	1.27E-08			1.48E-02 kg
	7	Dust	kg			7.66E-01	2.30E+02											2.30E+02 kg
	8	Particulates	kg			5.75E-06	1.73E-03	4.63E-06	5.35E-03	9.23E-06	6.77E-03	1.17E-04	4.69E-03	6.83E-05	1.50E-04			1.87E-02 kg
	9	Mercury	kg			3.05E-08	9.15E-06	4.33E-11	5.01E-08	8.21E-11	6.02E-08	2.34E-10	9.40E-09	1.83E-10	4.01E-10	7.35E-09	3.20E-08	9.30E-06 kg
	10	Lead	kg			7.72E-08	2.32E-05	1.52E-10	1.76E-07	3.03E-10	2.22E-07	3.55E-09	1.43E-07	2.23E-09	4.89E-09			2.37E-05 kg
	11	Cadmium	kg			6.36E-09	1.91E-06	3.19E-11	3.69E-08	6.35E-11	4.66E-08	7.39E-10	2.97E-08	4.67E-10	1.03E-09			2.02E-06 kg
	12	Copper	kg			1.55E-08	4.66E-06	2.16E-09	2.49E-06	4.29E-09	3.15E-06	4.23E-08	1.70E-06	3.14E-08	6.90E-08			1.21E-05 kg
	13	Chromium	kg			2.20E-09	6.61E-07	2.53E-10	2.93E-07	5.04E-10	3.70E-07	6.03E-09	2.42E-07	3.71E-09	8.15E-09			1.57E-06 kg
	14	Nickel	kg			4.87E-09	1.46E-06	2.49E-10	2.87E-07	4.95E-10	3.63E-07	5.79E-09	2.33E-07	3.64E-09	7.99E-09			2.35E-06 kg
	15	Zinc	kg			5.92E-08	1.77E-05	4.00E-09	4.63E-06	7.98E-09	5.85E-06	1.68E-07	6.74E-06	5.96E-08	1.31E-07			3.51E-05 kg
	16	Dioxins	kg			1.52E-12	4.56E-10	8.73E-14	1.01E-10	1.74E-13	1.28E-10	1.61E-12	6.49E-11	1.27E-12	2.79E-12			7.52E-10 kg
Waste	17	Waste heat	MJ	1.57E+01	1.57E+01	3.94E+00	1.18E+03	8.13E-02	9.40E+01	1.60E-01	1.17E+02	1.23E+00	4.94E+01	9.64E-01	2.12E+00			1.46E+03 MJ
	18	Waste (landfill)	kg	1.69E+01	1.69E+01	7.22E-05	2.17E-02											1.69E+01 kg
	19	Waste (recycle)	kg															kg
	20	Waste (incinerator)	kg	9.51E-02	9.51E-02	4.06E-05	1.22E-02	7.11E-06	8.22E-03	1.32E-05	9.68E-03							1.25E-01 kg
Environmental Inputs						from M-S5a		from M-S5b		from M-S5c		from M-X		from M-X				
Primary Resources	1	Bauxite	kg			1.08E-04	3.25E-02											3.25E-02 kg
	2	Clay	kg			4.04E-01	1.21E+02											1.21E+02 kg
	3	Gravel (in ground)	kg					1.60E+00	1.85E+03	2.97E+00	2.18E+03							4.03E+03 kg
	4	Gypsum (resource)	kg			8.00E-02	2.40E+01											2.40E+01 kg
	5	Iron Ore (resource)	kg															kg
	6	Limestone	kg			4.78E+01	1.44E+04											1.44E+04 kg
	7	Sand	kg			8.36E-03	2.51E+00											2.51E+00 kg
	8	Water	kg	1.86E+02	1.86E+02	5.31E+02	1.59E+05	2.12E+00	2.46E+03	3.94E+00	2.89E+03							1.65E+05 kg
	9	Wood	kg															kg
Energy	10	Coal Energy	MJ			1.26E+00	3.78E+02	2.58E-03	2.98E+00	4.78E-03	3.51E+00					6.15E-01	2.68E+00	3.87E+02 MJ
	11	Diesel Fuel Energy	MJ	2.27E+01	2.27E+01	9.62E-01	2.88E+02	6.55E-02	7.57E+01	1.30E-01	9.56E+01	1.21E+00	4.88E+01	9.53E-01	2.09E+00			5.33E+02 MJ
	12	Natural Gas Energy	MJ	1.16E+00	1.16E+00	8.98E-02	2.69E+01	3.18E-03	3.68E+00	5.91E-03	4.33E+00					7.60E-01	3.31E+00	3.94E+01 MJ
	13	Oil Energy	MJ	1.64E+01	1.64E+01	1.12E-01	3.37E+01	2.42E-03	2.80E+00	4.50E-03	3.30E+00					5.79E-01	2.53E+00	5.88E+01 MJ
	14	Other Energy	MJ			2.05E-01	6.15E+01	6.82E-03	7.88E+00	1.27E-02	9.28E+00					1.63E+00	7.10E+00	8.57E+01 MJ

Total Energy Input	1.10E+03 MJ
Total Nat'l Resource Input	1.83E+05 kg

Matrix S5a - CEMENT PRODUCTION

This matrix represents the inventory analysis for the production of Type I/II Portland Cement following the MWU outlined in the report.
It includes flows from clinker (M-S5a1a) and gypsum production facilities to shipment to cement storage facilities in and around Boston.

Given data:

	miles	km	
Inbound Mileage:		5500.00	Approximate distance traveled for gypsum delivery (from Spain) [via Cargo Ship]
	5	8.05	Approximate distance from ocean port (Albany) to cement production facility (Ravena, NY) [via Truck]
	3	4.83	Distance from cement storage facility (Boston) to batching facility (Boston) [via Truck]
Outbound Mileage:	5	8.05	Distance from cement production facility (Ravena, NY) to barge port (Albany) [via Truck]
	500	804.63	Approximate distance of travel from barge port (Albany) to storage facility (Boston) [via Barge]

		Processes:		Portland Cement Production		Gypsum Production		Clinker Production		Transport by Barge		Transport by 28T Truck		Transport by Cargo Ship		Electricity Production		Totals
			source:	EcoInvent-report #7 part II pg 46		EcoInvent-report #7 part VIII pgs11-12		from M-C1a1		from M-X		from M-X		from M-X		EPA Power Profile (12414 zip code)		
Economic Output			units:	kg		kg		kg		tkm		tkm		tkm		kWh		
		Portland Cement	kg	1	1	0.65	5.20E-02	1	9.03E-01	1	8.05E-01	1	2.66E-02	1	2.86E-01	1	2.93E-02	
Economic Inputs																		
	2	Clinker	kg	9.03E-01	9.03E-01													9.03E-01 kg
	3	Gypsum	kg	5.20E-02	5.20E-02													5.20E-02 kg
	4	Outbound Cement Transpo	tkm	8.05E-01	8.05E-01													8.05E-01 tkm
	5	In- Gypsum/Out- Cement Transpo	tkm	2.57E-02	2.57E-02	1.05E-02	8.37E-04											2.66E-02 tkm
	6	Inbound Gypsum Transpo	tkm			3.58E+00	2.86E-01											2.86E-01 tkm
	7	Electricity	kWh	2.92E-02	2.92E-02	9.16E-04	7.33E-05											2.93E-02 kWh
Environmental Outputs								from M-S5a1		from M-X		from M-X		from M-X				
Emissions	1	CO2	kg					8.96E-01	8.09E-01	1.80E-04	1.45E-04	6.62E-02	1.76E-03	4.65E-05	1.33E-05	3.82E-01	1.12E-02	8.22E-01 kg
	2	CO	kg					4.77E-04	4.31E-04	3.25E-06	2.62E-06	9.79E-05	2.60E-06	8.39E-07	2.40E-07			4.37E-04 kg
	3	NOx	kg					1.18E-03	1.07E-03	4.02E-06	3.23E-06	6.46E-04	1.72E-05	1.05E-06	3.00E-07	6.35E-04	1.86E-05	1.11E-03 kg
	4	SO2	kg					5.73E-04	5.17E-04	1.48E-07	1.19E-07	1.29E-05	3.42E-07	3.80E-08	1.09E-08	2.27E-03	6.64E-05	5.84E-04 kg
	5	Methane	kg					8.97E-06	8.10E-06	2.08E-08	1.67E-08	1.61E-06	4.27E-08	5.15E-09	1.47E-09			8.16E-06 kg
	6	Hydrocarbons	kg					5.46E-05	4.93E-05	2.80E-09	2.25E-09	5.80E-09	1.54E-10	7.24E-10	2.07E-10			4.93E-05 kg
	7	Dust	kg			1.60E-03	1.28E-04	8.48E-01	7.66E-01									7.66E-01 kg
	8	Particulates	kg					3.87E-06	3.49E-06	5.03E-07	4.05E-07	6.83E-05	1.82E-06	1.31E-07	3.74E-08			5.75E-06 kg
	9	Mercury	kg					3.35E-08	3.03E-08	8.77E-11	7.06E-11	1.83E-10	4.86E-12	2.27E-11	6.49E-12	5.26E-09	1.54E-10	3.05E-08 kg
	10	Lead	kg					8.51E-08	7.69E-08	3.38E-10	2.72E-10	2.23E-09	5.92E-11	8.62E-11	2.47E-11			7.72E-08 kg
	11	Cadmium	kg					7.03E-09	6.35E-09	3.53E-12	2.84E-12	4.67E-10	1.24E-11	9.11E-13	2.61E-13			6.36E-09 kg
	12	Copper	kg					1.62E-08	1.46E-08	8.86E-11	7.13E-11	3.14E-08	8.36E-10	2.31E-11	6.61E-12			1.55E-08 kg
	13	Chromium	kg					2.23E-09	2.02E-09	1.01E-10	8.13E-11	3.71E-09	9.87E-11	2.61E-11	7.46E-12			2.20E-09 kg
	14	Nickel	kg					5.23E-09	4.72E-09	5.68E-11	4.57E-11	3.64E-09	9.68E-11	1.47E-11	4.20E-12			4.87E-09 kg
	15	Zinc	kg					6.28E-08	5.67E-08	9.94E-10	8.00E-10	5.96E-08	1.58E-09	2.56E-10	7.32E-11			5.92E-08 kg
	16	Dioxins	kg					1.05E-12	9.49E-13	6.11E-13	4.92E-13	1.27E-12	3.38E-14	1.58E-13	4.52E-14			1.52E-12 kg
Waste	17	Waste heat	MJ	1.05E-01	1.05E-01	3.30E-03	2.64E-04	3.82E+00	3.45E+00	4.08E-01	3.28E-01	9.64E-01	2.56E-02	1.02E-01	2.92E-02			3.94E+00 MJ
	18	Waste (landfill)	kg					8.00E-05	7.22E-05									7.22E-05 kg
	19	Waste (recycle)	kg															kg
	20	Waste (incinerator)	kg					4.50E-05	4.06E-05									4.06E-05 kg
Environmental Inputs								from M-S5a1		from M-X		from M-X		from M-X				
Primary Resources	1	Bauxite	kg					1.20E-04	1.08E-04									1.08E-04 kg
	2	Clay	kg					4.48E-01	4.04E-01									4.04E-01 kg
	3	Gravel (in ground)	kg															kg
	4	Gypsum (resource)	kg			1.00E+00	8.00E-02											8.00E-02 kg
	5	Iron Ore (resource)	kg															kg
	6	Limestone	kg					5.30E+01	4.78E+01									4.78E+01 kg
	7	Sand	kg					9.26E-03	8.36E-03									8.36E-03 kg
	8	Water	kg					5.88E+02	5.31E+02									5.31E+02 kg
	9	Wood	kg															kg
Energy	10	Coal Energy	MJ					1.36E+00	1.23E+00							9.41E-01	2.76E-02	1.26E+00 MJ
	11	Diesel Fuel Energy	MJ			1.80E-02	1.44E-03	1.04E+00	9.35E-01			9.53E-01	2.53E-02					9.62E-01 MJ
	12	Natural Gas Energy	MJ					7.60E-02	6.86E-02							7.24E-01	2.12E-02	8.98E-02 MJ
	13	Oil Energy	MJ					1.19E-01	1.07E-01							1.81E-01	5.30E-03	1.12E-01 MJ
	14	Other Energy	MJ					1.69E-01	1.53E-01							1.77E+00	5.19E-02	2.05E-01 MJ

Total Energy Input	2.63E+00 MJ
Total Nat'l Resource Input	5.80E+02 kg

Matrix S5a1 - CLINKER PRODUCTION

This matrix represents the inventory analysis for the production of clinker (co-located with cement production).
It includes flows from delivery of limestone to production of clinker.
It is based solely on EcoInvent reports.

Given data:

	miles	km	
Inbound Mileage:	0.5	0.80	Distance from limestone quarry to primary crusher (Co-located) [via HD Dump]

		Processes:		**Clinker Production**		**Limestone Milling**		**Primary Crushing (for mill)**		**Marl Production**		**Crushing and Washing (for kiln)**		**Limestone Mining**		**Transport by HD Dump Truck**		**Electricity Production**		
			source:	EcoInvent-report #7 part II pgs19-25		EcoInvent-report #7 part VII pg 32		EcoInvent-report #7 part VII pg31		EcoInvent-report #7 part II pg37		EcoInvent-report #7 part VII pg30		EcoInvent-report #7 part VII pg20		from M-X		EPA Power Profile (12414 zip code)		
Economic Output			units:	kg		kg		kg		kg		kg		kg		tkm		kWh		
		Clinker	kg	1	1	1	8.41E-01	0.042	8.41E-01	1	4.66E-01	0.67	3.50E-01	0.38 0.51	2.00E+01 5.19E-01	1	8.52E-02	1	9.55E-02	
Economic Inputs																				**Totals**
	2	Milled Limestone	kg	8.41E-01	8.41E-01															8.41E-01 kg
	3	Marl	kg	4.66E-01	4.66E-01															4.66E-01 kg
	4	Limestone, crushed	kg			1.00E+00	8.41E-01													8.41E-01 kg
	5	Limestone,crushed & washed	kg							7.50E-01	3.50E-01									3.50E-01 kg
	6	Limestone at mine, to mill	kg					1.00E+00	2.00E+01											2.00E+01 kg
	7	Limestone at mine, to kiln	kg									1.00E+00	5.19E-01							5.19E-01 kg
	8	In- Raw Material Transpo	tkm											1.61E-03	8.52E-02					8.52E-02 tkm
	9	Electricity	kWh	5.80E-02	5.80E-02	3.20E-02	2.69E-02	5.10E-04	1.02E-02			7.20E-04	3.74E-04							9.55E-02 kWh
Environmental Outputs																from M-X				
Emissions	1	CO2	kg	8.55E-01	8.55E-01											5.60E-02	4.77E-03	3.82E-01	3.65E-02	8.96E-01 kg
	2	CO	kg	4.72E-04	4.72E-04											6.35E-05	5.41E-06			4.77E-04 kg
	3	NOx	kg	1.08E-03	1.08E-03											5.10E-04	4.35E-05	6.35E-04	6.07E-05	1.18E-03 kg
	4	SO2	kg	3.55E-04	3.55E-04											1.08E-05	9.21E-07	2.27E-03	2.17E-04	5.73E-04 kg
	5	Methane	kg	8.88E-06	8.88E-06											1.04E-06	8.87E-08			8.97E-06 kg
	6	HydroCarbons	kg	5.46E-05	5.46E-05											4.88E-09	4.16E-10			5.46E-05 kg
	7	Dust	kg	3.77E-05	3.77E-05			1.74E-05	3.49E-04			1.74E-05	9.05E-06	1.60E-02	8.48E-01					8.48E-01 kg
	8	Particulates	kg													4.54E-05	3.87E-06			3.87E-06 kg
	9	Mercury	kg	3.30E-08	3.30E-08											1.54E-10	1.31E-11	5.26E-09	5.03E-10	3.35E-08 kg
	10	Lead	kg	8.50E-08	8.50E-08											1.66E-09	1.42E-10			8.51E-08 kg
	11	Cadmium	kg	7.00E-09	7.00E-09											3.51E-10	2.99E-11			7.03E-09 kg
	12	Copper	kg	1.40E-08	1.40E-08											2.58E-08	2.20E-09			1.62E-08 kg
	13	Chromium	kg	2.00E-09	2.00E-09											2.75E-09	2.34E-10			2.23E-09 kg
	14	Nickel	kg	5.00E-09	5.00E-09											2.72E-09	2.32E-10			5.23E-09 kg
	15	Zinc	kg	6.00E-08	6.00E-08											3.27E-08	2.79E-09			6.28E-08 kg
	16	Dioxins	kg	9.60E-13	9.60E-13											1.07E-12	9.08E-14			1.05E-12 kg
Waste	17	Waste heat	MJ	3.62E+00	3.62E+00	1.15E-01	9.67E-02	1.84E-03	3.68E-02			2.59E-03	1.35E-03			8.10E-01	6.91E-02			3.82E+00 MJ
	18	Waste (landfill)	kg	8.00E-05	8.00E-05															8.00E-05 kg
	19	Waste (recycle)	kg																	kg
	20	Waste (incinerator)	kg	4.50E-05	4.50E-05															4.50E-05 kg
Environmental Inputs																from M-X				
Primary Resources	1	Bauxite	kg	1.20E-04	1.20E-04															1.20E-04 kg
	2	Clay	kg	3.31E-01	3.31E-01					2.50E-01	1.17E-01									4.48E-01 kg
	3	Gravel (in ground)	kg																	kg
	4	Gypsum (resource)	kg																	kg
	5	Iron Ore (resource)	kg																	kg
	6	Limestone	kg											1.00E+00	5.30E+01					5.30E+01 kg
	7	Sand	kg	9.26E-03	9.26E-03															9.26E-03 kg
	8	Water	kg	1.62E+00	1.62E+00			2.93E+01	5.87E+02			2.18E-02	1.13E-02							5.88E+02 kg
	9	Wood	kg																	kg
Energy	10	Coal Energy	MJ	1.27E+00	1.27E+00													9.41E-01	8.99E-02	1.36E+00 MJ
	11	Diesel Fuel Energy	MJ	1.34E-02	1.34E-02									1.80E-02	9.54E-01	8.00E-01	6.82E-02			1.04E+00 MJ
	12	Natural Gas Energy	MJ	6.81E-03	6.81E-03													7.24E-01	6.91E-02	7.60E-02 MJ
	13	Oil Energy	MJ	2.59E-02	2.59E-02	8.98E-02	7.55E-02											1.81E-01	1.73E-02	1.19E-01 MJ
	14	Other Energy	MJ															1.77E+00	1.69E-01	1.69E-01 MJ

Total Energy Input	2.76E+00 MJ
Total Nat'l Resource Input	6.42E+02 kg

APPENDIX B-14. COURSE AGGREGATE PRODUCTION INVENTORY

Matrix S5b - COARSE AGGREGATE PRODUCTION

This matrix represents the inventory analysis for the production of coarse aggregate following the MWU outlined in the report.
It includes flows from transport to primary crusher to shipment to concrete batching facilities in and around Boston
In this case the quarry and primary crusher are colocated and the aggregate is crushed on site

Given Data:

	miles	km	
Inbound Mileage:	1	1.61	Approximate distance from gravel quarry to primary crusher (within same facility) [via HD Dump]
Outbound Mileage:	20	32.19	Distance from gravel quarry to concrete batching facility [via Truck]

		Processes		Aggregate Production		Transport by 28T Truck		Transport by HD Dump Truck		Electricity Production		
			source:	EcoInvnet Report #7 part I pg15-16		from M-X		from M-X		EPA Power Profile (01907 zip code)		
Economic Output			unit:	kg		tkm		tkm		kWh		
		Aggregate (Gravel, round)	kg	0.650	1	1	6.44E-02	1	5.15E-03	1	4.18E-03	
Economic Inputs												**Totals**
	2	Outbound Transpo	tkm	4.18E-02	6.44E-02							6.44E-02 tkm
	3	Inbound Transpo	tkm	3.35E-03	5.15E-03							5.15E-03 tkm
	4	Electricity	kWh	2.72E-03	4.18E-03							4.18E-03 kWh
Environmental Outputs						from M-X		from M-X				
Emissions	1	CO2	kg			6.62E-02	4.26E-03	5.60E-02	2.88E-04	4.07E-01	1.70E-03	6.25E-03 kg
	2	CO	kg			9.79E-05	6.30E-06	6.35E-05	3.27E-07			6.63E-06 kg
	3	NOx	kg			6.46E-04	4.16E-05	5.10E-04	2.63E-06	6.81E-04	2.85E-06	4.71E-05 kg
	4	SO2	kg			1.29E-05	8.28E-07	1.08E-05	5.56E-08	1.72E-03	7.21E-06	8.10E-06 kg
	5	Methane	kg			1.61E-06	1.03E-07	1.04E-06	5.36E-09			1.09E-07 kg
	6	HydroCarbons	kg			5.80E-09	3.73E-10	4.88E-09	2.51E-11			3.98E-10 kg
	7	Dust	kg									kg
	8	Particulates	kg			6.83E-05	4.40E-06	4.54E-05	2.34E-07			4.63E-06 kg
	9	Mercury	kg			1.83E-10	1.18E-11	1.54E-10	7.93E-13	7.35E-09	3.08E-11	4.33E-11 kg
	10	Lead	kg			2.23E-09	1.43E-10	1.66E-09	8.55E-12			1.52E-10 kg
	11	Cadmium	kg			4.67E-10	3.01E-11	3.51E-10	1.81E-12			3.19E-11 kg
	12	Copper	kg			3.14E-08	2.02E-09	2.58E-08	1.33E-10			2.16E-09 kg
	13	Chromium	kg			3.71E-09	2.39E-10	2.75E-09	1.41E-11			2.53E-10 kg
	14	Nickel	kg			3.64E-09	2.34E-10	2.72E-09	1.40E-11			2.49E-10 kg
	15	Zinc	kg			5.96E-08	3.83E-09	3.27E-08	1.68E-10			4.00E-09 kg
	16	Dioxins	kg			1.27E-12	8.18E-14	1.07E-12	5.48E-15			8.73E-14 kg
Waste	17	Waste heat	MJ	9.77E-03	1.50E-02	9.64E-01	6.21E-02	8.10E-01	4.17E-03			8.13E-02 MJ
	18	Waste (landfill)	kg									kg
	19	Waste (recycle)	kg									kg
	20	Waste (incinerator)	kg	4.62E-06	7.11E-06							7.11E-06 kg
Environmental Inputs						from M-X		from M-X				
Primary Resources	1	Bauxite	kg									kg
	2	Clay	kg									kg
	3	Gravel (in ground)	kg	1.04E+00	1.60E+00							1.60E+00 kg
	4	Gypsum (resource)	kg									kg
	5	Iron Ore (resource)	kg									kg
	6	Limestone	kg									kg
	7	Sand	kg									kg
	8	Water	kg	1.38E+00	2.12E+00							2.12E+00 kg
	9	Wood	kg									kg
Energy	10	Coal Energy	MJ							6.15E-01	2.58E-03	2.58E-03 MJ
	11	Diesel Fuel Energy	MJ			9.53E-01	6.13E-02	8.00E-01	4.12E-03			6.55E-02 MJ
	12	Natural Gas Energy	MJ							7.60E-01	3.18E-03	3.18E-03 MJ
	13	Oil Energy	MJ							5.79E-01	2.42E-03	2.42E-03 MJ
	14	Other Energy	MJ							1.63E+00	6.82E-03	6.82E-03 MJ

Total Energy Input	8.05E-02 MJ
Total Nat'l Resource Input	3.72E+00 kg

APPENDIX B-15. FINE AGGREGATE PRODUCTION INVENTORY

Matrix S5c - FINE AGGREGATE PRODUCTION

This matrix represents the inventory analysis for the production of concrete aggregate following the MWU outlined in the report.
It includes flows from transport to primary crusher to shipment to concrete batching facilities in and around Boston
In this case the quarry and primary crusher are colocated and the aggregate is crushed on site

Given data:

	miles	km	
Inbound Mileage:	1	1.61	Approximate distance from quarry to primary crusher (within same facility) [via HD Dump]
Outbound Mileage:	40	64.37	Distance from quarry to concrete batching facility [via Rail]

		Processes		**Aggregate Production**		**Transport by Rail**		**Transport by HD Dump Truck**		**Electricity Production**		
			source:	EcoInvnet Report #7 part I pg15-16		from M-X		from M-X		EPA Power Profile (01907 zip code)		
Economic Output			unit:	kg		tkm		tkm		kWh		
		Fine Aggregate (Sand)	kg	0.350	1	1	1.29E-01	1	9.56E-03	1	7.77E-03	
Economic Inputs												**Totals**
	2	Outbound Transpo	tkm	4.51E-02	1.29E-01							1.29E-01 tkm
	3	Inbound Transpo	tkm	3.35E-03	9.56E-03							9.56E-03 tkm
	4	Electricity	kWh	2.72E-03	7.77E-03							7.77E-03 kWh
Environmental Outputs						from M-X		from M-X				
Emissions	1	CO2	kg			6.62E-02	8.52E-03	5.60E-02	5.36E-04	4.07E-01	3.16E-03	1.22E-02 kg
	2	CO	kg			9.79E-05	1.26E-05	6.35E-05	6.07E-07			1.32E-05 kg
	3	NOx	kg			6.46E-04	8.32E-05	5.10E-04	4.88E-06	6.81E-04	5.29E-06	9.34E-05 kg
	4	SO2	kg			1.29E-05	1.66E-06	1.08E-05	1.03E-07	1.72E-03	1.34E-05	1.52E-05 kg
	5	Methane	kg			1.61E-06	2.07E-07	1.04E-06	9.95E-09			2.17E-07 kg
	6	HydroCarbons	kg			5.80E-09	7.47E-10	4.88E-09	4.66E-11			7.93E-10 kg
	7	Dust	kg									kg
	8	Particulates	kg			6.83E-05	8.79E-06	4.54E-05	4.34E-07			9.23E-06 kg
	9	Mercury	kg			1.83E-10	2.35E-11	1.54E-10	1.47E-12	7.35E-09	5.71E-11	8.21E-11 kg
	10	Lead	kg			2.23E-09	2.87E-10	1.66E-09	1.59E-11			3.03E-10 kg
	11	Cadmium	kg			4.67E-10	6.01E-11	3.51E-10	3.36E-12			6.35E-11 kg
	12	Copper	kg			3.14E-08	4.05E-09	2.58E-08	2.46E-10			4.29E-09 kg
	13	Chromium	kg			3.71E-09	4.78E-10	2.75E-09	2.63E-11			5.04E-10 kg
	14	Nickel	kg			3.64E-09	4.69E-10	2.72E-09	2.60E-11			4.95E-10 kg
	15	Zinc	kg			5.96E-08	7.67E-09	3.27E-08	3.13E-10			7.98E-09 kg
	16	Dioxins	kg			1.27E-12	1.64E-13	1.07E-12	1.02E-14			1.74E-13 kg
Waste	17	Waste heat	MJ	9.77E-03	2.79E-02	9.64E-01	1.24E-01	8.10E-01	7.75E-03			1.60E-01 MJ
	18	Waste (landfill)	kg									kg
	19	Waste (recycle)	kg									kg
	20	Waste (incinerator)	kg	4.62E-06	1.32E-05							1.32E-05 kg
Environmental Inputs						from M-X		from M-X				
Primary Resources	1	Bauxite	kg									kg
	2	Clay	kg									kg
	3	Gravel (in ground)	kg	1.04E+00	2.97E+00							2.97E+00 kg
	4	Gypsum (resource)	kg									kg
	5	Iron Ore (resource)	kg									kg
	6	Limestone	kg									kg
	7	Sand	kg									kg
	8	Water	kg	1.38E+00	3.94E+00							3.94E+00 kg
	9	Wood	kg									kg
Energy	10	Coal Energy	MJ							6.15E-01	4.78E-03	4.78E-03 MJ
	11	Diesel Fuel Energy	MJ			9.53E-01	1.23E-01	8.00E-01	7.65E-03			1.30E-01 MJ
	12	Natural Gas Energy	MJ							7.60E-01	5.91E-03	5.91E-03 MJ
	13	Oil Energy	MJ							5.79E-01	4.50E-03	4.50E-03 MJ
	14	Other Energy	MJ							1.63E+00	1.27E-02	1.27E-02 MJ

Total Energy Input	1.58E-01 MJ
Total Nat'l Resource Input	6.91E+00 kg

APPENDIX C-1. TRANSPORTATION ASSET INVENTORY

Matrix X - TRANSPORTATION ASSETS

This matrix includes outputs for each type of transportation asset.
It is based on data received from the EcoInvent Reports.

Assumptions:

		Processes		**16T Truck Transportation**		**28T Truck Transportation**		**40T Truck Transportation**		**Rail Transportation**		**Barge Transport**		**Cargo Ship Transport**	
			source	EcoInvent Report #14 pg42		EcoInvent Report #14 pg42		EcoInvent Report #14 pg42		EcoInvent Report #14 pg113		EcoInvent Database		EcoInvnet Database	
Economic Output			unit:	tkm		tkm		tkm		tkm		tkm		tkm	
		Transport Operation		8	1	14	1	20	1	1	1	1	1	1	1
Economic Inputs															
		Diesel	kg	2.11E-01	2.64E-02	2.90E-01	2.07E-02	3.48E-01	1.74E-02	1.07E-02	1.07E-02				
Environmental Outputs															
Emissions	1	CO2	kg	6.76E-01	8.45E-02	9.27E-01	6.62E-02	1.12E+00	5.60E-02	3.38E-02	3.38E-02	1.80E-04	1.80E-04	4.65E-05	4.65E-05
	2	CO	kg	1.47E-03	1.84E-04	1.37E-03	9.79E-05	1.27E-03	6.35E-05	1.73E-04	1.73E-04	3.25E-06	3.25E-06	8.39E-07	8.39E-07
	3	NOx	kg	6.50E-03	8.13E-04	9.05E-03	6.46E-04	1.02E-02	5.10E-04	5.92E-04	5.92E-04	4.02E-06	4.02E-06	1.05E-06	1.05E-06
	4	SO2	kg	1.31E-04	1.64E-05	1.80E-04	1.29E-05	2.16E-04	1.08E-05	6.58E-06	6.58E-06	1.48E-07	1.48E-07	3.80E-08	3.80E-08
	5	Methane	kg	2.58E-05	3.23E-06	2.25E-05	1.61E-06	2.08E-05	1.04E-06	1.41E-06	1.41E-06	2.08E-08	2.08E-08	5.15E-09	5.15E-09
	6	Hydrocarbons	kg	5.91E-08	7.39E-09	8.12E-08	5.80E-09	9.75E-08	4.88E-09	3.17E-09	3.17E-09	2.80E-09	2.80E-09	7.24E-10	7.24E-10
	7	Dust	kg												
	8	Particulates	kg	9.32E-04	1.17E-04	9.56E-04	6.83E-05	9.08E-04	4.54E-05	8.76E-05	8.76E-05	5.03E-07	5.03E-07	1.31E-07	1.31E-07
	9	Mercury	kg	1.87E-09	2.34E-10	2.56E-09	1.83E-10	3.08E-09	1.54E-10	9.97E-11	9.97E-11	8.77E-11	8.77E-11	2.27E-11	2.27E-11
	10	Lead	kg	2.84E-08	3.55E-09	3.12E-08	2.23E-09	3.32E-08	1.66E-09	3.84E-10	3.84E-10	3.38E-10	3.38E-10	8.62E-11	8.62E-11
	11	Cadmium	kg	5.91E-09	7.39E-10	6.54E-09	4.67E-10	7.02E-09	3.51E-10	1.11E-10	1.11E-10	3.53E-12	3.53E-12	9.11E-13	9.11E-13
	12	Copper	kg	3.38E-07	4.23E-08	4.40E-07	3.14E-08	5.15E-07	2.58E-08	1.83E-08	1.83E-08	8.86E-11	8.86E-11	2.31E-11	2.31E-11
	13	Chromium	kg	4.82E-08	6.03E-09	5.20E-08	3.71E-09	5.49E-08	2.75E-09	6.48E-10	6.48E-10	1.01E-10	1.01E-10	2.61E-11	2.61E-11
	14	Nickel	kg	4.63E-08	5.79E-09	5.10E-08	3.64E-09	5.44E-08	2.72E-09	8.11E-10	8.11E-10	5.68E-11	5.68E-11	1.47E-11	1.47E-11
	15	Zinc	kg	1.34E-06	1.68E-07	8.34E-07	5.96E-08	6.54E-07	3.27E-08	1.18E-08	1.18E-08	9.94E-10	9.94E-10	2.56E-10	2.56E-10
	16	Dioxins	kg	1.29E-11	1.61E-12	1.78E-11	1.27E-12	2.13E-11	1.07E-12	6.93E-13	6.93E-13	6.11E-13	6.11E-13	1.58E-13	1.58E-13
Waste	17	Waste heat	MJ	9.83E+00	1.23E+00	1.35E+01	9.64E-01	1.62E+01	8.10E-01	4.92E-01	4.92E-01	4.08E-01	4.08E-01	1.02E-01	1.02E-01
	18	Waste (landfill)	kg												
	19	Waste (recycle)	kg												
	20	Waste (incinerator)	kg												
Environmental Inputs															
Resource Depletion	1	Bauxite	kg												
	2	Clay	kg												
	3	Gravel (in ground)	kg												
	4	Gypsum (resource)	kg												
	5	Iron Ore (resource)	kg												
	6	Limestone	kg												
	7	Bentonite	kg												
	8	Water	kg												
	9	Wood	kg												
Energy	10	Coal Energy	MJ												
	11	Diesel Energy	MJ	9.71E+00	1.21E+00	1.33E+01	9.53E-01	1.60E+01	8.00E-01	4.92E-01	4.92E-01				
	12	Natural Gas Energy	MJ												
	13	Oil Energy	MJ												
	14	Other Energy	MJ												

APPENDIX D-1. CHARACTERIZATION MATRIX (CONCRETE)

		Inventory Amounts from M-C	Equivalency Factors[1]			Weighted Results		
			GWP	AP	HT	GWP	AP	HT
Emissions to Air	Carbon Dioxide (CO_2) kg	1.64E+06	1.0			1.64E+06		
	Carbon Monoxide (CO) kg	2.19E+03			0.012			2.63E+01
	Nitrogen Oxide (NO_x) kg	5.96E+03		0.700	0.780		4.17E+03	4.65E+03
	Sulphur Dioxide (SO_2) kg	2.44E+03		1.0	1.2		2.44E+03	2.93E+03
	Methane (CH_4) kg	1.51E+01	11.0			1.66E+02		
	Hydro Carbons (C_xH_y) kg	3.43E+02						
	Mercury (Hg) kg	7.63E-01			120.0			9.16E+01
	Lead (Pb) kg	6.99E-01			160.0			1.12E+02
	Cadmium (Cd) kg	2.16E-02			580.0			1.26E+01
	Chromium (Cr) kg	5.22E-01			4.7E-04			2.46E-04
							TOTALS	
						1.64E+06	6.62E+03	7.83E+03

APPENDIX E-1. CHARACTERIZATION MATRIX (STEEL)

		Inventory Amounts from M-C	Equivalency Factors[1]			Weighted Results		
			GWP	AP	HT	GWP	AP	HT
Emissions to Air	Carbon Dioxide (CO_2) kg	1.24E+06	1.0			1.24E+06		
	Carbon Monoxide (CO) kg	3.30E+03			0.012			3.96E+01
	Nitrogen Oxide (NO_x) kg	6.15E+03		0.700	0.780		4.31E+03	4.80E+03
	Sulphur Dioxide (SO_2) kg	2.40E+03		1.0	1.2		2.40E+03	2.88E+03
	Methane (CH_4) kg	8.26E+00	11.0			9.09E+01		
	Hydro Carbons (C_xH_y) kg	5.53E+02						
	Mercury (Hg) kg	1.15E+01			120.0			1.37E+03
	Lead (Pb) kg	1.16E+00			160.0			1.86E+02
	Cadmium (Cd) kg	2.45E-02			580.0			1.42E+01
	Chromium (Cr) kg	9.23E-01			4.7E-04			4.34E-04
							TOTALS	
						1.24E+06	6.70E+03	9.29E+03