A HYBRID LIFE CYCLE ASSESSMENT MODEL
FOR
CONSTRUCTION PROCESSES

by

Melissa M. Bilec

Bachelor of Science, University of Pittsburgh, 1998

Master of Science, University of Pittsburgh, 1999

Submitted to the Graduate Faculty of

the School of Engineering in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2007

UNIVERSITY OF PITTSBURGH

SCHOOL OF ENGINEERING

This dissertation was presented

by

Melissa M. Bilec

It was defended on

May 14, 2007

and approved by

H. Scott Matthews, Ph.D., Associate Professor, Department of Civil and Environmental Engineering/Engineering and Public Policy, Carnegie Mellon University

Kim LaScola Needy, Ph.D., Associate Professor, Departmental of Industrial Engineering

Ronald Neufeld, Ph.D., Professor, Department of Civil and Environmental Engineering

John Oyler, Ph.D., Adjunct Professor, Department of Civil and Environmental Engineering

Dissertation Director: Robert J. Ries, Assistant Professor, Department of Civil and Environmental Engineering

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Melissa M. Bilec, PhD

University of Pittsburgh, 2007

This research qualitatively and quantitatively examined the environmental impacts due to the construction phase of commercial buildings. Previous building research often overlooked the construction phase and focused on the material and use phases, discounting the significant environmental impacts due to construction. The research was conducted using life cycle assessment (LCA) methodology, which is a systematic environmental management tool that analyzes and assesses holistically the environmental impacts of a product or process. This research contributed to further developing LCA research by focusing efforts on hybrid LCA modeling. The context of this research was established through examining green building rating systems, policy review, and project delivery methods with respect to the modeled results.

Documented life cycle inventory results focused on PM emissions, GWP, SO_x, NO_x, CO, Pb, non-methane VOCs, energy usage, and solid and liquid wastes. Results compared with the entire building life cycle indicated that construction, while not as significant as the use phase, is as important as the other life cycle stages.

In terms of hybrid LCA modeling, the augmented process based LCA proved to be effective in modeling the construction phase and allowed for efficiently combining process and input-output inventories. Including input-output results, especially construction service sectors, is critical in construction LCA modeling. One case study's results demonstrated that services had the highest level of methane emissions and were a significant contributor to CO_2 emissions.

Recommendations are made in terms of green building rating systems and national policies, including placing higher significance on construction activities within the United States Green Building Council's Leadership in Energy and Environmental Design (LEED) green building rating system.

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PREFACE

Completing my doctoral degree is a life-long personal goal, and I wish to thank several instrumental people who have helped and guided me on this fulfilling journey.

First, I want to thank my doctoral committee of Dr. Neufeld, Dr. Oyler, Dr. Needy, Dr. Matthews, and Dr. Ries. Dr. Neufeld's insightful overall vision of a doctoral degree helped to frame and focus the research to truly contribute to the profession. Dr. Oyler, my Master's advisor, has given me a deep appreciation for teaching and the importance of history and heritage in Civil Engineering. His inspiration gave me the fortitude to drive the design and construction of the Hot Metal Pedestrian Bridge. I am thankful that I was able to be one of his students, and I am grateful for his wonderful wisdom. For over three years, I had the pleasure to work on a focused and interesting research team with Dr. Needy. Dr. Needy has been a true mentor and has helped me to understand and enjoy conducting research. Since she is a mentor and friend, I wish to express my sincere thanks for her advice in life and work, and finding the balance between the two. Before I started the doctoral program at the University of Pittsburgh, I met with Dr. Matthews, and our meeting truly exemplifies that "timing is everything." One of my best memories of this journey is our scenic, non-stop talking trip to Washington, D.C with Dr. Matthews. Since this research is a joint research effort between University of Pittsburgh and Carnegie Mellon University, Dr. Matthews has served as a key committee member and was the first person that taught me about LCA. I am grateful to have learned from him, and he has helped me to see the broader picture in my research and career. I am truly appreciative for all his kindness, knowledge, and conversation.

My sincere appreciation and deep gratitude is extended to my advisor, Dr. Robert Ries. Dr. Ries has given me steady and continued support. His unwavering commitment to creating a more sustainable society has been inspiring. In his insightful ways, he has helped me with this research both in terms of breadth and depth.

To my CMU research colleague, Aurora Sharrard, I wish to thank her for making this journey more delightful. I wish to thank her for being a friend and a person who always amazes me.

This research could not have been completed without the support of my family and friends, Dani, Sharon, Jen M., Janice, Jen J., Renee, Allison, and Michael. As a new parent, I truly appreciate the wisdom and support when I told my Dad that I wanted to be an engineer, and he fully supported my decision. I thank my Dad for his support, reminders to enjoy life, and great sense of humor.

To my husband, Doug, I thank him for his unwavering support and love, including help during many weekends, and faith in me to pursue this degree.

To my daughter, Isabella, I thank her for being an active baby and toddler, making me laugh, and inspiring me. My hope is that this degree can show you that “dreams that you dare to dream, really do come true.”

Finally, I dedicate this dissertation to my mom who has shown me unconditional support and love. In many ways, this degree is for both of us.

GLOSSARY

AEC:	Architectural, engineering, and construction
AF:	Amplification Factor
AGC:	Association of General Contractors of America
AHP:	Analytical Hierarchy Process
ANP:	Analytical Network Process
ANSI:	American National Standards Institute
BCY:	Bank Cubic Yards
BEES:	Building for Environmental and Economic Sustainability
BMP:	Best Management Practices
CAA:	Clean Air Act
CCY:	Compacted Cubic Yards
CEDST:	Construction Environmental Decision Support Tool
CF:	Characterization Factor
CFC:	Chlorofluorocarbons
CGP:	Construction General Permit
CH_4:	Methane
CM:	Construction Management
CM:	Construction Management at Risk
CNG:	Compressed Natural Gas
Co:	Cobalt
CO:	Carbon Monoxide
CO_2:	Carbon Dioxide
CO_2E:	Carbon Dioxide Equivalent
Cr:	Chromium

CREST:	Center for Renewable Energy and Sustainable Technology
CSF:	Critical Success Factors
CWA:	Clean Water Act
CY:	Cubic yards
DALYs:	Daily adjusted life years
DBB:	Design-Build
DBB:	Design-Bid-Build
DF:	Damage Factor
DOC:	United States Department of Commerce
DOCs:	Diesel Oxidation Catalysts
DOE:	United States Department of Energy
EF:	Emission Factors
EIO-LCA:	Economic Input-Output Life Cycle Assessment
EPA:	United States Environmental Protection Agency
ESA:	Endangered Species Acts
ESC:	Erosion and Sedimentation Control Plan
EUSES:	European Uniform System for the Evaluation of Substances
FCAW:	Flux Cored Arc Welding
FEL:	Front end-loader
GJ:	Gigajoule
GMAW:	Gas Metal Arc Welding
GMP:	Guaranteed Maximum Price
GSA:	United States General Services Administration
GWP:	Global Warming Potential
HAP:	Hazardous Air Pollutant
HC:	Hydrocarbons
HCFCs:	Hydrochlorofluorocarbons
hp:	horsepower
HTP:	Human Toxicity Potential
HU:	Hazard Units
IARC:	International Agency for Research on Cancer

IAQ:	Indoor Air Quality
IEQ:	Indoor Environmental Quality
I-O:	Input-Output
IRIS:	Integrated Risk Information Systems
ISO:	International Organization for Standardization
kg:	Kilogram
kWh:	Kilowatt Hours
LCA:	Life cycle assessment
LCI:	Life cycle inventory
LCIA:	Life cycle impact assessment
LCY:	Loose Cubic Yards
LBNL:	Lawrence Berkeley National Laboratory
LPG:	Liquefied Petroleum Gas
MAUT:	Multi-Attribute Utility Theory
MCDA:	Multi-Criteria Decision Analysis
Mg:	Manganese
MJ:	Megajoule
MWh:	Megawatt hours
NAAQS:	National Ambient Air Quality Standards
NEPA:	National Environmental Policy Act
NH_3:	Ammonia
Ni:	Nickel
NIOSH:	National Institute for Occupational Safety and Health
NMHC:	Non-Methane Hydrocarbons
NMOG:	Non-Methane Organic Gas
NMVOC:	Non-methane Volatile Organic Carbon
N_2O:	Nitrous Oxide
NOEC:	No Observed Effect Concentration
NO_x:	Nitrogen oxides
NPDES:	National Pollution Discharge Elimination System
ODP:	Ozone Depletion Potential

OSHA:	Occupational Safety and Health Administration
P2:	Pollution Prevention
PAF:	Potentially Affected Fraction
Pb:	Lead
PDF:	Potential Disappearance Factor
PDM:	Project Delivery Method
PM:	Particulate matter
$PM_{2.5}$:	Particulate matter with aerodynamic diameter of less than 2.5 micrometers
PM_{10}:	Particulate matter with aerodynamic diameter of less than 10 micrometers
PM_{15}:	Particulate matter with aerodynamic diameter of less than 15 micrometers
PM_{30}:	Particulate matter with aerodynamic diameter of less than 30 micrometers
PSR:	Power Systems Research
RCRA:	Resource Conservation and Recovery Act
RFP:	Request for Proposal
SAW:	Submerged Arc Welding
SCC:	Source Classification Codes
SF:	Square Feet
SMAW:	Shield Metal Arc Welding
SO_x:	Sulfur dioxides
THC:	Total Hydrocarbons
TOG:	Total Organic Gases
TRI:	Toxic release inventory
USGBC:	United States Green Building Council
UR:	Unit risk
VLF:	Vertical linear feet
VKT:	Vehicle Kilometers Traveled
VOC:	Volatile organic compound
YLD:	Years lived disabled
YLL:	Years of life lost

1.0 INTRODUCTION

This research focused on qualitatively and quantitatively understanding the environmental impacts of primarily on-site construction processes for buildings. Building research has focused on other phases of a building's life cycle. The on-site construction phase is often overlooked when the entire life cycle is considered, leading to a gap in understanding the whole spectrum and possible sources of environmental impacts on the built environment. Additionally, the impacts associated with design and related service sectors are also often excluded and were investigated as a part of this research.

The research used life cycle assessment (LCA) methodology. LCA is a systematic environmental management tool that holistically analyzes and assesses the environmental impacts of a product or process. LCA is a decision-making tool that inherently promotes stewardship by considering global, national, and regional impacts on social and environmental problems like human health, resource depletion, and ecosystem quality.

This research was comprised of three main components: modeling construction processes and associated construction service sectors, hybrid life cycle assessment (LCA), and policy review and recommendations to develop contextual importance. First, construction processes for commercial buildings were investigated and relevant processes were modeled with the required output for the next stage. Then, hybrid LCA methodology for construction was developed to quantify the environmental impacts from the first stage. A large portion of this research developed a deeper understanding of hybrid LCA modeling, and will provide recommendations beyond construction. Third, the context of this research was established through examining the construction industry and results with respect to green building rating systems, policy implications, and project delivery systems. While this research focused on commercial buildings in the United States, the framework can be extended to other projects.

1.1 MOTIVATION

The built environment contributes significantly to environmental impacts regionally, nationally, and globally. The built environment consists of anything manmade such as public and private infrastructure, residential single and multifamily homes, manufacturing and industrial buildings, and commercial buildings. While all of the components of the built environment contribute to environmental impacts, this research focused on the construction of commercial buildings. On a global scale, buildings account for 16% of the world's freshwater usage, 25% of its wood harvest, and 40% of its material and energy flows; nearly 25% of all ozone-depleting chlorofluorocarbons (CFC) are emitted by building air conditioners and processes to manufacture building materials (1998). In the United States, buildings use 70% of total electricity (U.S. Energy Information Administration 2001a), require over 39% of primary energy (U.S. Energy Information Administration 2001b), emit 39% of the greenhouse gas emissions (U.S. Energy Information Administration 2005), contribute 136 million tons of construction and demolition waste (U.S. Environmental Protection Agency 1998), consume 11% of the potable water (U.S. Geological Survey 2000), and use 40% of raw materials globally (U.S. Green Building Council 2004).

There are 223,114 establishments/businesses in the building industry. These businesses represent more than $531 billion in annual revenues and nearly $62 billion in annual payroll with more than 1.7 million employees in 2002 (U.S. Census Bureau 2002). In 1999, there were approximately 4.6 million buildings, with an additional 15 million projected by the year 2010 in the U.S. (Augenbroe et al. 1998; U.S. Department of Energy 1999).

All phases of a building's life cycle (Figure 1) – design, raw material extraction and processing, manufacturing, construction, use and maintenance, and deconstruction – contribute to environmental impacts and energy use. A fair amount of research has focused on the material phase and the associated impacts from extraction and manufacturing. The development of green materials research has resulted in certification programs and databases, some U.S. examples include:

- Building for Environmental and Economic Sustainability (BEES), a windows-based decision support software tool analyzing environmental and economic performance for some building products.

- Green Building Products and Materials Resource Directory, which provides an on-line listing of environmentally-friendly and energy and resource efficient building materials; and the Green Building Resource Guide, providing information on green building materials and products.
- Environmental Buildings News Product Catalog helps architects, designers, and builders identify green building products.
- Used Building Materials Association listing the companies and organizations that are interested in acquiring or redistributing used building materials (Augenbroe et al. 1998).

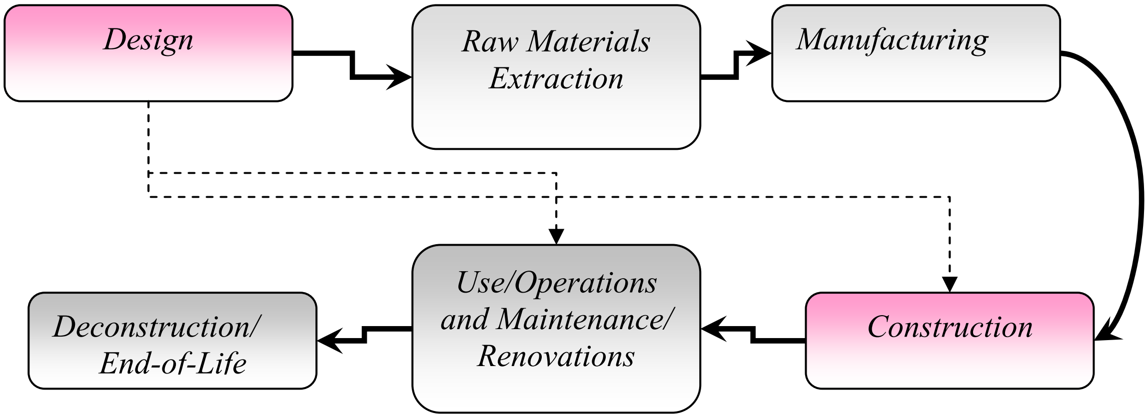


Figure 1. Building Life Cycle

Building research has also focused on the use phase, which is justifiable because most energy is consumed in the use phase (Keoleian et al. 2001). Some initiatives in the U.S. to reduce energy consumption and increase efficiency include:

- Energy Star, a government supported program aimed at supporting businesses and individuals with energy efficient solutions (Energy Star 2005).
- Buildings for the 21st Century, an effort by the U.S. Department of Energy (DOE), Office of Building Technology, State, and Community programs to increase the energy efficiency of new homes by 50%, existing homes by 20%, and existing commercial buildings by 20% by the year 2010.
- U.S. Environmental Protection Agency's (EPA) Pollution Prevention (P2) program to help manufacturers optimize their production processes and reduce pollution.
- National research and development programs such as the U.S. DOE's, Center for Renewable Energy and Sustainable Technology (CREST) program, National Renewable Energy program, and Construction Industry's Research Prospectuses for the 21st century (Augenbroe et al. 1998).

Other research has looked at end-of-life options for commercial buildings (Guggemos and Horvath 2003). In summary, research has examined raw materials extraction, manufacturing, use, and deconstruction; however, a relatively small amount of research has focused on the construction phase and associated support services, such as design. If one is to understand the entire life cycle of a building, then a detailed assessment of all the phases should be considered and quantified, including construction and design. Some existing research on the construction phase has assumed the impacts are negligible (Junnila and Horvath 2003), while others have indicated that the environmental impacts associated with construction are underestimated (Hendrickson and Horvath 2000).

This research focuses on construction and support sectors. Quantification of environmental impacts can be difficult because construction data can be inaccurate: widespread reliable data does not exist because the construction industry does not consistently report emissions or wastes to the U.S. EPA. The number and variety of contracts, namely subcontracts, typical in any project in construction industry makes available public and survey data unreliable.

One environmental management tool used to assess the life cycle of buildings is life cycle assessment (LCA), a framework that holistically evaluates the environmental effects of a product or process by analyzing the entire life cycle of that particular product or activity. LCA was used in this research to quantify the environmental impacts of the construction phase along with associated support sectors. Many LCAs utilize either the process-based (Keoleian et al. 2001) or input-output techniques (Ochoa et al. 2002). This research examined and developed hybrid LCA modeling for construction, which attempts to combine the strengths of both techniques.

1.2 RESEARCH PROBLEM STATEMENT

This research focused on two significant areas in the environmental impact for construction processes through the development and use of hybrid LCA methodology. The model specifically focuses on commercial construction in the United States. First, since a limited amount of research has focused on the environmental effects of the construction phase; this research filled a gap in the existing knowledge of the building life cycle. Quantification of the construction phase allowed for a complete understanding of the building life cycle. With this knowledge, key aspects in all of the phases are better understood and can be targeted for reductions in environmental impacts and energy usage. Even if the environmental impacts from construction are small compared to other phases, these impacts may be large when looked at in a specific time frame and place. Identification of key environmental impacts of construction can be considered by policymakers and organizations like the United States Green Building Council (USGBC) in their green building rating system, Leadership in Energy and Environmental Design (LEED) and the U.S. EPA.

Second, LCA development continues to evolve, and a key aspect to LCA's evolution is developing hybrid modeling techniques. This research contributed to understanding the continuum of hybrid LCA techniques and made specific recommendations for hybrid LCA modeling for construction that has general applications beyond construction.

After developing the hybrid model to quantify the environmental effects of construction processes, the relevance of the research to the architectural, engineering, and construction (AEC) industry was explored through examining project management delivery options, existing and proposed legislative actions, national initiatives, and existing building rating systems.

1.3 RESEARCH QUESTIONS

The following research questions were investigated:

1. Construction: Focusing on commercial core and shell construction in the United States, with LCA as the framework, what is the life cycle inventory and life cycle impact assessment of the construction processes of a commercial building, and with existing data how does this information compare with the entire building life cycle?

2. Hybrid LCA modeling: How are input-output and process LCAs best combined in modeling construction processes? How is a construction hybrid LCA structured? With the determined recommendations for construction processes, how can this information be used for future hybrid LCAs?

3. Context: What guidelines can be offered to existing green building rating systems? What new or revised national legislative and initiatives are suggested? What project management delivery systems best complement sustainable design projects?

1.4 CONTEXT

The context of this research was framed in three distinct areas: (1) green building rating systems, (2) policy implications, and (3) project delivery systems. The first component examined how the construction phase was treated in existing green building rating systems, looking specifically at LEED. The discussion provided possible improvements to the rating systems. For example, LEED products have a four-level classification system of Certified (26 to 32 points), Silver (33 to 38 points), Gold (39 to 51 points), and Platinum (52 to 69 points) related to different point totals. Points are achieved by fulfilling a variety of mandatory and credit opportunities. The points are unequally distributed between six categories: Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, and Innovation and Design. The applicable credits related to construction processes were determined. Of the 69 total points, 13 points directly relate to construction processes and construction workers, representing almost 20% of the total points not including two categories that are required. An evaluation of these credits was performed with recommendations of adding categories. One suggestion was to decrease the radius of locally purchased products because transportation is a significant contributor to environmental issues.

Second, a review of major federal legislation and national initiatives for construction was examined to provide suggestions in conjunction with the outcomes from the model. For example, the U.S. government attempted to regulate on-site construction activities by implementing regulations related to new nonroad diesel emission standards, such as construction equipment, as one part of its Clean Diesel Programs. The new engine standards reduce the amount of particulate matter (PM) and nitrogen oxides (NO_x). Although the comprehensive rule was finalized in 2004, these tiered regulations first came into effect in 1994 as Tier 1 for all new nonroad diesel engines greater than 37 kW (50 hp) and were phased in for different engine sizes between 1996 to 2000. In 1998, the U.S. EPA adopted Tier 2 and 3 emission standards for NO_x, hydrocarbons (HC), and PM for new nonroad diesel engines and phases in more stringent standards given engine sizes and timing. The May 2004 emission standards complement the existing program and include reducing emissions from sulfur used in diesel fuel for nonroad equipment (U.S. Environmental Protection Agency 2004c).

Third, since ultimately this research was related to green design and construction, a qualitative discussion regarding project delivery systems and the relationship with green buildings was conducted and provided. The discussion was centered on research done in conjunction with an independent project, funded through the Lawrence Berkeley National Laboratory (LBNL), which investigated the relationship between green design and project delivery methods for public sector projects.

1.5 CONTRIBUTION

The research contribution exists in parallel with the two major research questions related to the construction phase of a building's life cycle and hybrid LCA modeling. In the design and construction sectors, awareness of sustainability and green design are increasingly prevalent. However, the amount of research on the construction phase is lacking when compared with the other building phases, particularly materials and use. This research fills an existing gap of a building life cycle. Often, when a building's life span is considered, say 50 years, the impacts of the construction phase may be considered to be less important relative to operations and maintenance. Since construction represents a significant portion of the U.S. economy, approximately 5% of the gross domestic product (GDP) (U.S. Bureau of Economic Analysis 2005), opportunities exist to examine the construction phase and identify areas where a reduction in environmental impacts could occur. Further exploring the construction phase can allow decision makers to better understand and more significantly consider this phase. Ultimately, the outcomes from this research can be used by other researchers, tool developers, and the AEC community to improve the characterization of the building construction phase.

LCA is an important technique to determine and measure the environmental performance of a product or process; however, LCA has been faulted for being expensive, time-consuming, and not scientific (Arnold 1993; Curran 1996; Portney 1993-1994). Contributing to the development of hybrid modeling is an essential component to the development of LCA to address these limitations. While this research focuses on construction, the research contribution in hybrid modeling are applicable to LCA modeling in general.

2.0 BACKGROUND AND LITERATURE REVIEW

A limited number of studies have been published on LCA and commercial buildings. Few of these studies comprehensively considered on-site construction processes. Some studies stated construction was included; however, the definition of construction included various stages of material extraction, production, and transportation and not on-site construction processes (Horvath and Hendrickson 1998; Treloar et al. 2004; Treloar et al. 2000). As such, this background section first presents an overview of construction and the environment as discussed by Ofori (1992). A brief overview of LCA is discussed followed by published LCA studies of buildings and construction. Because limited research is available for commercial building construction, some residential and infrastructure case studies are discussed to develop a perspective of construction activities within the entire life cycle of a building. Three LCA techniques are summarized, including an analysis of respective strengths and weaknesses.

2.1 OVERVIEW

Ofori (1992) first presented a broad historical and evolutionary perspective on environmental issues, and then focused on building and construction and the relationship with key environmental aspects. In Europe, environmental protests led to the abandonment of different stages of construction. For example, the Nagymaros dam in Hungary was cancelled, along with the construction of a barrage across the Danube. In the (then) West Germany, the construction industry developed a campaign against the country's influential environmentalist lobby who called for a stop on all new construction because this group believed that the country had 'enough' constructed items. Ofori believed some of the major environmental issues related to construction include: (1) resource deterioration including energy use in production, transportation, and on-site construction activity; (2) physical disruption such as the loss of fauna and flora along with possible health hazards of a disturbed ecosystem; and (3) chemical pollution from the production and transportation of building materials, asbestos fibers released during construction or demolition, accidental spills on the construction site, and the unlawful or unregulated disposal of construction waste. Other environmental impacts are social and visual impacts from temporary construction, uncompleted buildings, and disorganized sites. A more direct environmental impact of construction activity is the exposure of workers. For example, it is estimated that some 50,000 people in the UK and 2,000,000 in the U.S. will die from diseases related to asbestos in a 30-year period. Another example is the exposure of workers to paints containing first lead and then benzene and formaldehyde.

Ofori concluded that possible solutions and responses of the construction industry are the recycling of construction materials such as glass or recycled asphalt; using construction equipment that is more productive along with reduced fumes, dust, vibrations, and noise; efficiently using recycled materials; and minimizing transportation and storage methods that limit pollution.

2.2 LCA, CONSTRUCTION, AND THE ENVIRONMENT

2.2.1 LIFE CYCLE ASSESSMENT BACKGROUND

Life cycle assessment (LCA) is a systematic approach to analyze and assess the environmental impacts of a product or process over its entire life cycle. A typical LCA includes the major stages of raw material extraction, manufacturing, construction, use, and end-of-life scenarios for a product or process. Guidelines for performing an LCA are delineated by the American National Standards Institute (ANSI) and International Organization of Standardization's (ISO) 14040 series (American National Standards Institute/International Organization for Standardization (ANSI/ISO) 1997). The ISO 9000 series, which focuses on quality management, is widely recognized and used. The ISO 14040 series is a part of the ISO 14000 collection covering environmental management standards. Combined, ISO 9000 and 14000 are used by over 634,000 organizations and 152 countries (International Organization for

Standardization 2004). The ISO 14000 series model includes the stages of “Plan,” “Do,” “Act,” and “Check” with different ISO series representing multiple categories. The series in ISO’s model are: design for the environment (ISO 14062), environmental labels and declarations (ISO 14020), environmental communication (ISO 14063), environmental performance (ISO 14030), environmental management and auditing systems (ISO 19011), and LCA (ISO 14040) (International Organization for Standardization 2002).

Many European countries are using LCA to create policy regulations in areas such as eco-labeling and product take-back. In the United States, the federal government has recommended using LCA to help determine procurement strategies for environmentally preferred products and services (Executive Order 1998).

As defined by the ISO 14040 series, LCA is an iterative four-step process including goal and scope definitions, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation. The LCI step is often where the LCA studies terminate due to framework, development, and subjectivity inconsistencies in the LCIA stage.

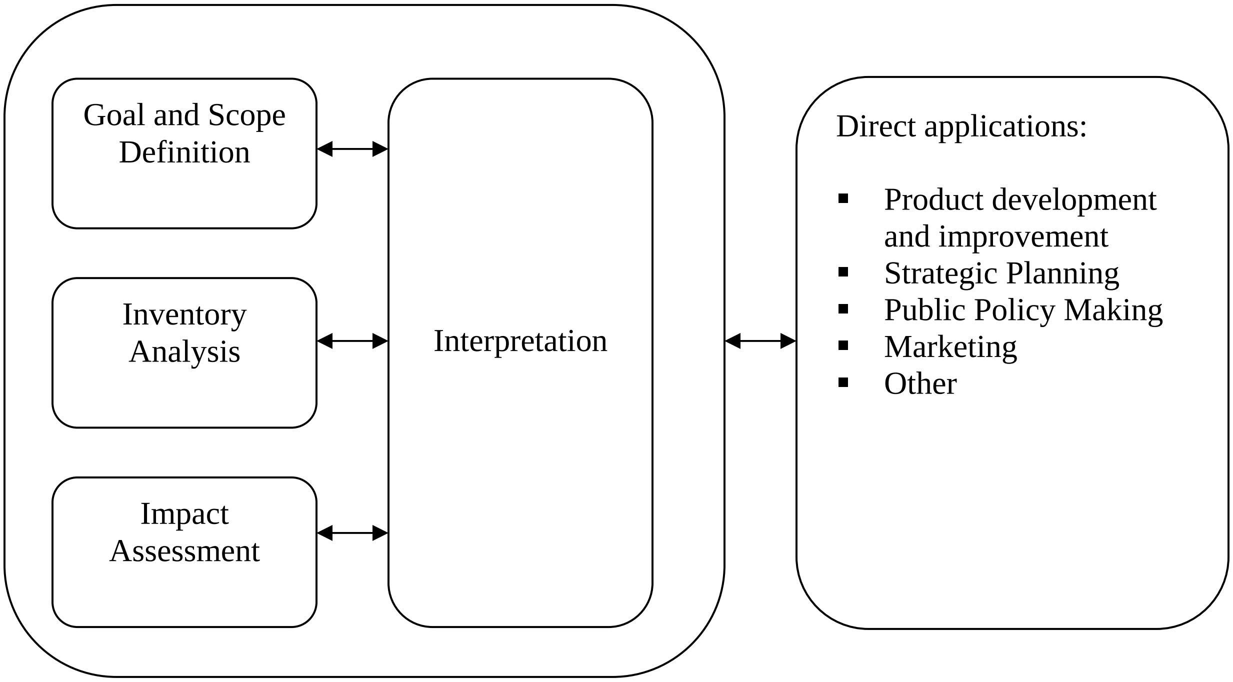


Figure 2. Phases of an LCA (ANSI/ISO 1997)

2.3 LCA LITERATURE REVIEW

Junnila and Horvath (2003) examined a 15,600 m^2 (gross floor area) cast-in-place concrete commercial building located in Finland. The building's life cycle was divided into five main phases of building materials manufacturing, construction processes, use, maintenance, and demolition. The environmental aspects examined were climate change in CO_2 equivalents, acidification in SO_2 equivalents, summer smog in H_2C_4 equivalents, eutrophication in PO_4 equivalents, and heavy metals in Pb equivalents. The construction activities included all materials and energy used in on-site activities including use of electricity, heat, steam, equipment use, transportation of building materials to the site, temporary materials used on site, waste management, and water use. The total materials and energy flows for the construction phase only were 1,100 MWh for electricity and heat; 110,000 kg fuels; 290,000 kg building materials; 3,000 m^3 water; 194,000 kg; and 100,000 kg land filled materials. The two most significant environmental impacts for construction were from the use of construction equipment and temporary materials, contributing about 75% of the impacts. Table 1 shows the reported environmental impacts from Junnila and Horvath's case study. Transportation of materials was relatively small due to the location of the concrete plant, and concrete was responsible for 65% of the total weight of the transported materials. Overall, the construction and demolition were found to have a relatively small contribution to the entire building's life cycle, assumed to be 50 years, with the most significant impacts associated with electricity use and building materials manufacturing.

Keoleian et al. (2001) analyzed a residential house with a life cycle description of pre-use (materials production and construction), use (including maintenance and improvement), and demolition; the study quantifies mass, primary life-cycle energy consumption with the associated greenhouse gases, and the related costs for construction and use over a 50-year time period for both standard and energy efficient homes. Although the authors state that the construction phase included foundation and site earthwork, concrete pouring, structural framing, roofing and siding installation, mechanical and electrical installation, painting and cleanup, the authors only included transportation from the supplier to the jobsite.

Table 1. Environmental Impacts Construction of Office Building (Junnila and Horvath 2003)

Construction	Climate Change (ton CO_2 equiv.)	Acid-ification (kg SO_2 equiv.)	Summer smog (kg H_2C_4 equiv.)	Eutro-phication (kg PO_4 equiv.)	Heavy metals (kg PB equiv.)
Equipment	360	3,200	360	520	0
Electricity	170	570	13	48	0.08
Materials in construction	160	1,600	140	140	0.24
Heat	82	210	4	19	0.01
Transportation of building materials	32	270	11	50	0
Steam	15	25	0.4	4	0
Construction waste, transportation and landfill	2	17	4	3	0
Water	1	4	2	180	0

Hendrickson and Horvath estimated the resources, energy usage, emissions, and wastes from the U.S. construction industry along with identifying the major economic commodity sectors from direct and indirect perspectives. Using 1992 U.S. output data, the authors identified four major sectors representing 6.5% of the U.S. gross domestic product (GDP) in 1992: highway, bridge and other horizontal construction; industrial facilities, commercial and office buildings; residential one-unit buildings; and other construction such as towers, water, sewer, and irrigation systems. Using publicly available U.S economic, environmental, and energy statistical data, the results indicated that the four major U.S. construction sectors used fewer resources, had lower emissions, and emitted less waste than expected when considered in context of the relatively high GDP percentage and nature of the industry. The two exceptions are particulate matter due to dust on construction sites and NO_x emissions from burning fuel (Hendrickson and Horvath 2000).

Ochoa et al. (2002) estimated resources, electricity and energy usage, greenhouse gas emissions, hazardous waste emissions, and toxic air releases for three phases of a typical U.S. residential home. The phases included in the life cycle were construction, usage, and demolition where the construction phase includes raw material acquisition, manufacturing, and transportation to the construction site, but not physical construction at the site.. The construction phase contributed to the highest amount of hazardous waste and toxic air emissions, while the usage phase significantly contributed as the highest phase for electricity consumption, energy usage, and greenhouse gas emissions.

Guggemos and Horvath (2005) present the most comprehensive LCA for construction processes in a comparative case study between steel- and concrete-framed buildings. The comparative LCA examines the energy use and environmental emissions during the construction phase and then presents an overall view of the entire life cycle by examining the service life of a building. Hybrid LCA methodology, using both process-based and input-output approaches, was employed. To perform the process-based construction LCA, flow diagrams were developed along with a Construction Environmental Decision Support Tool (CEDST). CEDST includes the effects of temporary materials, equipment, and transportation. Transportation includes both material and equipment by using three types of trucks: a concrete mixer, small-capacity truck, and a large-capacity truck. Transportation assumptions included distances of materials and equipment, models with years, fuel efficiency, and capacity in order to calculate energy usage and emissions. Temporary materials were quantified using R.S. Means and associated environmental emissions from manufacturing were calculated from EIO-LCA. Equipment usage and type was estimated using R.S. Means and then the power source (diesel or gasoline), power, and associated energy use and emissions were determined. In summary, the concrete structural-frame construction has greater energy use, CO_2, CO, NO_2, particulate matter, SO_2, and hydrocarbon emissions mainly due to a more extensive use of formwork, larger transportation impacts, and more equipment use due to a longer construction phase. Conversely, the steel-frame building construction phase exhibited a greater amount of volatile organic compound emissions (VOCs) and heavy metals because of painting, torch cutting, and welding of steel. When the entire life cycle is considered, the construction phase represented a relatively small part, 0.4 to 11%.

A recent study conducted by Junilla et al. (2006) examined and compared the entire life cycle from material production, construction, use, maintenance, and end-of-life treatment of two office buildings located in Europe, Southern Finland, and the United States' midwest region. Both buildings were assumed to have a fifty year life cycle.

In terms of hybrid modeling and data information, the European building's data was mainly process data and was generally collected from material manufacturers and energy suppliers in Finland. The emissions data does include supply-chain emissions that have been verified by an independent third-party. The paper does not indicate if services have been included. Combined heat and power production was used to supply the building. The building in the United States uses process-based emission data for all life-cycle phases, with the exceptions of materials manufacturing phase, and electricity in all the phases. In parallel with the European building, the material emissions data does include supply-chain emissions estimated using EIO-LCA. Building size information and included life-cycle phases are shown in Table 2.

Table 2. Building Information and Life-Cycle Stages from Junnila et al. 2006

Building Location	Building Area (m^2)	Building Volume (m^3)	Building Frame	Life-Cycle Phases
Europe	4,400	17,300	Steel reinforced concrete beam and column system	All
United States	4,400	16,400	Steel reinforced concrete beam and column system	All

The results from both the European and the United States building case studies show that the use-phase clearly dominates, see Table 3 and Table 4. The construction phase caused fewer emissions than the other phases. The authors note that within the construction and demolition phases the construction equipment produces the most emissions.

Table 3. Energy Usage, CO_2, and SO_2 Emissions in Two Buildings for Each Life Cycle Phase from Junnila et al. 2006

Phase	Europe	United States	Europe	United States	Europe	United States
	Energy		CO_2		SO_2	
	GJ		Mg		kg	
Materials Total	15,000	31,100	1,300	2,000	2,300	9,300
Construction Total	4,800	5,500	200	400	500	800
Use Total	204,000	297,600	11,000	22,200	9,900	82,700
Maintenance Total	9,500	21,600	700	1,300	2,300	5,200
End of Life Total	800	3,300	60	200	50	400
Total	234,100	359,100	13,260	26,100	15,050	98,400

Table 4. NO_x and PM_{10} Emissions for Each Life Cycle Phase (Junnila et al. 2006)

Phase	Europe	United States	Europe	United States
	NO_x		PM_{10}	
	kg		kg	
Materials Total	4,000	8,000	2,100	2,700
Construction Total	1,800	8,300	400	700
Use Total	20,000	48,500	3,700	3,400
Maintenance Total	2,500	5,000	1,100	2,100
End of Life Total	700	5,800	90	400
Total	29,000	75,600	7,390	9,300

In summary, published research on LCA for the construction phase is limited; a consensus on methodology or quantification has not been developed. Furthermore, a comparison between the relevant summaries is difficult because the description of the building life cycle phases is different; for example, Ochoa et al. (2002) includes raw material acquisition, manufacturing, and transportation to the construction site as the construction phase. Conversely, Junnila and Horvath (2003) consider the construction phase to include on-site activities and transportation. Guggemos and Horvath (2005) and Junnila et al. (2006) have the most applicable and developed model for construction of which the published results will be compared with results from this research. A summary of the construction boundaries, or what is and is not included, for Junnila et al. (2006) and Guggemos and Horvath (2005) is shown Figure 3.

Table 5. Construction Boundary from Junnilla et al. 2006 and Guggemos and Horvath 2005

	Junnila, Horvath, Guggemos 2006	Guggemos and Horvath 2005
On-site energy	x	x
Equipment utilization	x	x
Transportation	x	x
Temporary Materials	x	x
Construction Workers		
Construction Services		
Equipment Manufacturing		
Fugitive Dust		

2.4 DIFFERENT APPROACHES TO LIFE CYCLE ASSESSMENT

Three options exist for life cycle assessment, or more specifically, a life cycle inventory, are process, input-output, and hybrid. Process and input-output methods are widely used and have strengths and limitations. Hybrid modeling combines both approaches and addresses the limitations in each approach. The three options are discussed in detail below.

2.4.1 Process Life Cycle Assessment

The process LCA method systematically models the known environmental inputs and outputs by utilizing a process flow diagram. The scope of the process model continues to the point where the flow between process and emissions are negligible. The process approach was further developed with the framework established in the ISO 14040 series. This approach requires data collection from public sources, company or product specific information, and published research. Several organizations developed software and tools to support process based LCAs. Some software programs which mainly use the process framework include SimaPro, GaBi, and Gemis.

2.4.2 Input-Output Life Cycle Assessment

Another LCI method is input-output (I-O) analysis. Economic I-O analysis was developed by Wassily Leontief in the 1930s (Leontief 1936). Leontief developed an interdependency model that quantifies proportional interrelationships among economic sectors in an economy. I-O LCA combines national sector-by-sector economic interaction data, which quantifies the dependencies between sectors, with sector level environmental effects and resource use data. Using matrix operations, a change in economic demand from a sector can be quantified in environmental effects or resource use. The U.S. economy is represented by about 500 sectors (U.S. Department of Commerce 1997). Given the range of economic products, many sectors represent a wide range of product types. I-O LCA considers both direct and indirect impacts. For example, for the purchase of a car, direct impacts would include steel, aluminum, and plastic. Also included, for example, are the indirect impacts from the production of steel as well the entire supply chain of the automobile through the economy. While the U.S. has the largest number of defined sectors and a broad range of publicly available environmental data, other countries, including Japan, Netherlands, and Australia, have developed I-O LCAs (Kondo et al. 1998; Lenzen 1998; Pesonen et al. 2000), using similar techniques to link economic and environmental data. Early work combining I-O data with energy analysis was completed by Bullard et. al (1978).

Carnegie Mellon University has developed an I-O based LCA tool, Economic Input-Output LCA (EIO-LCA) (Hendrickson et al. 1998; Lave et al. 1995). EIO-LCA is a linear model. Data on which EIO-LCA is based includes 1997 commodity/commodity input-output (I-O) matrix developed by the U.S. Department of Commerce (DOC); Census of Manufacturers and I-O work files for electricity use; commodity purchases contained in I-O work files for fuel, ore, and fertilizer use; U.S. EPA’s AIRS conventional pollutant emissions; EPA’s AP-42 emission factors for conventional pollutant emissions (for fuel use); EPA’s toxic release inventory (TRI); the Resource Conservation and Recovery Act (RCRA) for hazardous waste generation, management, and shipment; DOC “Water Use in Manufacturing;” and Occupational Safety and Health Administration (OSHA) data (Green Design Institute 2005).

2.4.3 Hybrid Life Cycle Assessment

Because there are advantages and disadvantages associated with both process and I-O approaches, several researchers have proposed a hybrid approach that combines the strengths of both methods. Advantages and disadvantages are listed in Section 2.4.4.

The following sections describe four types of hybrid models: tiered, input-output based, integrated, and 'augmented process-based.' Although the models are classified into groups, they all combine process and I-O methods and differ primarily in the proportions of input-output and process data. As a whole the models represent a continuum of hybrid model development. Tiered hybrid analysis uses mainly input-output data and augmented process-based uses the largest proportion of process information. Tiered hybrid analysis was developed by Bullard et al. (1978). The model uses input-output analysis iteratively each step, increasing the detail of the model in a process-like framework in order to determine the energy burden of a product system. Input-output analysis is used to determine the energy flows crossing the process system boundary.

In tiered hybrid analysis, the first approximation is at the whole-economy level: the cost of a product is multiplied by the energy intensity per unit gross domestic product (GDP). Increasing levels or tiers of detail can be added by associating parts of the product system to individual I-O sectors, increasing the specificity of the analysis. The disaggregated parts of the product system are categorized as either typical or atypical products of existing I-O sectors. The energy requirements of typical products can be determined directly from the I-O sector and energy use factors. The atypical products require further disaggregation and an iterative input-output approach. (Note that Bullard uses input-output for both typical and atypical products.) An error term determines the appropriate tier based on the uncertainty goals of the analysis. All investigation levels include adjustments for margins of error, budget uncertainty, and energy intensity uncertainty.

Bullard et al. believe this hybrid approach is best suited for large atypical systems such as the energy costs associated with constructing a power plant (Bullard et al. 1978). The authors used available data such as line-item plant budget or expert consultant data with the objective of determining the energy cost within an uncertainty of ±10%. The first approximation was based on the power plant construction of $88 million (in $1970), and an average energy intensity of

68,960 Btu/$ in 1970. Using the following Equation 1 and Equation 2 to calculate the errors resulted in an error range of +114% and -65%, where ε was the energy intensity, a was the budget figure, and $\Delta\varepsilon$ and Δa were calculated by multiplying ε and a by their respective percentage errors. The second approximation determined the major expenses in the power plant construction budget and associated them with the appropriate sector. The targeted line items such as structural steel, turbines, construction machinery, transformers, energy, and miscellaneous were multiplied by the average intensity of each sector. Uncertainties are self-determined and tabulated in Bullard et al.'s appendix. The above equations were used to calculate the second approximation with error bounds of +53% and -30%, exceeding the original error goal of 10%. The procedure was repeated with budget information at a more refined level until the error goal of 10% was achieved.

Equation 1.

$$+(\varepsilon\Delta a)+(a\Delta\varepsilon)=+6.9\times10^{12}\,BTU(114\%)$$

Equation 2.

$$-(\varepsilon\Delta a)-(a\Delta\varepsilon)=+3.9\times10^{12}\,BTU(-65\%)$$

In summary, this hybrid methodology determines the energy demand for an atypical product by disaggregating the product with budget information or other data into representative sectors and associated energy intensities. The main disadvantage of this hybrid approach is its fairly subjective selection of the error goal. In terms of the hybrid model continuum, the tiered hybrid analysis model uses mainly input-output data. Other examples of the tiered approach as noted in Suh et al. (2004) are Moriguchi et al. (1993) and Munksgaard et al. (2000).

The second hybrid analysis method, input-output based hybrid analysis, focuses on disaggregating sectors according to detailed economic information. Joshi (2000) describes three models in this category, namely Models II, III, and IV.

Model I is not a hybrid model and will not be reviewed herein. Model II can be used when an existing product is not well represented in an existing I-O commodity sector or a completely new product is introduced into the economy. If the production inputs and the environmental burdens are known, then a new sector can be inserted into the EIO-LCA model to determine the economy-wide economic and environmental effects. However, the key assumption, and a key disadvantage of this approach is that the original technical coefficient matrix remains unchanged. Conversely, Model III creates a framework for modifying the technical coefficient matrix through disaggregation of a sector. The advantages of this approach are that detailed process information can be included without double counting and the framework is presented in a consistent manner. The use and end-of-life stages need to be added to the results, typical of all I-O LCAs. Also, if an economy is highly dependent upon imports, then the results should be combined with other methods (Suh et al. 2004). Model IV expands the technical and environmental matrices through an iterative process of disaggregating existing sectors and adding new sectors for which process LCA information is available. Model IV combines the advantages of both process LCA and I-O, namely detailed process information with the entire economy as the boundary.

Joshi (2000) presented a comparative case study between steel and plastic fuel tank systems for automobiles using the input-output hybrid Model II. First, a description of the life cycle stages for each fuel tank was developed, and then costs associated with each major component for each phase was determined and linked to an existing commodity sector. For example, for the steel tank, the monetary amount of carbon steel sheet metal was $23.53 per tank and was represented by the sector, “Blast Furnaces and Steel Mill Products.” The total results of each fuel tank was summarized with respect to economic impact, non-renewable ores consumed, energy consumption, fertilizers used, toxic releases, conventional pollutants, and summary indices (global warming potential, ozone depletion potential, and acidification potential). Model II is similar to the tiered hybrid model with additional environmental process data included in the life cycle inventory.

The third method, integrated hybrid analysis, was developed by Suh (2004) in which process-based LCA with I-O is combined in a mathematical framework. The process data is described in a technology matrix with physical units per operation time for each process; while, the units of the I-O model are monetary. The process-based and I-O data for an integrated hybrid model is linked through a make and use framework that is connected through the flows at the boundary of each system. The advantages of the integrated hybrid model are the consistent mathematical framework for the entire life cycle, avoidance of double-counting, and application in analytical tools; the disadvantage is that it is data and time intensive (Suh et al. 2004).

An ‘augmented process-based’ hybrid model was utilized by Guggemos and Horvath (2005) for modeling the life cycle of a commercial building. This hybrid approach begins with a process description of a system and uses both I-O and process data in the analysis. The life cycle is represented as material manufacturing, construction, operation, maintenance, and end-of-life. The manufacturing stage is modeled by estimating the materials used and their costs, and then using the best-matching sectors in EIO-LCA. This process is also used to model the life cycle inventory for temporary materials in the construction phase, fossil fuel, and electricity use in the operations phase, and lifetime maintenance materials. Emission factors are used for on-site equipment and transportation in the construction, maintenance, and end-of-life stages. The results of this approach is similar to Joshi’s Model IV because it (a) incorporates a detailed process framework, (b) uses I-O to maintain the whole economy as the boundary of analysis, and (c) includes missing processes with process data.

2.4.4 Discussion on Types of LCAs

Process-based, input-output, and hybrid methods all have advantages and disadvantages. The development of all three techniques was not progressive; that is, process did not evolve into input-output, and input-output into hybrid, e.g., Bullard et. al’s hybrid technique was developed in 1978. Also, it cannot be definitively stated that hybrid modeling is the best option for all LCAs, or which approach to hybrid modeling would be preferred in a given application. Suh et. al. (2004) take the approach that the method that produces the largest life cycle inventory is the best approach. This may not be the case, as overestimation of a life cycle inventory is also possible. At this point, there is no straightforward guidance for the LCA practitioner wishing to use hybrid modeling. The LCA practitioner will need to make the decision based on the best available data and information. To date, a consensus or method to determine and compare approaches to hybrid modeling has not been defined by ISO or the LCA community.

The advantages and disadvantages of process and input-output LCAs are often cited as the advantage of developing a hybrid LCA model and are shown in Table 6. One of the major limitations of the process model is the subjective determination of the boundary location; conversely, I-O LCA effectively eliminates the boundary issue by considering the interactions in an entire economy. As an example of the boundary issue, again consider the production of a car, whose direct components include materials like steel, aluminum, tires, plastic, and paint. For each of those direct components, the LCA practitioner is required to trace the inputs to environmental impacts, a process that continues both upstream and downstream from the car until the set boundary limits are reached. The boundary for process LCAs is typically drawn around the direct impacts and to a point acceptable to the LCA practitioner; whereas, the boundary using I-O is able to capture all of the components. A major disadvantage of I-O LCA is that it typically does not include the use and end-of-life phases, necessitating the combination of process data.

The exclusion of the indirect impacts can be considerable. Lenzen used input-output analysis to quantify the possible truncation errors in process LCAs assuming that a process LCA's boundary extended only to the first order. He compared the first-order impacts with the total supply chain impacts for energy in Australian input-output accounts. The results of his analysis found that 132 first-order LCAs produced truncation errors of higher than 50% (Lenzen 2001). However, Lenzen assumed that the process LCA's boundary included only the first order, which is problematic because there is a variable degree of depth in actual process LCAs.

Because errors in process LCA models can be high and there is no scientific basis for determining an LCA's boundary, the credibility of pure process LCA as a technical tool is questionable (Lave et al. 1995; Suh et al. 2004). The boundary selection process defined in ISO 14041 is iterative. First, an initial system boundary is selected; then, throughout the LCA boundary levels can change as more information and understanding is developed. As ISO clause 5.3.3 states: "Decisions shall be made regarding which unit processes shall be modeled by the study and the level of detail to which these unit processes shall be studied. Resources need not be expended on the quantification of such inputs and outputs that will not significantly change the overall conclusions of the study…(American National Standards Institute/International Organization for Standardization (ANSI/ISO) 1997)." Consequently, if any processes are excluded, justification should be included in the LCA. However, in practice it is difficult to determine what unit processes will have significant environmental impacts before the data collection stage begins and after the LCI is compiled.

Table 6. **Process LCA and I-O LCA Model Comparisons**

	Process Model	**EIO-LCA**
Advantages	• Detailed analysis of specific processes • Product Comparisons • Identify process improvements	• Boundary is defined as the entire economy. • Economy-wide, system LCA • Publicly available data • Reproducible results
Disadvantages	• Subjective boundary selection • Lack of comprehensive data in many cases • Time and cost intensive • Proprietary data • Uncertainty	• Aggregated level of data • Identification of process improvements are difficult • Imports treated as U.S. products • Uncertainty • Limited non-U.S. data • Product use and end-of-life options not included

ISO does provide some guidance on criteria that can be used to select the boundary (i.e. mass, energy, and environmental relevance). Suh et al. (2004) describe three problems associated with these criteria. First, the decision to include or exclude unit processes based on mass or energy is not performed with a theoretical or empirical method guaranteed to eliminate results that have negligible environmental impacts. Second, the magnitude of these impacts may not be accurately inferred based on mass and energy. Third, the boundary cut-offs may not be individually significant with respect to a unit process, but the sum of all the cut-offs may be considerable. This concept of truncation can be especially important when comparing two processes or products.

While the process LCA model can be limited by boundary definitions, I-O limitations center on the level of aggregation in the economic sector model. With I-O LCA, evaluation of a specific product is not possible due to the aggregation of products into sectors. Specific I-O with process-based LCA models at the derived level of detail can be created. For example, a comparative LCA of a Ford Focus and a Honda Civic cannot be done with I-O LCA because there is only one passenger car sector in the U.S. economic sector model in which individual differences in the materials and manufacturing process of cars are not distinguished. Consequently, because specific products cannot be modeled, it is also difficult to model process improvements; I-O cannot easily identify the processes within car manufacturing that could be improved. I-O and process analysis can be used for system analysis. For example, if the U.S. government offered substantial incentives for residential housing, it is possible to model the expansion of the direct and indirect sectors that would result in growth of the residential sector. For instance with I-O, if the final demand of the "residential housing" sector increased, then demand for sawmills, plumbing fixtures, and ready-mix concrete would also increase.

Another disadvantage of the process LCA model is that it is often difficult for an LCA practitioner to obtain the necessary data to complete a thorough LCA either because data is not available or a specific company is unwilling to contribute proprietary information. However, the number of sectors and amount of environmental data available for other countries for I-O modeling is not as extensive as in the U.S. (Suh et al. 2004).

The goal of a hybrid LCA is to combine the advantages of both approaches. As previously noted, there are several types of hybrid models. Tiered, I-O based hybrid, integrated, and augmented process-based analyses are four examples that describe the range of applications. Tiered and I-O based are similar in that they both begin with I-O models and model a system primarily with I-O data. The augmented process approach begins with a process diagram, uses I-O sectors to model individual components, and uses additional sources for processes that cannot be modeled with I-O methods. The tiered and Model II I-O-based models use a cost breakdown and result in a similar approach. Both the tiered and I-O hybrid models rely heavily on budget information. The final outcome of both of these approaches may still be a higher level of aggregation than ultimately desired since the model relies heavily on the I-O framework. Conversely, the augmented process-based model relies heavily on a process framework along with relevant process and I-O data for unit processes that cannot be modeled efficiently with process data. While the integrated hybrid model may provide a comprehensive hybrid framework, the time and data constraints of this model may make this hybrid model time and cost prohibitive.

After considering the applicability of process-only, input-output-only, and the range of hybrid LCA models, an augmented process-based LCA approach was selected to develop the hybrid model for construction processes. This approach was chosen because of poor data availability, the existing construction industry structure, and comprehensive use. Since construction is a deregulated sector in the U.S., process data is limited. However, when available, process data was used in conjunction with typical project records and practices. Additionally, the construction industry has existing financial construction data in estimating software and scheduling tools. This monetary data can be used in I-O tools such as EIO-LCA without the need to collect additional data. Two main goals in hybrid LCA models are improving the time and cost associated with process-based LCAs and developing an inclusive boundary. Using an augmented process-based hybrid LCA approach achieves both of those goals. Additional information on how to structure an augmented process-based LCA is located in Section 7.2.

3.0 LIFE CYCLE IMPACT ASSESSMENT

The purpose of the life cycle impact assessment (LCIA) as defined by ISO 14042 is to "assess a product system's life cycle inventory analysis results to better understand their environmental significance. The LCIA phase models selected environmental issues, called impact categories, and uses category indicators to condense and explain the LCI results" (International Organization for Standardization 2000). However, in practice ISO 14042 provides little guidance as exemplified by the various methodological, technical, and philosophical differences represented in the LCIA modeling tools. One major difference between modeling tools, although not the only, is the argument between endpoints and midpoints.

The life cycle impact assessment stage is an important aspect of the entire LCA process because this stage translates LCI into presentable and comprehensive data. The LCI may have relatively insignificant meaning to not only an average person but also an experienced LCA practitioner. For example, if one is comparing the results from two LCI processes, and then to actually understanding the impact of 1000 kg of NO_x versus 300 kg NO_x, requires more tangible measures. The impact assessment stage assists in providing these translations. The key steps of a life cycle impact assessment include the following (International Organization for Standardization 2000):

1. Selection and definition of impact categories
   The selection and definition of impact categories step identifies the targeted impact categories, such as, global warming potential, human health, etc. Selecting the impact categories should be included as a part of the goal and scope.

2. Classification
   The classification step organizes the LCI results into the impact categories; for example, carbon dioxide emissions are allocated to global warming potential.

3. Characterization
   Characterization applies characterization factors to convert and combine the LCI results into representative indicators. Characterization is a method of translating the LCI results into common measures. Impact indicators are generated by multiplying the inventory data and the characterization factors. For example, characterization estimates the relative global warming potential between greenhouse gases by multiplying the associated inventory results by CO_2 equivalents and summing to calculate the total.

4. Normalization
   This step normalizes the impact indicator results into data that allows for comparison between the impact categories. Normalization requires the selection of reference values for each set of indicator results. The reference values vary and can include selecting total emissions for a given area or for a given area on a per capita basis, baseline data, and highest values. Normalized data can only be compared within an impact category.

5. Grouping
   Grouping further aggregates, sorts, or ranks the indicator results to present easily comprehensible results.

6. Weighting
   The weighting step is the most controversial step in LCIA because this step assigns weights of values to impact categories. Basically, in the weighting step, decision makers are required to decide if global warming is more or less important than human toxicity, for example. The controversy of the weighting step is centered on the non-scientific nature of value judgments, possibly bringing into question the entire scientific basis for LCA because the final results can be presented based on valuations.

7. Evaluation and reporting LCIA results
   This step examines and creates an understanding of the LCIA results.

ISO 14042 standards for the LCIA stage states that the first three steps and the seventh step are required – impact category selection, classification, characterization, and evaluation. The other stages are optional.

The LCIA methods used in this hybrid model are Eco-Indicator 99 and Impact 2002+. Eco-Indicator 99, a damage based approach, is a common method used in Europe and often used in LCAs. When this research started, Eco-Indicator was “the method” to use. As LCIA continues to evolve, other methods are further developed and used more prevalently, for example, Impact 2002+. Impact 2002+, also a damage based approach, was included in the hybrid model to represent the continuing evolution of LCIA methods. Eco-Indicator 99 can present the results in a single score with three perspectives; whereas, other LCIA methods present the data at the midpoint level to allow the user to view results such as global warming potential, human health cancer effects, human health non-cancer, and several other categories. This is only one example of the many differences in LCIA models. The LCA community has not developed consensus with respect to LCIA's framework or impact categories making this stage in the LCA subject to misunderstanding and scrutiny in the modeling tools and subsequent results.

LCIA methods are extremely complex, and require a thorough understanding of many science and medical fields. The following discussion on the methods used in the hybrid construction models are presented as a high-level overview, mainly focusing on the framework of the LCIA methods used in the developed model. Additional information can be found in Goedkoop and Spriensma (2001).

3.1 ECO-INDICATOR 99

Eco-indicator 99 was developed with a "top down" approach, meaning that framework actually starts at the final end score with associated weighting points. Impacts are modeled at the damage level in three main damage categories of damage to resources, ecosystem quality, and human health. While Eco-Indicator is an end-point LCIA method, the developed LCA model created as part of this research only calculates mid-points because of value and issue debates of end-points. The four main steps of this LCIA method are normalization and weighting; damage analysis; exposure and effect analysis; and resource, land-use, and fate analyses.

The following information is from mainly Goedkoop and Spriensma (2001) and Bilec and Thabrew (2005). Fate analysis means the transformation of emissions to concentrations in the environment; the effect and exposure analyses further transforms concentrations to hazard units; and the damage analysis expresses the hazards in damage units. The method provides combination of damage factors, normalized damage factors, and weighted damage factors in terms of three perspectives explained in the Concept of Cultural Theory (Hofstetter 1998). Three perspectives of Individualist, Egalitarian, and Hierarchist were developed with the goal of accounting for uncertainty and guiding decision making. Examples of the three perspectives are: Egalitarians consider longer substance life as they would be more concerned with long-term effects; Individualists give more priority to human health over ecosystem quality, and represent the short-term perspective; Hierarchists give equal value to human health and ecosystem quality, and balance short-term and long-term perspectives. The developers of Eco-Indicator 99 recommend the damage factors given under Hierarchist perspective with average weightings. In the SimaPro software program, the Hierarchist view is the default. Depending on the perspective, parameters, weighting, and normalization have different estimates in the model. Normalization is based on European emissions, extractions, and land use.

Table 7 gives an overview of the major damage categories (human health, ecosystem quality, and resources), the main "causes" of damages, and the associated units. Table 7 is further referenced in the subsequent sections.

Table 7. Eco-Indicator 99 - Damage Categories, Causes, and Units

Damage category	**Caused by**	**Damage unit**
Human health	Carcinogenic effects	DALY/kg of emission
	Respiratory effects by organics	
	Respiratory effects by inorganics	
	Ionizing radiations	
	Ozone layer depletion	
	Climate change	
Ecosystem quality	Toxic emissions	PDF.m^2.yr/kg of emission
	Combination effect of acidification and eutrophication	
	Land occupation and land conversion	PDF.m^2.yr/kg of emission/m^2.yr
Resources	Extraction of minerals	MJ surplus energy/(kg of extracted fuel, or m^3 of extracted gas, or MJ extracted energy)
	Extraction of fossil fuel	

3.1.1 Damage Categories

This section describes the three major damage categories and sub-categories in Eco-Indicator 99.

3.1.1.1 Human Health

Human health is defined as the absence of premature death, sickness, or irritation caused by anthropogenic emissions to the environment. Human health category includes, damages caused by carcinogenic substances, respiratory effects, climate change, ionizing radiation and ozone layer depletion.

DALYs

Both Eco-Indicator 99 and Impact 2002+ employ the concept Disability Adjusted Life Years (DALYs). Common to many aspects of LCIA, DALYs are controversial due to the ethical dilemmas associated with health-indicators, such as placing a numerical value on human life. The overall concept of DALYs was developed to find a scale to measure the health of a population including factors of numbers of effected people, duration of suffering (or lifetime lost), and severity of health problems. The concept of DALYs was collaboratively developed by the World Bank (1993) with intentions to use the health indicator in health economics to allocate funds to health care. DALYs attempt to measure the amount of ill-health from specific diseases and compares years lived disabled (YLD) and years of life lost (YLL). Another way to think of DALYs is a damage of “1” means one life year of one individual is lost.

Damage to human health caused by carcinogenic substances

The impact category, damage to human health from carcinogenic substances, attempts to reconcile the complex relationship between agent and tumor incident, through considering various experimental results and epidemiological studies. Eco-Indicator 99 relied heavily on information from the International Agency for Research on Cancer (IARC) and their associated classification system. The fate analysis of the emissions is carried out using the European Uniform System for the Evaluation of Substances (EUSES) regional model modified for LCA purposes, including more global perspectives. The exposure and effect analysis uses the Unit

Risk (UR) concept for the estimation of dose response relationship, and most of them are derived from the U.S. EPA’s Integrated Risk Information System (IRIS). The exposed population densities vary depending on atmospheric residence time. For example, if residence time is one day—the average population density of Western Europe is chosen, and if the residence time is one year, the average population density of the world is used. Using above information, the cancer incidence factors are determined for the emissions with respect to their relevant intake pathways of inhalation and oral uptake. The damage factors are calculated by multiplying the incidence factors by the respective Disability Adjusted Life Years (DALYs) per incidence formulated by Hofstetter (1998).

Damage to human health caused by respiratory effects

Epidemiological research has shown that non-organic emissions have respiratory effects on humans. The overall concept of this impact category relies heavily on epidemiological research. The substances included in this category are PM_{10}, $PM_{2.5}$, NO_x, NH_3, CO, VOCs, and SO_x. The fate factors are primarily derived using a simple model which takes into account the residence time and dilution height, but a different fate factor is used to calculate non-methane VOCs. Since an accepted list of unit risks is unavailable for respiratory diseases, the exposure-effect slopes are compiled using information from ExternE (ExternE 1997). Final DALYs were estimated from the seriousness and duration of associated disease.

Damage to human health caused by climate change

Modeling the relationship between human health and climate change presents many challenges including long-term time ranges, regional aspects, and balancing and accounting for positive and negative health impacts. A major assumption in modeling climate change is that the current emissions will create damage in the future. The impact of emissions emitted in Europe is assumed to be contributing to the damage in the world scale. The FUND 2.0 model is used for determining marginal damage of release of greenhouse gases. Both positive and negative damages are presented with different perspectives.

Damage to human health caused by ozone layer depletion

No real fate models or factors were developed for ozone layer depletion, but the fate factor for CFC-11 is calculated using the area under the predicted yearly concentration curves developed according to the London protocol. For ODP substances, equivalency factors are used. The time horizon is 500 years. Effect is expressed as amplification factor (AF) from Armstrong (1994) and United National Environment Programme (1998), which is multiplication of percent increase in incidence due to 1% increase in UV radiation and % increase in UV radiation per percent increase in ozone layer depletion. Damage is calculated in DALYs with respect to skin cancer and eye cataract using the method developed by Hofstetter (1998).

3.1.1.2 Ecosystem Quality

For monitoring ecosystem, the information flow on the species level is focused upon, and it is assumed, the diversity of species is an adequate representative for this category. The damage caused by an emission is assumed to be a temporary stress on the ecosystem, given that the functional unit is given a limited time perspective. Ecosystem quality includes damage caused by ecosystem substances, acidification, eutrophication, and land use. In general, the total damage to Ecosystem Quality is a function of the fraction of species, area, and time.

Damage to ecosystem quality by ecotoxic substances

The fate analysis is carried out with EUSES linking emissions to air, water, agricultural soil, industrial soil, and natural soil. The main exposure path for ecosystems is assumed to be water for aquatic ecosystem and pore water for terrestrial ecosystem. The dose effect curve is based on log function of No Observed Effect Concentration (NOEC) for a single species.

Combined Potentially Affected Fraction (PAF) of species is calculated in multiple substance exposure situations. The increase in concentrations of individual substances is divided by average NOEC to give standardized hazard units (HU). The dose response is given by a log curve representing the relationship between PAF vs. HU. The ambient concentration is assumed to be an average concentration equally spread over Europe and converted to HU to get incremental PAF for incremental HU. The damage is expressed in PDF*m^2*yr.

Damage to ecosystem quality by acidification and eutrophication

This category evaluates the combined effect of acidification and eutrophication due to deposition of inorganic substances over natural ecosystem. The primary effect is the change in acidity and nutrient levels in the soil, leading to potential shifts in species populations. To find the extent of the species' shifts, target populations are modeled using SMART and MOVE. SMART develops fate factors, and MOVE develops damage factors. The models assume a closed system with approximately 60% of land mass consisting of natural soil. Hence, only 60% of the emissions are considered to be actually deposited. Damage units are PDF*m^2*yr for target species.

3.1.1.3 Resource

Damage to resources caused by mineral and fossil fuel

Only mineral resources and fossil fuel are modeled in this category. Geostatical models are used to carry out resource analysis to evaluate the relation between the availability and the quality of the minerals and fossil fuel. The decrease of concentration as a result of extraction is modeled. All the minerals are given equal importance and substitution or recycling is not taken into account. Fossil fuel includes conventional oil, gas, and coal. For fossil fuel, substitution is assumed with a future energy mix of 50% shale and 50% coal. To evaluate damage, surplus energy concept is used. Surplus energy is defined as the difference between the energy required to extract a resource now and at some point of time. The future surplus energy is calculated as Q*N, where Q is quantity that has been extracted before 1990 and N is the number of times extracted. The damage to resource dose relationship lacks absolute meaning and, the only purpose of the surplus energy is to provide a relative measure for damage created by depletion of resources.

3.2 IMPACT 2002+

Impact 2002+ adopted several previously developed methods from Eco-Indicator 99 Goedkoop and Spriensma (2001), CML 2002 (Guinee et al. 2002), IPCC (Intergovernmental Panel on Climate Change 2001), U.S. EPA ozone depletion list, and the Eco-Invent database. In addition, Impact 2002+ developed new methods related to human toxicity and ecotoxicity. Impact 2002+ classifies the life cycle inventory into 14 midpoint categories and 4 damage categories. A comparison between Eco-Indicator 99 and Impact 2002+ is given in Table 8.

All midpoint "scores" are expressed in units of a reference substance; the referenced substances are related to four damage categories human health (DALYs), ecosystem quality (PDF*m^2*yr), climate change (kg_{eq} CO_2), and resources (MJ). Normalization is possible either at midpoint or damage level. Characterization factors can be directly multiplied with the emissions given in kilograms to calculate the impact of a substance at the midpoint or at the damage level. Midpoint characterization factors are expressed as kilogram equivalent of a reference substance and damage factors are expressed in respective units according to the damage category. The principal scope is common to all impact categories: overall long-term effects are being considered through the use of infinite time horizons (sometimes approximated by 500 years horizon). All Impact 2002+ factors are available at http://www.epfl.ch/impact.

Table 8. Impact Category Comparison between Eco-Indicator 99 and Impact 2002+

Eco-Indicator 99	Impact 2002+
Carcinogens	Carcinogens
	Non-carcinogens
Respiratory Inorganics	Respiratory Inorganics
Respiratory Organics	Respiratory Organics
GWP (DF)	GWP (DF)
Ozone Depletion Potential	Ozone Depletion Potential
Ecotoxicity	Aquatic and Terrestrial Toxicity
Acidification and Eutrophication	Terrestrial Acidification and Nutrification
	GWP (CF)
	Aquatic Acidification
	Terrestrial Eutrophication
Resource (Energy)	Resource (Energy)
Resource (Mineral)	Resource (Mineral)

3.2.1 Impact Categories in Impact 2002+

This section briefly describes Impact 2002+'s life cycle impact assessment categories with more detailed information provided in (Humbert et al. 2004).

For Carcinogens and Non-Carcinogens, characterization factors for human toxicity at the midpoint are termed as Human Toxicity Potential (HTP). The characterization factors are determined using the Impact 2002 model, the predecessor of Impact 2002+. Human toxicity includes all impacts on human health except respiratory effects from specific inorganics, ionizing radiation, ozone depletion layer, and photochemical oxidation. Therefore, the carcinogens impact category in Impact 2002+ is not a direct comparison to Eco-Indicator 99. An impact pathway framework for human toxicity takes into account chemical fate, human exposure, and severity to develop intake fractions and effect factors. The characterization factors are estimated for four main compartments of air, water, soil, and agricultural soil for both carcinogenic and non-carcinogenic impact categories. The damage factors (DF) for all chemicals belonging to carcinogenic and noncarcinogenic categories are expressed in DALYs per kilogam of substance. The reference substance for human toxicity (carcinogenic and noncarcinogenic) is chloroethylene into air and the numerical estimation of its damage factor is 1.45E-06 DALY per one kilogram of chloroethylene. In the Impact 2002+ model, the mid point characterization factors are expressed as the damage factor of the chemical concerned in a particular compartment divided by the damage factor of the reference substance. One important note about Impact 2002+ is emission fate and transport is modeled up to the damage level, and the midpoint characterization factors are derived with respect to the end damage.

For Aquatic and Terrestrial Ecotoxicity, the aquatic ecosystem represents the fresh surface water bodies like lakes and streams while the terrestrial ecosystem represents the aqueous phase of soil. The aquatic and terrestrial ecotoxicity potentials are determined using the Impact 2002 model. For both categories, the damage factors units are PDF*m^2*yr. The midpoint characterization factors are obtained as a ratio of damage factors of the substance concerned to the reference substance. Reference substance is triethylene glycol into water and soil respectively.

For Respiratory Effects, Ionizing Radiation, Photochemical Oxidation, Terrestrial Acidification and Nitrification, Mineral Extraction, and Ozone Layer Depletion are impact categories in Impact 2002+ with damage factors that are directly from Eco-indicator 99 and characterization factors derived by dividing the damage factor of the substance considered by the damage factor of the reference substance. For respiratory effects, photochemical oxidation and terrestrial acidification and nitrification, the characterization factors are given for emissions to air only, and for ionizing radiation, they are available for emissions into both air and water.

Aquatic Acidification and Eutrophication midpoint characterization factors are from CML (Guinee et al. 2002). Global Warming characterization factors are given for emissions to air. The latest global warming potentials with 500 year time scale are directly obtained from the IPCC 2001 list.

4.0 HYBRID LCA MODEL FOR CONSTRUCTION PROCESSES

The major component of this research was creating a hybrid life cycle assessment model for construction processes. After providing a high-level overview, this section describes the model in three main components: User Input, Detailed Model, and Results. The majority of the detailed information such as data sources and process mapping are included in the "Detailed Model" section.

4.1 MODEL OVERVIEW

The hybrid LCA construction model was created in the software program, Analytica, a highly visual modeling tool that creates, analyzes, and communicates process decision models (Lumina Decision Systems 2006). Analytica has been used with other LCAs (Thabrew et al. 2007), (Lloyd and Ries 2007). An attractive feature of Analytica is its statistical capabilities and uncertainty analyses. While Analytica is not a free software package like EIO-LCA, a fifteen-day free trial is available. In addition to Analytica, Microsoft Excel was used to pre- and post-process some information (Microsoft Corporation 2002).

The model's overall organization and process models are based on CSI format and R.S. Means (R.S. Means 2006). The construction model was structured in three modules: User Input, Detailed Model, and Results, as shown in Figure 3. The model combines several data sources, including both process and EIO-LCA data, into one common LCA framework. Examples of the type of user input required are dollar value of construction, quantity of brick, and hours of generator operations. Face validity with industry was used to confirm usability and applicability of the model. The LCIA stage is included with results in impact categories. Weighted single scores are not used. Additionally, more construction relevant inventory results are also displayed, such as transportation, equipment, and construction services. The intent of the model is to help LCA practitioners and construction decision makers understand the environmental aspects of building construction processes, and visualize the flow of construction operations.

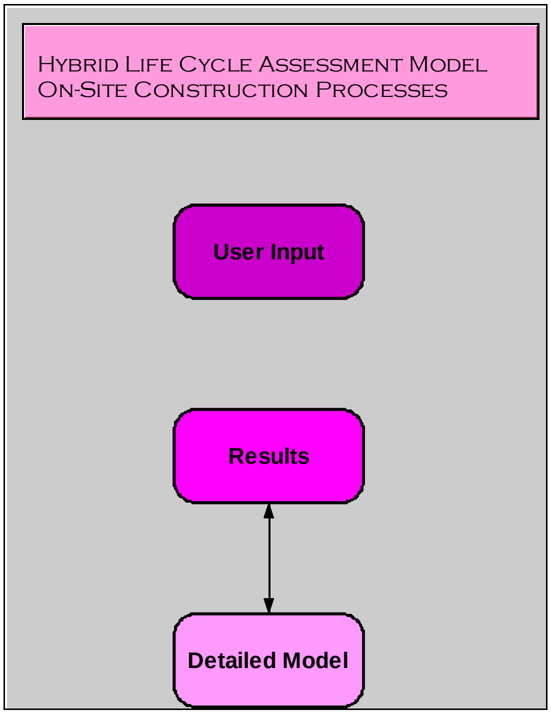


Figure 3. Hybrid LCA Construction Model: Top-Level Model Overview

4.1.1 Model Boundaries and Major Construction Categories

The model's scope is on-site construction activities, transportation from the manufacturer or supplier to the construction site, and construction service sectors. A graphical illustration of the boundary is shown in Figure 1. The model captures major construction categories listed in Table 9 with detailed information found in the "Detailed Model" section. Transportation can include both truck transportation for materials and equipment and worker transportation to and from the site. Electricity primarily represents on-site electricity usage for trailers, small equipment, and lighting. Construction equipment includes not only fuel combustion but also fuel usage, production, and distribution; construction services represent sectors like inspection, architects, engineers, and surveyors. Environmental effects from manufacturing permanent materials are not included in this LCA, but the full life-cycle of temporary materials such as concrete forms is included. Both on-site construction waste and concrete wastewater are included, along with emissions from welding and surface application such as paints and sealants. The category "Paved and Unpaved Roads" captures emissions from vehicles traveling over a surface, typically from brake wear, tire wear, and resuspended loose road materials. Dust generation from construction operations consists of information related to particulate generation due to construction operations.

Table 9. Environmental Impacts in Hybrid LCA Construction Model

Transportation of materials – fuel combustion, extraction, distribution
Electricity – On-site usage, generation, distribution
Construction Equipment – fuel combustion, extraction, distribution, and equipment manufacturing
Construction Services – Input-output analysis
Temporary Construction Materials – Input-output analysis
Waste – Solid and liquid wastes
Welding – Hazardous metals and PM
Surface Applications – Application of paints, sealants, etc.
Dust from Driving on Paved and Unpaved Roads
Dust Generation during Construction Operations

4.2 USER INPUT

The User Input module allows the user to input project specific information. There are nine categories in this module, as shown in Figure 4. Within each of the nine categories, information can be entered. If a field is not relevant to the project, zero values can be entered. The input values are linked to process models within the Detailed Model module. The process models are described in Section 4.3.6. Data can be entered as a distribution of a single value. R.S. Means was used as a guide to determine both the main categories and input data within the categories.

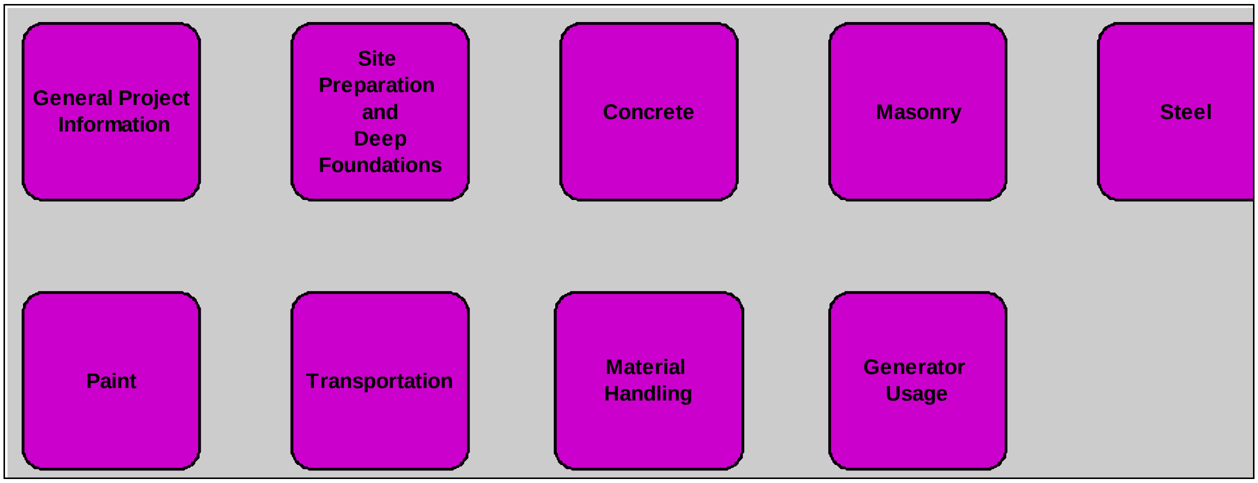


Figure 4. Nine Categories in the User Input Module

4.2.1 General Project Information

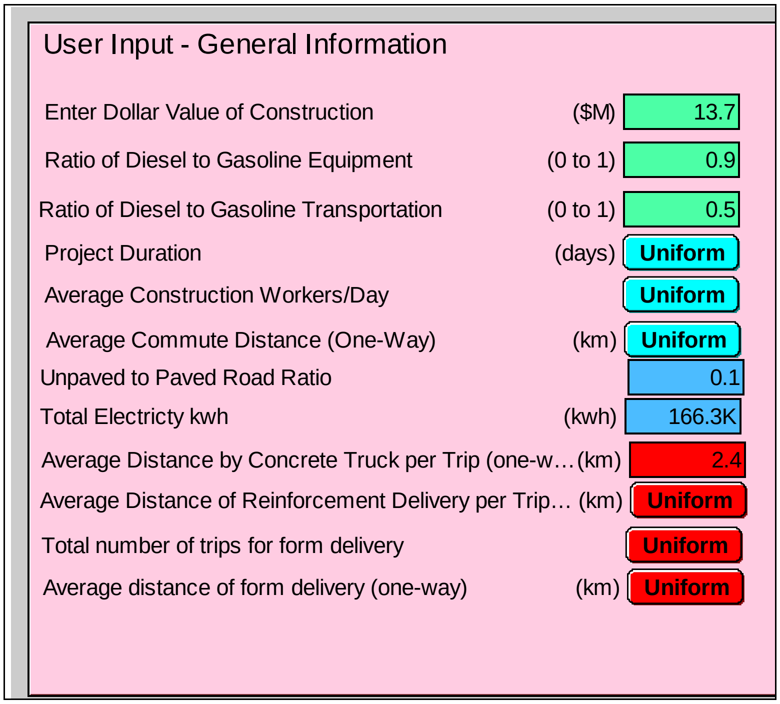
Figure 5 illustrates the first category, General Project Information. While some categories include more common construction information such as the dollar value of construction, project duration (as a distribution), and average distance (one-way) by a concrete truck; other categories are more specific to life cycle assessment. One example LCA information is the ratio of diesel to gasoline engines for equipment and transportation vehicle engines, which require the user to estimate the proportion of diesel and gasoline. It is necessary to determine this because of the inherent emission differences between the two fuel types. Default values are provided. While the default ration may not be exact, it was not practical to assume that every user would know the fuel type of construction equipment and transportation vehicles. These ratios are currently not modeled as distributions, but the user can easily enter information as a distribution.

Another subjective category is the average number of construction workers/day. This information is used in conjunction with average commute distance (one-way) to determine the environmental impacts of worker transportation. While worker transportation is typically not included in most LCAs, it is included in this hybrid LCA model. The decision to include the worker transportation was mainly due to the nature of construction; that is, since construction is not at a permanent location such as a fixed steel mill, it is important to capture worker transport. In other words, worker transportation can be considered a change in the normal traffic pattern and therefore the environmental impacts will be different from normal conditions. Both line items are modeled as uniform distributions. The accuracy of the average number of construction workers/day depends on when the user enters the information. If the number is input before construction begins, then the accuracy will be lower; if the number is input after construction is completed, then the accuracy will be higher.

The input line “Unpaved to Paved Road Ratio” operates in a similar manner as the ratio for diesel and gasoline. The user estimates the ratio between unpaved and paved roads from 0 to 1.

Electricity is entered in kilowatt-hours. Should the user be unsure of total electricity usage, average monthly usage information is provided within the line item description based on average case study data.

The last three input lines, established as distributions, relate to concrete reinforcement and form delivery information. This information is not included in the Concrete category because this information is also a part of the Site Preparation and Deep Foundations category.



User Input - General Information

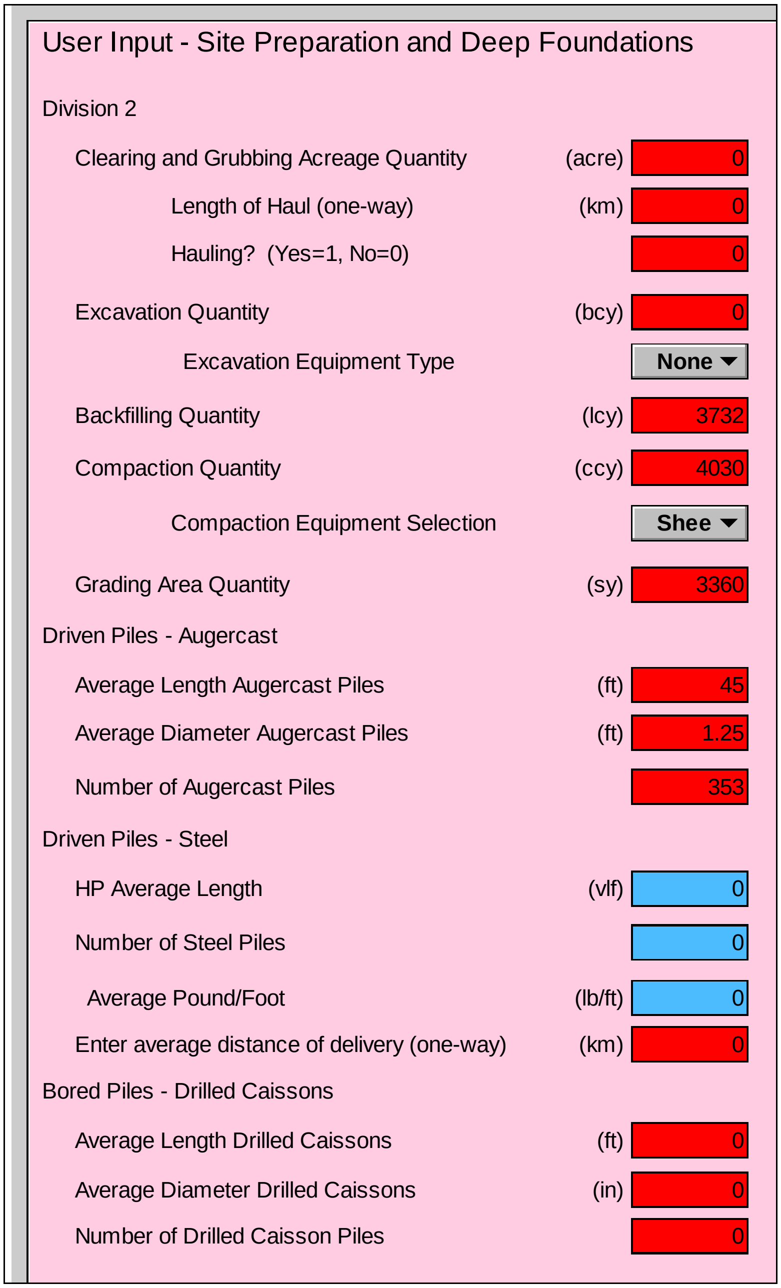
Enter Dollar Value of Construction	($M)	13.7
Ratio of Diesel to Gasoline Equipment	(0 to 1)	0.9
Ratio of Diesel to Gasoline Transportation	(0 to 1)	0.5
Project Duration	(days)	Uniform
Average Construction Workers/Day		Uniform
Average Commute Distance (One-Way)	(km)	Uniform
Unpaved to Paved Road Ratio		0.1
Total Electricty kwh	(kwh)	166.3K
Average Distance by Concrete Truck per Trip (one-w…	(km)	2.4
Average Distance of Reinforcement Delivery per Trip…	(km)	Uniform
Total number of trips for form delivery		Uniform
Average distance of form delivery (one-way)	(km)	Uniform

Figure 5. General Project Information

4.2.2 Site Preparation and Deep Foundations

The User Input for Site Preparation and Deep Foundation primarily encompasses operations including clearing and grubbing, excavation, backfilling, compaction, grading, and different pile types. The visual representation for this category is shown in Figure 6. For the Clearing and Grubbing category, the user enters information such as required acreage, along with the decision of whether the material will be hauled off-site, and if so, the distance of the haul. Excavation operations are entered in units of bank cubic yard (BCY), and the user has the option to select either a front end loader or a hydraulic excavator. Backfilling quantity is entered in units of loose cubic yards (LCY). Compaction quantity is entered in units of compacted cubic yard (CCY), along with equipment selection options of sheepsfoot, wobbly wheel, or vibratory plate.

For deep foundations, the user has the option of augercast driven piles, steel driven piles, and drilled caissons. Required information for augercast driven piles include the average length of piles in feet, average pile diameter in feet, and total number of piles. Average concrete transportation distance is not required because this data is a part of the General Project Information module. Input data for steel driven piles are average length in feet, number of steel piles, average pounds per foot, and average transportation distance. For drilled caissons, information on average length of caissons in feet, average diameter of caissons in feet, and number of caissons required.



User Input - Site Preparation and Deep Foundations

Division 2		
Clearing and Grubbing Acreage Quantity	(acre)	0
Length of Haul (one-way)	(km)	0
Hauling? (Yes=1, No=0)		0
Excavation Quantity	(bcy)	0
Excavation Equipment Type		None
Backfilling Quantity	(lcy)	3732
Compaction Quantity	(ccy)	4030
Compaction Equipment Selection		Shee
Grading Area Quantity	(sy)	3360
Driven Piles - Augercast		
Average Length Augercast Piles	(ft)	45
Average Diameter Augercast Piles	(ft)	1.25
Number of Augercast Piles		353
Driven Piles - Steel		
HP Average Length	(vlf)	0
Number of Steel Piles		0
Average Pound/Foot	(lb/ft)	0
Enter average distance of delivery (one-way)	(km)	0
Bored Piles - Drilled Caissons		
Average Length Drilled Caissons	(ft)	0
Average Diameter Drilled Caissons	(in)	0
Number of Drilled Caisson Piles		0

Figure 6. Site Preparation and Deep Foundations – User Input

4.2.3 Concrete

The User Input for the Concrete category has many different elements such as columns, beams, elevated slabs, spread footings, pile caps, retaining walls, grade walls, and slab on grade as shown in Figure 7. Concrete column material information includes area and average length;

concrete column transportation information is number of reinforcement deliveries. In terms of forms, the user can select form type: plywood with wood frame, plywood with steel frame, round fiberglass, round fiber tube, and round steel. If wood forms are selected, the user selects the number of uses, one through four, and this selection is important because the number of uses distributes the material production emissions per the number of uses. For example, if the form is used two times, the material emissions are divided by two.

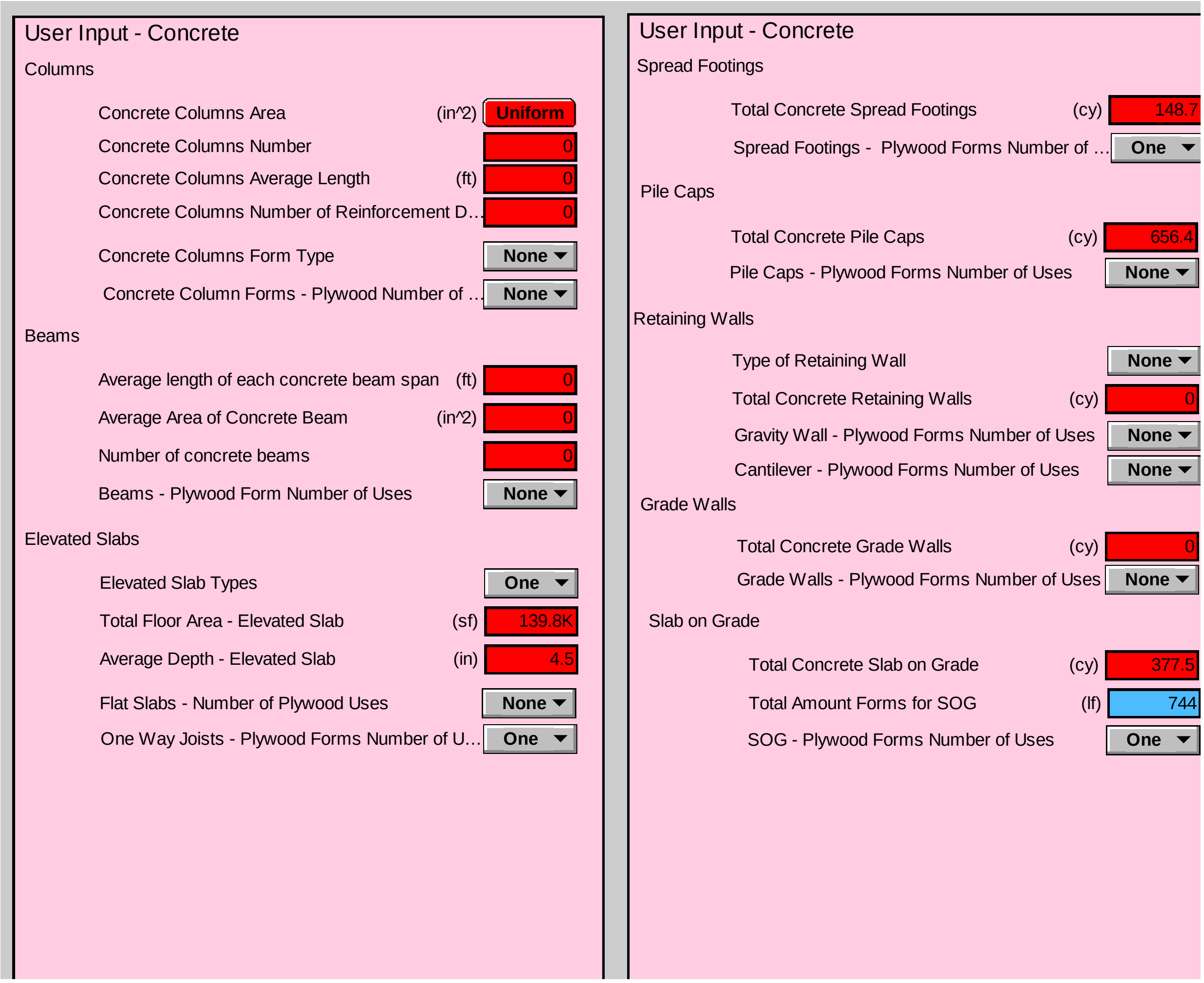
Concrete beam information is similar to column information. User input includes average length of beam span, average area, number of beams, and number of form uses. It is assumed wood forms are used.

In terms of elevated slabs, the user selects the type of elevated slabs: either one-way joists or flat slab, which are two of the most common elevated slabs. Input information is total floor area, average depth, and number of form uses.

Spread footing, pile cap, and grade wall quantity information is entered as total cubic yards (cy) of concrete, along with number of form uses.

Input for retaining walls includes selection of the type of retaining wall, gravity or cantilever, then total concrete in cubic yards, followed by the number of form uses.

Finally, slab on grade user input information includes total concrete in cubic yards, total amount of forms in linear feet, and number of form uses. Form quantity is required as an input for the slab on grade because the assumption that form area is the same as the contact surface area does not apply in this case.



User Input - Concrete

Columns

Concrete Columns Area (in^2) Uniform

Concrete Columns Number 0

Concrete Columns Average Length (ft) 0

Concrete Columns Number of Reinforcement D… 0

Concrete Columns Form Type None

Concrete Column Forms - Plywood Number of … None

Beams

Average length of each concrete beam span (ft) 0

Average Area of Concrete Beam (in^2) 0

Number of concrete beams 0

Beams - Plywood Form Number of Uses None

Elevated Slabs

Elevated Slab Types One

Total Floor Area - Elevated Slab (sf) 139.8K

Average Depth - Elevated Slab (in) 4.5

Flat Slabs - Number of Plywood Uses None

One Way Joists - Plywood Forms Number of U… One

User Input - Concrete

Spread Footings

Total Concrete Spread Footings (cy) 148.7

Spread Footings - Plywood Forms Number of … One

Pile Caps

Total Concrete Pile Caps (cy) 656.4

Pile Caps - Plywood Forms Number of Uses None

Retaining Walls

Type of Retaining Wall None

Total Concrete Retaining Walls (cy) 0

Gravity Wall - Plywood Forms Number of Uses None

Cantilever - Plywood Forms Number of Uses None

Grade Walls

Total Concrete Grade Walls (cy) 0

Grade Walls - Plywood Forms Number of Uses None

Slab on Grade

Total Concrete Slab on Grade (cy) 377.5

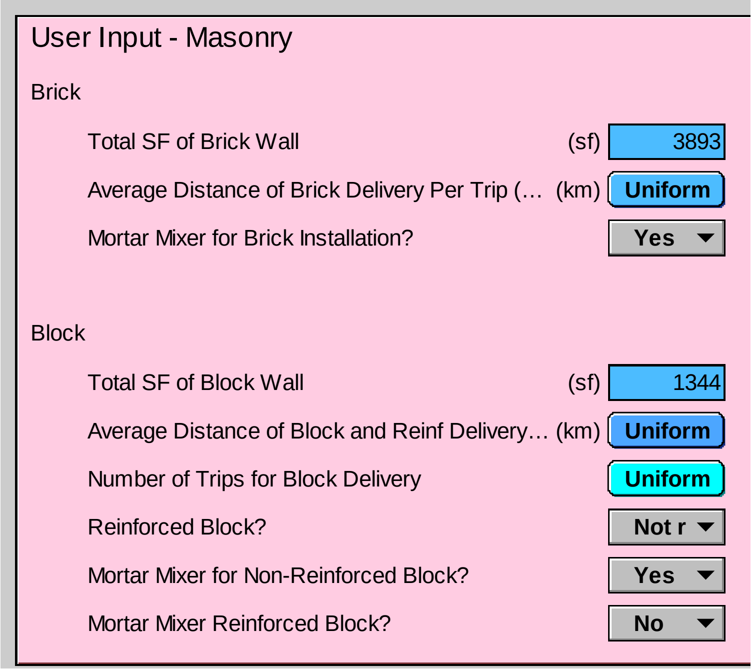
Total Amount Forms for SOG (lf) 744

SOG - Plywood Forms Number of Uses One

Figure 7. Concrete - User Input

4.2.4 Masonry

The two main aspects of the masonry category are brick and block, see Figure 8. For brick input, the user enters quantity information on the total area of the brick wall in square feet and average distance of brick delivery. The user has the decision to use or not to use a mortar mixer. Block input is similar to brick input, except additional information on reinforcement is required.



User Input - Masonry

Brick

Total SF of Brick Wall	(sf)	3893
Average Distance of Brick Delivery Per Trip (…	(km)	Uniform
Mortar Mixer for Brick Installation?		Yes

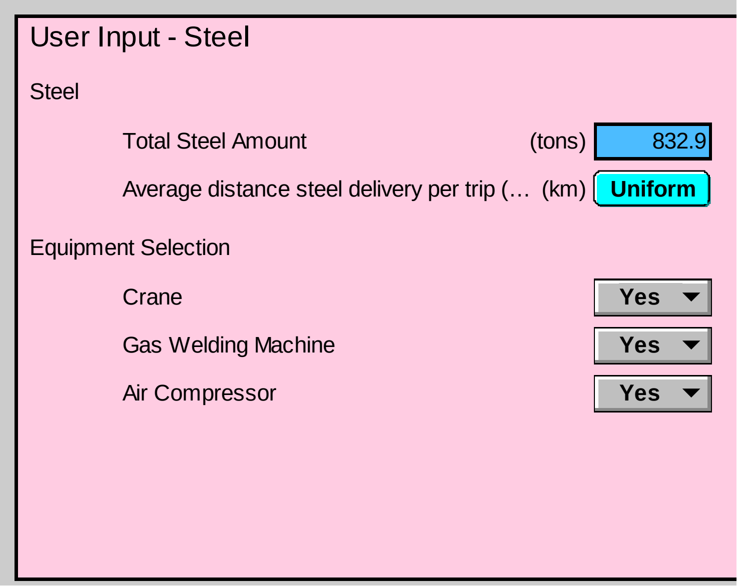
Block

Total SF of Block Wall	(sf)	1344
Average Distance of Block and Reinf Delivery…	(km)	Uniform
Number of Trips for Block Delivery		Uniform
Reinforced Block?		Not r
Mortar Mixer for Non-Reinforced Block?		Yes
Mortar Mixer Reinforced Block?		No

Figure 8. Masonry - User Input

4.2.5 Steel

The steel category is structured in a different manner, when compared with other categories such as concrete as shown in Figure 9. The total quantity of steel is input in tons, and the average distance for transportation is input in kilometers. The user selects from three types of equipment options for steel installation and erection: crane, gas welding machine, and air compressor.


User Input - Steel

Steel

Total Steel Amount (tons) 832.9

Average distance steel delivery per trip (… (km) Uniform

Equipment Selection

Crane Yes

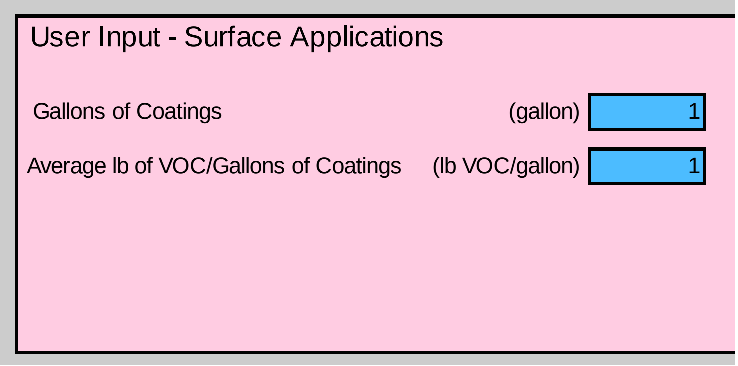
Gas Welding Machine Yes

Air Compressor Yes

Figure 9. Steel - User Input

4.2.6 Surface Applications

Surface applications are entered accorded to quantity and average pounds of VOCs/gallon of coating, as shown in Figure 10.


User Input - Surface Applications

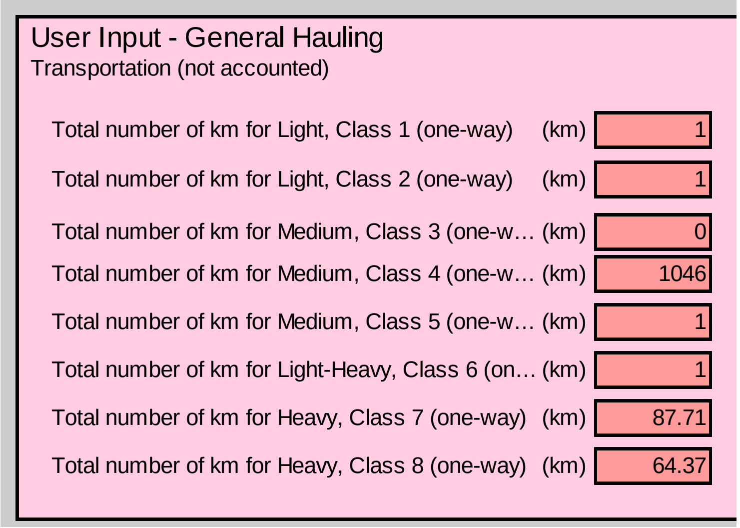
Gallons of Coatings (gallon) 1

Average lb of VOC/Gallons of Coatings (lb VOC/gallon) 1

Figure 10. Surface Applications - User Input

4.2.7 General Hauling

In general, transportation is included within each of the individual processes previously mentioned. Since many deliveries are made to construction projects, the user is able to input information related to transportation not otherwise accounted for in the other categories. One example is delivery of mechanical systems such as heating, ventilation, and air conditions components and elevators. This transportation category is organized and modeled according to eight different vehicle classes: Light Class 1, Light Class 2, Medium Class 3, Medium Class 4, Medium Class 5, Light-Heavy Class 6, Heavy Class 7, and Heavy Class 8, as indicated in Figure 11. The system is based on standard classifications. Information on the type of typical vehicle associated with the class is provided in the line item description in the model, so the user can make informed decisions. For example, Light Class 1 represents pick-ups and vans, Heavy Class 7 represents dump trucks and buses. While more detailed modeling information is documented in subsequent sections, it is important to note that the model does not require the user to enter specific weight information, only transportation distances with respect to vehicle class. Vehicles are assumed fully loaded to the project, and return load is assumed empty through the use of a load factor. This approach simplifies user information, which may be difficult and time prohibitive to obtain, and is consistent with other transportation processes used in the model.



User Input - General Hauling

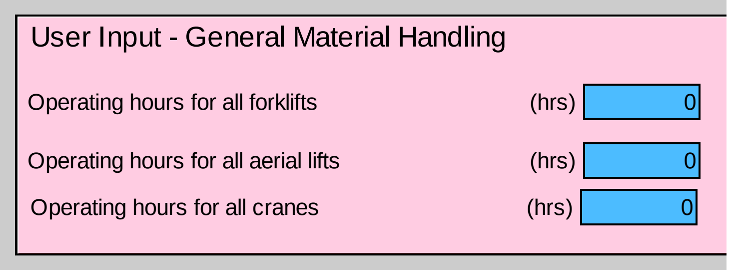
Transportation (not accounted)

Total number of km for Light, Class 1 (one-way)	(km)	1
Total number of km for Light, Class 2 (one-way)	(km)	1
Total number of km for Medium, Class 3 (one-w…	(km)	0
Total number of km for Medium, Class 4 (one-w…	(km)	1046
Total number of km for Medium, Class 5 (one-w…	(km)	1
Total number of km for Light-Heavy, Class 6 (on…	(km)	1
Total number of km for Heavy, Class 7 (one-way)	(km)	87.71
Total number of km for Heavy, Class 8 (one-way)	(km)	64.37

Figure 11. Transportation – User Input

4.2.8 Material Handling

The material handling category is similar to transportation because this category captures material handling efforts not captured within the other modeled processes. The main pieces of equipment are forklifts, aerial lifts, and cranes of which the user enters the hours of usage. This category is graphically shown in Figure 12.


User Input - General Material Handling

Operating hours for all forklifts (hrs) 0

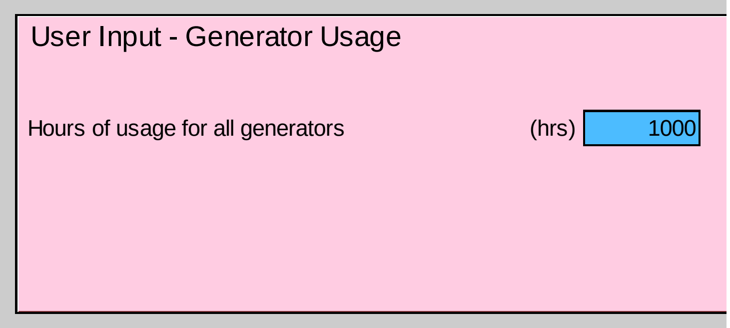
Operating hours for all aerial lifts (hrs) 0

Operating hours for all cranes (hrs) 0

Figure 12. Material Handling - User Input

4.2.9 Generators

This final category, Generators, is a relatively minor but important category due to the comparison potential between on-grid electricity emissions and generator emissions. The user inputs information on an hourly basis as shown in Figure 13.


User Input - Generator Usage

Hours of usage for all generators (hrs) 1000

Figure 13. Generator - User Input

In summary, project information is required in order to create a hybrid LCA construction model. The overall goal of this model was to maintain the highest level of accuracy with the appropriate level of efficiency. While the overall model outline is consistent, each category was modeled uniquely due to the nature of individual construction processes.

4.3 DETAILED MODEL

The detailed model module contains the main portion of the hybrid life cycle assessment model. In general, this module has two basic components: construction processes, shown in the fifth column in Figure 14, and data sources, located in the first four columns of Figure 14. The construction processes section models all of the relevant construction processes while drawing from the data sources of AP-42 emission factors, EIO-LCA information, Nonroad output, and existing unit processes. This section first documents and explains the data sources used in the model and concludes with information related to the construction processes. The order of the discussion follows the columns as shown in Figure 14.

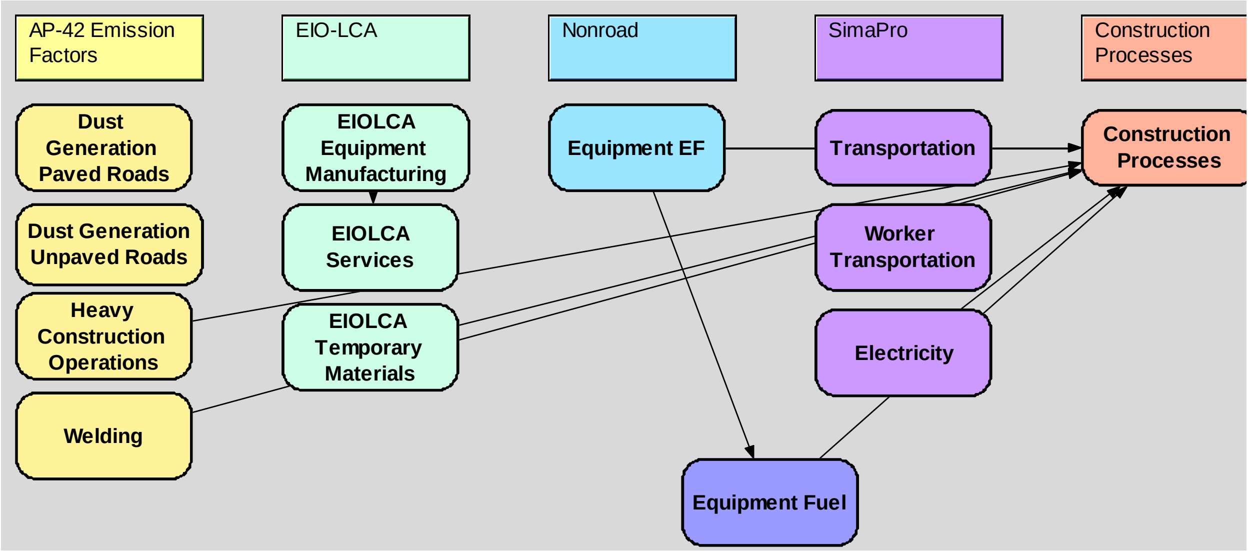


Figure 14. Detailed Model Overview

4.3.1 AP-42 Emission Factors

AP-42 emissions factors were used for four different elements of the model: Dust Generation Paved Roads, Dust Generation Unpaved Roads, Heavy Construction Operations, and Welding. This data source, AP-42, was selected because the four elements are important aspects of construction, but none of the other data sources capture the emissions associated with the four elements. This section describes each of the four emission factors (U.S. Environmental Protection Agency 2003).

4.3.1.1 Dust Generation – Paved Roads

Emissions from particulate matter are generated when vehicles pass over a paved surface. The emissions are typically from brake wear, tire wear, and resuspension of loose road materials. Resuspended particulate emissions are typically from loose matter on the paved surface generated from a continual process of surface loading from various contributing factors such as wind erosion, rainfall, street sweeping, ice and snow controls, pavement wear, speed of vehicles traveling on the road, average daily traffic, and number of lanes.

Prior to October 2002, the United States Environmental Protection Agency developed and used emission factors for paved roads, published in AP-42, that included exhaust, brake wear, tire wear, and resuspended road surface material emissions. The most recent version of AP-42, dated November 2006, used in this analysis, represents emission factors for paved roads that only includes particulate emissions from resuspended road surface materials. The other emissions are captured in the SimaPro processes, which do not capture resuspended particulates.

Equation 3 from AP-42, Section 13.2.1, Paved Roads was used to determine dust generation from paved roads in converted units of kg/vehicle kilometers traveled (VKT). The emissions generated from Equation 3 are PM-2.5, PM-10, PM-15, and PM-30. k was determined from Table 13.2-1.1; C was determined from Table 13.2.1-2 sL was entered as a distribution in a range from 0.1 to 0.4 g/m^2, and W was also entered as a distribution in a range from 2 to 40 tons. According to this AP-42 section, units are converted in the provided emission equation variables. While this section does provide information on means to control emissions and climate variability, the hybrid model assumes standard conditions. The graphical representation of how Equation 3 is modeled in Analytica is shown in Appendix C, Figure 105.

Equation 3.

$$E = k\left(\frac{sL}{2}\right)^{0.65} \times \left(\frac{W}{3}\right)^{1.5} - C$$

where:

E = Particulate emission factor

k = Particle size multiplier for particle size range

sL = Road surface silt loading

W = Average weight of vehicles traveling the road

C = Emission factor

4.3.1.2 Dust Generation – Unpaved Roads

Similar to paved roads, emissions occur from vehicles traveling over unpaved roads. Surface materials are lifted due to several factors including the force from the wheels and wind currents. Also similar to paved roads, the older version emission factor equation in the Unpaved Road Section of AP-42 included emissions from exhaust, brake wear, tire wear, and resuspended road surface materials. The most recent emission factor equation, which was used in this research, includes emissions from resuspended road surface material. Other emissions are captured in related Simapro processes.

Equation 4 from AP-42, Section 13.2.2, Unpaved Roads was used to calculate PM-2.5, PM-10, and PM-30:

Equation 4.

$$E = k\left(\frac{s}{12}\right)^{a} \times \left(\frac{W}{3}\right)^{b}$$

where: E = size-specific emission factor

s = surface material silt content (%)

W = mean vehicle weight (tons)

Where k, a, and b are empirical constants

Calculation of PM-15 was not possible due to limitations in available AP-42, Unpaved Roads information. Values for the above variables were obtained from the same AP-42 section as the equation, Unpaved Roads. The values for *k, a,* and *b,* were calculated from Table 13.2.2-2, Constants for Equations 1a and 1b, assuming unpaved roads in construction projects were more similar to industrial roads. The values for variable, s, range from .56% to 23%. The values for W range from 2 to 40 tons. All units are converted to kg/VKT. The graphical representation of Equation 4 is illustrated in Appendix C, Figure 106.

4.3.1.3 Heavy Construction Operations

The U.S EPA's AP-42, Section 13.2.3, Heavy Construction Operations, depicts heavy construction activities as having significant temporary impact on local air quality from dust emissions, citing both building and road construction activities with high emissions potential. Specific activities generating emissions include land clearing, drilling and blasting, ground excavation, and cut and fill operations. AP-42's Heavy Construction Operations section mentions the wide variability in construction activity emissions on a day-to-day basis due to dependence on level and type of activity, and meteorological conditions. While construction activities have wide ranges of emissions variability, commonality exists in construction sites because tasks have definable start and end points. Construction activity differs from other fugitive dust sources, where the emissions are relatively steady.

AP-42, Section 13.2.3, provides two methods to estimate construction emission, either area-wide or process specific. The area-wide method calculates total suspended particulates (TSP) based on one set of field measurements during construction of apartments and shopping centers. The area-wide equation provided in this AP-42 section includes a derived constant while considering the area of land being worked and the duration of the construction activity. Use of this equation is not recommended because a direct extrapolation from TSP to PM-10 will result in conservatively high estimates; further, the equation does not provide depth of information concerning which construction activities have the greatest emission potential. This section does recommend the process specific approach "that when emissions are to be estimated for a particular construction site, the construction process be broken down into component operations." Table 13.2.3-1 provides information on the associated sources along with recommended emission factors. This research used an information process specific approach as outlined in Table 13.2.-1, specifically, information related to dozer equations in AP-42, Section 11.9, Western Surface Coal Mining, Tables 11.9-1 and 11.9-2. The graphical representation is shown in Appendix C, Figure 107

4.3.1.4 Electric Arc Welding

Welding is the act of merging two parts of metal by forming a connection with an electrode. While over 80 different types of welding operations exist, the two most common general types are electric arc or gas-oxygen flame. Electric arc is the most common, but has the greatest emission potential. The percentages of electrodes consumed in 1991, by process types are (U.S. Environmental Protection Agency 2003):

- Shield metal arc welding (SMAW) – 45%
- Gas metal arc welding (GMAW) – 34%
- Flux cored arc welding (FCAW) – 17%
- Submerged arc welding (SAW) – 4%

The emissions generated during welding are particulate matter and hazardous metals with only electric arc welding generating the pollutants in sizeable quantities. Most of the particulate matter generated is submicron in size and all PMs are considered to be PM-10. While emissions vary according to electrode type, the hazardous metals designated in the 1990 Clean Air Act Amendments recorded in welding include manganese (Mg), nickel (Ni), chromium (Cr), cobalt (Co), and lead (Pb). No gas phase pollutants are considered, such as carbon dioxide, carbon monoxide, nitrogen dioxide, or ozone, since minimal information is available on these pollutants. The emission factors utilized for SMAW, GMAW, FCAW, and SAW from Table 12.19-1, PM-10, Emission Factors for Welding Operations, and Table 12.19-2, Hazardous Air Pollutant (HAP) Emission Factors for Welding Operations. While detailed information for each of the four welding types with associated electrode types is available in Tables 12.19-1 and 12.19-2, the information was analyzed and filtered to develop distributions since specific information on welding operations during construction is typically difficult to predict.

4.3.2 EIO-LCA Information

Inventory results from Economic Input-Output Life Cycle Assessment (EIO-LCA) were used for three major areas: construction equipment manufacturing, construction services, and temporary materials manufacturing. While general I-O information was previously described, more detailed information related specifically to EIO-LCA can be found in Appendix A.

4.3.2.1 Construction Equipment Manufacturing

Since construction equipment is a major component of construction and it is consumed in the construction process, it is important to include the manufacturing of construction equipment in the LCA. Different modeling approaches were considered for this category. For example, one option is to enter the dollar value of total project construction equipment into the associated economic sector in I-O. This option proved to have too many variables such as the age of the equipment and associated depreciated values, and knowledge of specific manufacturing makes and models. The second option is to enter the total value of construction in the associated sector in I-O and identify the construction equipment sectors. The sector results were then scanned and selected for relevancy to construction equipment manufacturing, as shown in Table 10.

Table 10. EIO-LCA Construction Equipment Manufacturing – Detailed Model

Lawn and garden equipment manufacturing
Construction machinery manufacturing
Other commercial and service industry machinery manufacturing
Other engine equipment manufacturing
Pump and pumping equipment manufacturing
Air and gas compressor manufacturing
Power-driven hand tool manufacturing
Welding and soldering equipment manufacturing
Fluid power cylinder and actuator manufacturing
Fluid power pump and motor manufacturing
Motor and generator manufacturing
Machinery and equipment rental and leasing

In the model, the user inputs the dollar value of construction in the User Input section. The dollar value of construction is then multiplied by the segregated construction manufacturing equipment results from EIO-LCA. Figure 15 illustrates the visual model in Analytica.

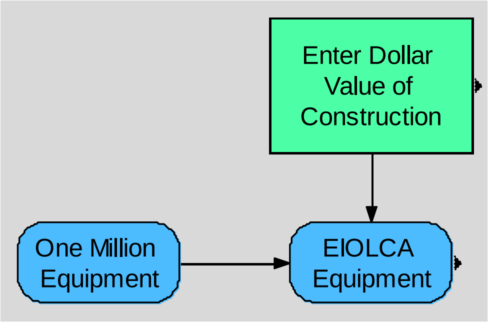


Figure 15. Manufacturing Equipment - Detailed Model

4.3.2.2 Construction Services

Construction services were modeled in the same method as construction equipment manufacturing. The results from EIO-LCA's Commercial and Institutional Building sector were reviewed to determine whether the sector was a construction service sector. Determining the appropriateness of a sector was more difficult in construction services. For the hybrid LCA model, a fairly broad interpretation of construction service sectors was used as represented in Table 11.

Table 11. EIO-LCA Construction Service Sectors - Detailed Model

Support activities for oil and gas operations	Specialized design services
Support activities for other mining	Custom computer programming services
Retail trade	Computer systems design services
Newspaper publishers	Other computer related services, including facilities management
Periodical publishers	Environmental and other technical consulting services
Book publishers	Scientific research and development services
Database, directory, and other publishers	Advertising and related services
Software publishers	Photographic services
Motion picture and video industries	Veterinary services
Sound recording industries	All other miscellaneous professional and technical services
Radio and television broadcasting	Management of companies and enterprises
Cable networks and program distribution	Office administrative services
Telecommunications	Facilities support services
Information services	Employment services
Data processing services	Business support services
Nondepository credit intermediation and related activities	Travel arrangement and reservation services
Securities, commodity contracts, investments	Investigation and security services
Insurance carriers	Services to buildings and dwellings
Insurance agencies, brokerages, and related serv.	Other support services
Funds, trusts, and other financial vehicles	Waste management and remediation services
Monetary authorities and depository credit intermediation	Elementary and secondary schools
Real estate	Colleges, universities, and junior colleges
Automotive equipment rental and leasing	Other educational services
Video tape and disc rental	Other ambulatory health care services
General and consumer goods rental except video tapes and discs	Child day care services
Lessors of nonfinancial intangible assets	Social assistance, except child day care services
Legal services	Hotels and motels, including casino hotels
Accounting and bookkeeping services	Other accommodations
Architectural and engineering services	Food services and drinking places
	Civic, social, professional and similar organizations

4.3.2.3 Temporary Materials

While the boundary for this hybrid LCA construction model does not include permanent materials, temporary materials are included. Temporary is defined as material that will not become a part of the permanent building. It is necessary to include temporary material in the construction phase because these materials are used directly and exclusively in the construction process. The temporary materials for this model are related to concrete forms. Within each of the concrete construction processes, a sub-module of concrete forms was created. Temporary materials as forms include wood, steel, fiberglass, and cardboard. Unlike construction equipment and services, temporary materials cannot be selected from Commercial and Institutional Construction sectors because they are identical to permanent construction materials. Detailed material cost information was available from R.S. Means, minimizing the risk of unknowns experienced in the construction equipment and service sectors. Individual EIO-LCA results were generated for four respective materials. Because R.S. Means cost data was from 2006 and the EIO-LCA data was from 1997 model (the most recent available) adjustments were made for inflation.

4.3.3 Nonroad Output and Model Details

The U.S. EPA's developed software program, Nonroad 2005 (U.S. Environmental Protection Agency 2005d) was used to model emissions from primarily nonroad equipment combustion. Appendix B provides more detailed explanations of the Nonroad model and association output.

While Nonroad provides several estimating and reporting capabilities for this research, the emission factor information was most prevalently used, which provided emission factors including: grams per operating hour by source classification codes (SCC), grams per operation hour by horsepower (hp) and SCC, grams per day by SCC; grams per day by hp and SCC, grams per hp-hour by SCC, and grams per hp-hour and SCC (U.S. Environmental Protection Agency 2005f). Emission factors (EF) are generally calculated by Equation 5 and are based predominately on emission tests that were adjusted for in-use operation that differs from typical testing conditions (U.S. Environmental Protection Agency 2004a).

Equation 5.

$$EF = ZHL \times TAF \times DF$$

where:

$EF =$ *Final emission factor used in the model (g/hp-hr)*

$ZHL =$ *Zero-hour level at a steady-state (g/hp-hr)*

$TAF =$ *Transient adjustment factor (unitless)*

$DF =$ *Deterioration Factor (unitless)*

ZHL, a function of the model year and horsepower technology, was determined from several sources including new engine test data, National Engine and Vehicle Emission Study (NEVES) and California's Air Resources Board (CARB) OFFROAD diesel emission factors. TAF adjusts the ZHLs to account for variations in engine speed and load. The DF adjusts for age-related deterioration and mal-maintenance. CO_2 emissions are based on brake-specific fuel consumption and a derived formula; SO_x is based on fuel consumption and fuel sulfur content. Crankcase emissions are based on percentages of exhaust emissions.

In summary, the created hybrid LCA model uses Nonroad output to calculate fuel usage and Equation 5 for emission factors. The list of equipment with associated fuel types available for use in the hybrid model is shown in Table 12.

Table 12. Construction Equipment with Fuel Types in Hybrid LCA Construction Model

Equipment	**Fuel**	
Chippers	Gasoline	Diesel
Loaders	Gasoline	Diesel
Compaction Plate	Gasoline	Diesel
Roller	Gasoline	Diesel
Drill Rig	Gasoline	Diesel
Crane	Gasoline	Diesel
Pumps	Gasoline	Diesel
Other Construction Equipment	Gasoline	Diesel
Cement and Mortar Mixers	Gasoline	Diesel
Air Compressor	Gasoline	Diesel
Generator	Gasoline	Diesel
Aerial Lifts	Gasoline	Diesel
Forklifts	Gasoline	Diesel
Chainsaws	Gasoline	
Crawler/Tractor		Diesel
Excavator		Diesel
Grader		Diesel
Welding Machine	Gasoline	

As previously mentioned in the User Input section, the user inputs a ratio of diesel to gasoline equipment. This ratio is then used in the model between the respective pieces of construction equipment. For example, if the project uses a loader, and the user enters 0.5 as the ratio, then the output is based on 50% emissions from loaders that use diesel fuel and 50% emissions from gasoline loaders that use gasoline fuel. The input ratio is constant for the entire project; that is, the user cannot assume a ratio of 0.5 for one piece of equipment and 0.5 for another piece of equipment. While the majority of construction equipment in Nonroad provides results for several fuel types, some equipment type results are only provided as a single fuel source, such as Chainsaws. The visual representation of Nonroad information including the fuel ratio is shown in Figure 16.

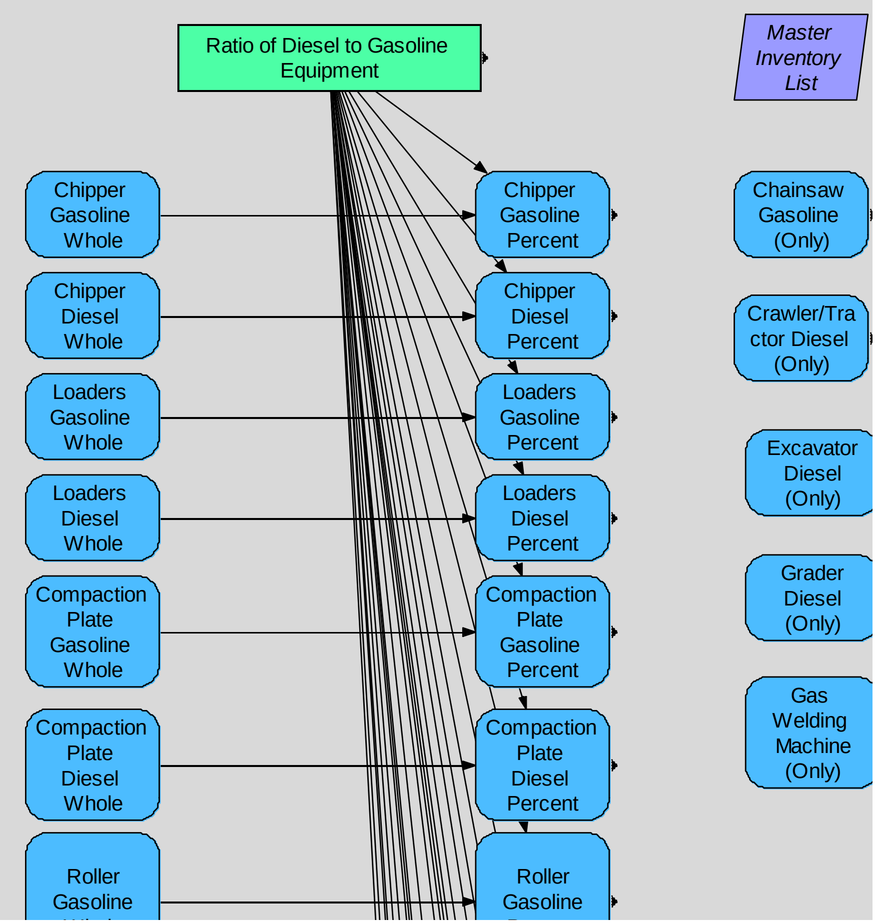


Figure 16. Partial Construction Equipment – Detailed Model

4.3.4 Process LCA from Existing Database

SimaPro, an LCA software package, allows users to conduct an LCA with preexisting unit processes, built-in impact assessment methods, and end-of-life options. SimaPro 5.0 is supported by several databases with ETH-ESU and Franklin the most extensive. Many unit processes are available varying from “Paint” to “Production of Paper Bags.” SimaPro, which was created in Europe, contains more European processes and impact assessment modeling.

The unit processes from SimaPro that were incorporated into the hybrid LCA model were primarily from the Franklin database, which focuses on United States' processes. ETH-ESU and Idemat 2001 were also used on a minimal basis when Franklin information was not available or combined with supplement Franklin information in a distribution. The three higher level categories are transportation, worker transportation, and electricity, as shown in Figure 14. A list of the processes used in the model is shown in Table 13.

Table 13. Existing Process Data Used in the Hybrid LCA Construction Model

Existing Processes	Database
Diesel Truck	Franklin
Gasoline Truck	Franklin
Diesel Trailer	Franklin
Gasoline Trailer	Franklin
Worker Transportation	ETH-ESU
Electricity	Franklin
Gasoline (Production, Distribution, etc.)	Franklin
Diesel (Production, Distribution, etc.)	Franklin and Idemat 2001

4.3.4.1 Transportation

As shown in Table 13, several Franklin database transportation processes were used in the development of the hybrid model. One truck and one tractor trailer was used with two fuel options. Similar to construction equipment, the user input ratio for truck and trailer transportation is allocated to the respective processes.

Eight classes of trucks are used within the model. Truck classification was used instead of specific weights of deliveries to reduce user input as it can be difficult to inventory the weights of all shipments during the bidding or design phases of projects. The classification system is based on codes from California (City of Berkley 2007) and is shown in Table 14.

Truck class information is embedded within construction processes; for example, it is assumed that a Heavy, Class 8 will deliver steel members. A user is not required to enter process specific information but can make changes as required. Additionally, a user can add unique project transportation components in the transportation modules, as shown in Figure 11. A truck delivery is assumed to ship full and return empty which is represented in a load factor. The load factor used in the model is a uniform distribution from 0.5 to 0.6 to account for unknowns in return weights.

Table 14. Truck Definitions and Classifications

Descriptive Size	Class	Gross Vehicle Weight (lbs)	Representative Vehicle
Light	1	<6,000	Pick-up, Van
Light	2	6000 - 10,000	Step Van, Small Courier Van
Medium	3	10,000 - 14,000	Metro Van, Small Tow Truck
Medium	4	14,000 - 16,000	Flat Bed
Medium	5	16,000 - 19,500	Large Tow Truck, Stake Truck, Package Delivery Van
Light-Heavy	6	19,500 - 26,000	Single Unit Truck (30'), Moving Van, Beverage Truck, Home Heating Oil Truck, Armored Car, Mini Bus
Heavy	7	26,000 - 33,000	Tractor/Trailer (40'), Moving Truck, Dump Truck, Transit Bus
Heavy	8	>33,000	Tractor/Trailer (50'), Moving Truck, Freight Truck, Concrete Truck, Gravel Truck, Articulated Bus, Greyhound Bus

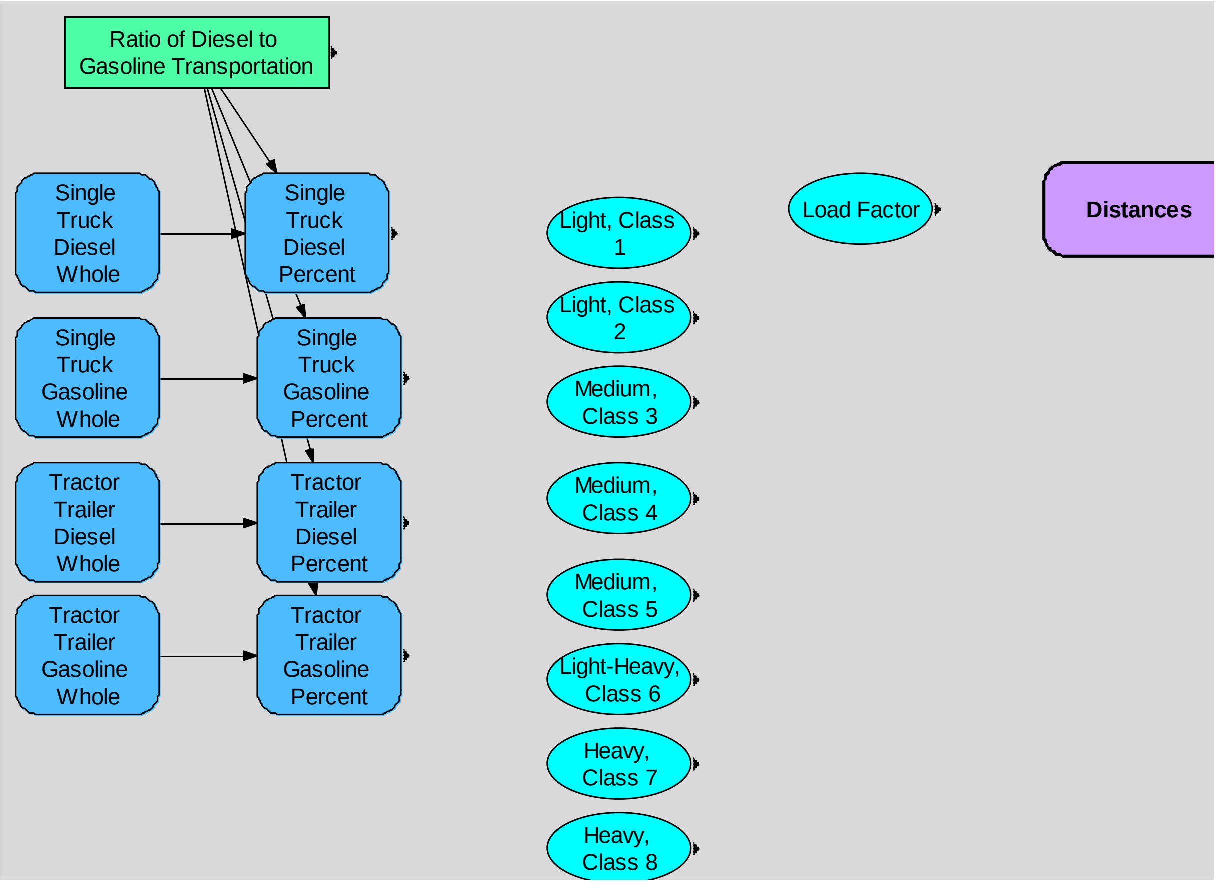


Figure 17. Transportation - Detailed Model

4.3.4.2 Worker Transportation

Worker transportation is modeled using the ETH-ESU process, Passenger car W-Europe ETH. U.S. Franklin passenger car information was not available. The process diagram for worker transportation is shown in Figure 18. User input is required for project duration, average construction workers/day, and average commute distance.

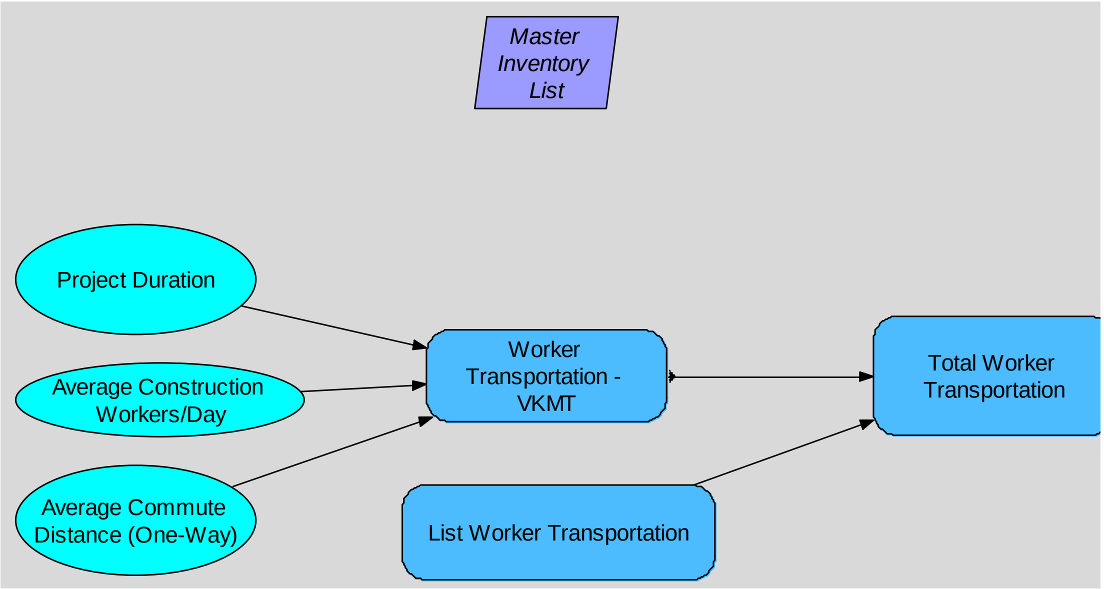


Figure 18. Worker Transportation - Detailed Model

4.3.4.3 Electricity

Electricity is modeled using the, Electricity average kWh USA, from the Franklin database. The model can be adjusted for specific regional electricity modeling by changing the existing unit process, if required by the user or the project. The unit process includes generation and distribution and accounts for line losses of about 8%.

4.3.5 Concrete Waste and Wastewater

Independent laboratory concrete wastewater results were included in the model whenever concrete installation occurs (Concrete Washout 2007). Additionally, solid concrete waste is included in the model.

4.3.6 Construction Processes

Modeling the construction process was a major portion of this research. The basic structure of the model and data is based on R.S. Means (R.S. Means 2006). Pre-processing R.S. Means information was done in Excel, before additional model development in Analytica. The available construction processes in the hybrid LCA construction model is shown in Figure 19 and aggregated into eight main categories of site preparation, deep foundations, concrete, masonry, steel, paints and sealants, general hauling and material handling, and energy. Information within each construction process draws from the references previously mentioned.

Construction has a multitude of processes, and modeling every process was not practical. The selected construction processes represent the major core and shell processes, which is the focus of this research. While building fit-out is not included, it is possible for the user to input information related to this phase or the building use phase in the general hauling, material handling, paints, sealants, and energy categories.

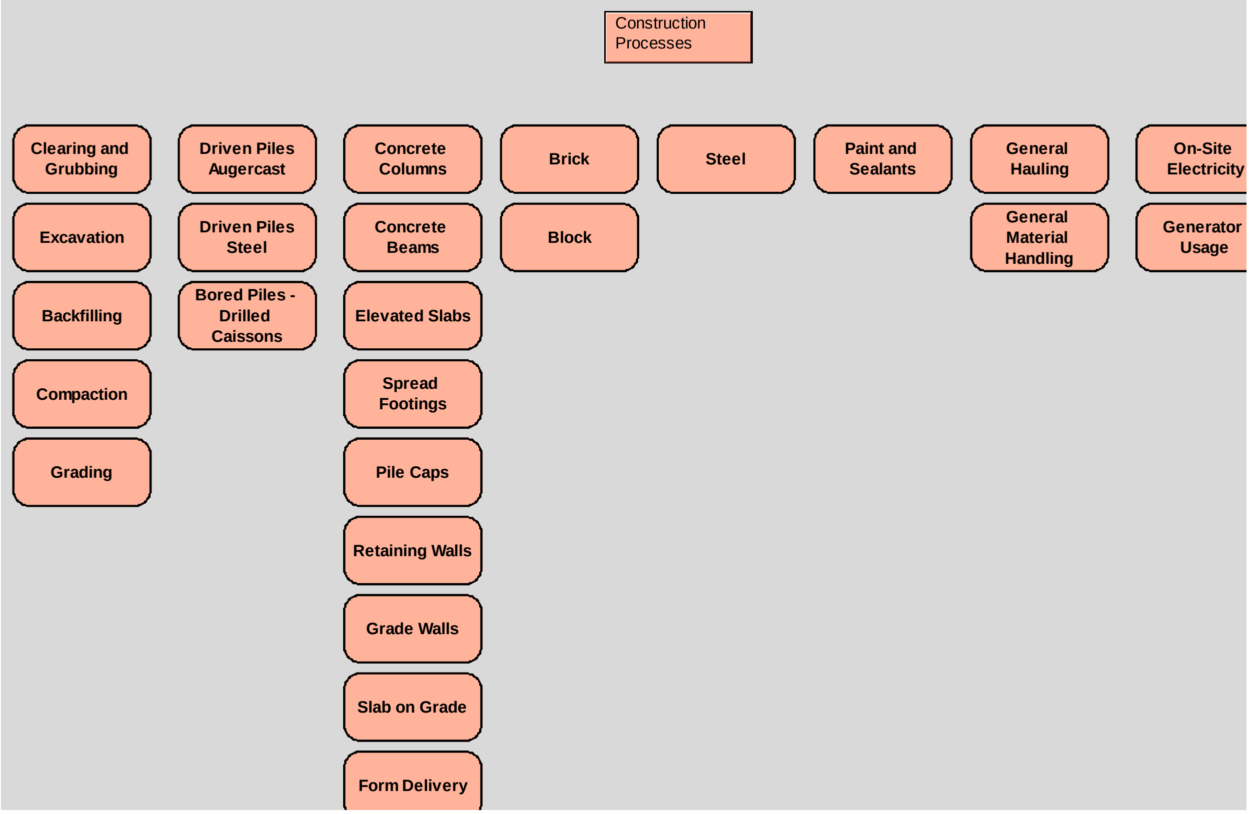


Figure 19. Construction Processes - Detailed Model

This section first describes one representative process in each of the eight categories, and then concludes with a summary of themes in the construction process model. The process diagram from the remaining construction processes can be found in Appendix C. While each construction process is unique, there are themes which are common in all processes.

4.3.6.1 Site Preparation

Five major construction processes are within the site preparation category: clearing and grubbing, excavation, backfilling, compaction, and grading. This section describes excavation, a representative construction process in this category, and is visually represented in Figure 20, the process diagram created in Analytica. Clearing and grubbing (Figure 108), backfilling (Figure 109), compaction (Figure 110), and grading (Figure 111) are located in Appendix C.

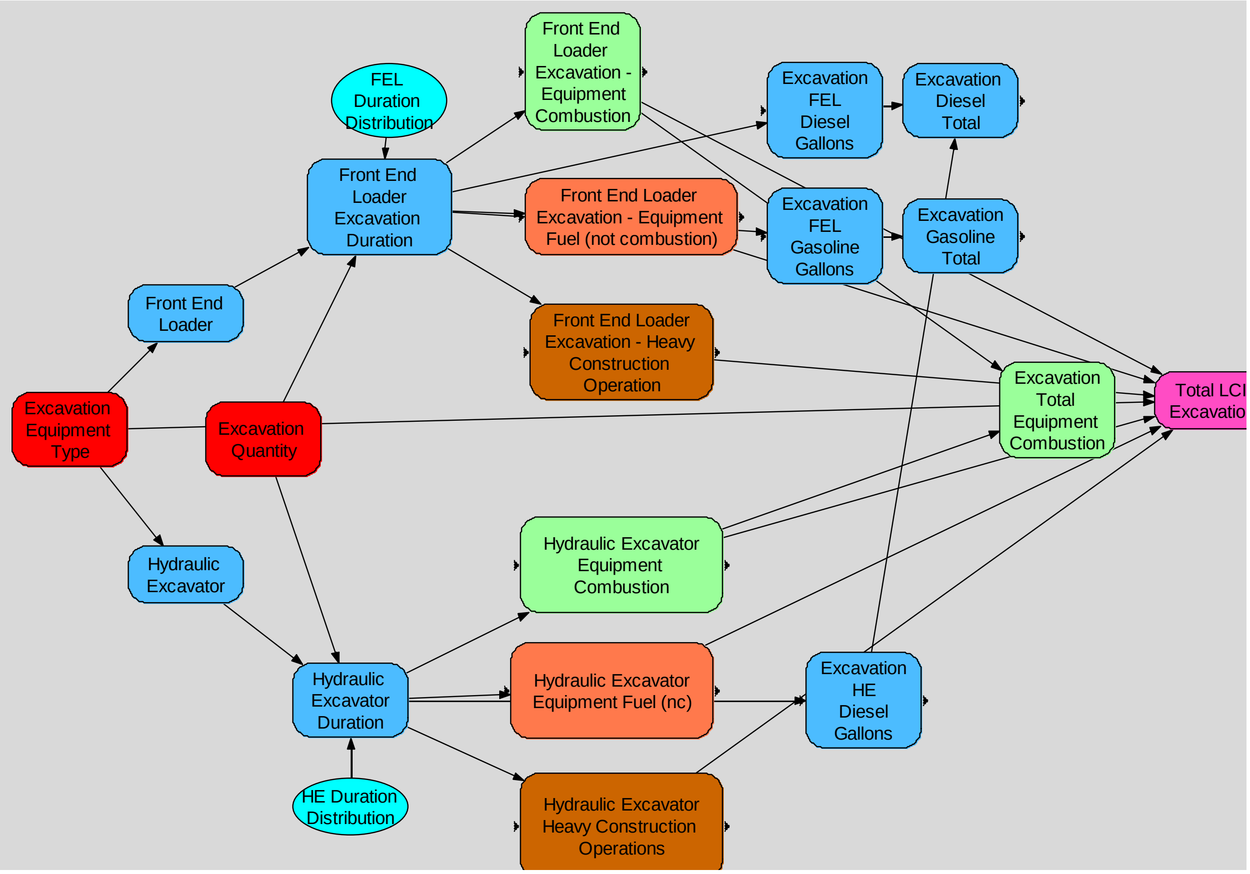


Figure 20. Excavation - Detailed Model

The first "node" in Figure 20 is "Excavation equipment type". From information provided by the user in the User Input section, the type of equipment is selected, either front end loader or hydraulic excavator, indicating a direction in the decision path. R.S. Means provides information on Crew Types, which provides information on the number and type of tradesmen (Carpenter, Mason, Laborer, etc.) and the type of equipment (concrete pump, crane, concrete mixer, etc.). The equipment information from R.S. Means' crew types was used throughout the development of the model.

For this discussion, assume the user selected a front end loader; the process for a hydraulic excavator is similar. Additionally, the user enters the quantity of excavation. The quantity is then directed to the node “Front end loader excavation duration,” along with the chance node “FEL Duration Distribution.”

Detailed descriptive information contained within “FEL duration distribution” is from R.S. Means (2006) and is provided to allow the user to have a more thorough understanding of detailed model information. The detailed information defining the chance node is represented in Table 15 and includes referencing information such as the entire CSI Masterformat classification system, R.S. Means specific numbers, relevant pages in R.S. Means, and specific title of task. The main data from R.S. Means for this process is “labor hours/cy” defined as the required labor hours to excavate one cubic yard. Since labor hour/cy is dependent on the capacity of equipment, a distribution was established to account for variations. If the user is knowledgeable of project specific equipment capacity, then more precise information can be entered. The decision to use distributions over precise project information was motivated by the overall goal to minimize the amount of required user input.

Table 15. Excavation, Front End Loader, Duration Distribution Information

Excavation	Bucket Size (cy)	Labor Hours/cy	Min	Median	Max
RS Means 02315-424-1200 through 1350 Page 37 Excavating, Bulk Bank Measure Front End Loader, Track Mounted	1.5	0.021	0.009	0.014	0.021
	2.25	0.016			
	2.5	0.012			
	5	0.009			

Information from “FEL duration distribution” and “Excavation quantity” is processed in the node “Front End Loader Excavation Duration” to obtain the total hours. It is assumed that labor hours/cy parallels the same amount of time the equipment will be used, which is consistent with Nonroad data and modeling.

The results from “Front end loader equipment duration” is multiplied by the equipment combustion data from Nonroad output and allocated according to the diesel and gasoline ratio in the node “Front End Loader Equipment Combustion,” providing the results for equipment combustion.

The results from the node, “Front end loader excavation – equipment fuel (not combustion),” include the inventories for gasoline and diesel generation and distribution, and the total gallons of fuel used. Within this node is the result from “Front end loader excavation duration” in hours multiplied by the Nonroad fuel usage data in gallons per hour, and the diesel and gasoline ratio.

“Excavation FEL diesel gallons” and “Excavation FEL gasoline gallons” also draws upon the Nonroad fuel usage data in gallons per hour and total hours of operations to calculate total gallons of gasoline and diesel for the front end loader. The total fuel usage for excavation is summed in “Excavation diesel total” and “Excavation gasoline total.”

“Front end loader excavation – heavy construction operations” calculates the PM from construction operations by multiplying the equipment duration and emission factors from AP-42, Heavy Construction Operations emissions factors previously described.

Finally, all the information is summated in “Total LCI excavation.” R.S. Means data associated with the hydraulic excavator is shown in Appendix D, Table 27.

4.3.6.2 Deep Foundations

Deep foundations are represented in three major categories of driven augercast piles, driven steel piles, and bored piles as drilled caissons. This section describes driven augercast piles, as shown in Figure 21. The process diagrams and R.S. Means data for driven steel piles and bored piles as drilled caissons are shown in Appendix C, Figure 112 and Figure 113; Appendix D, Table 28 and Table 29 respectively.

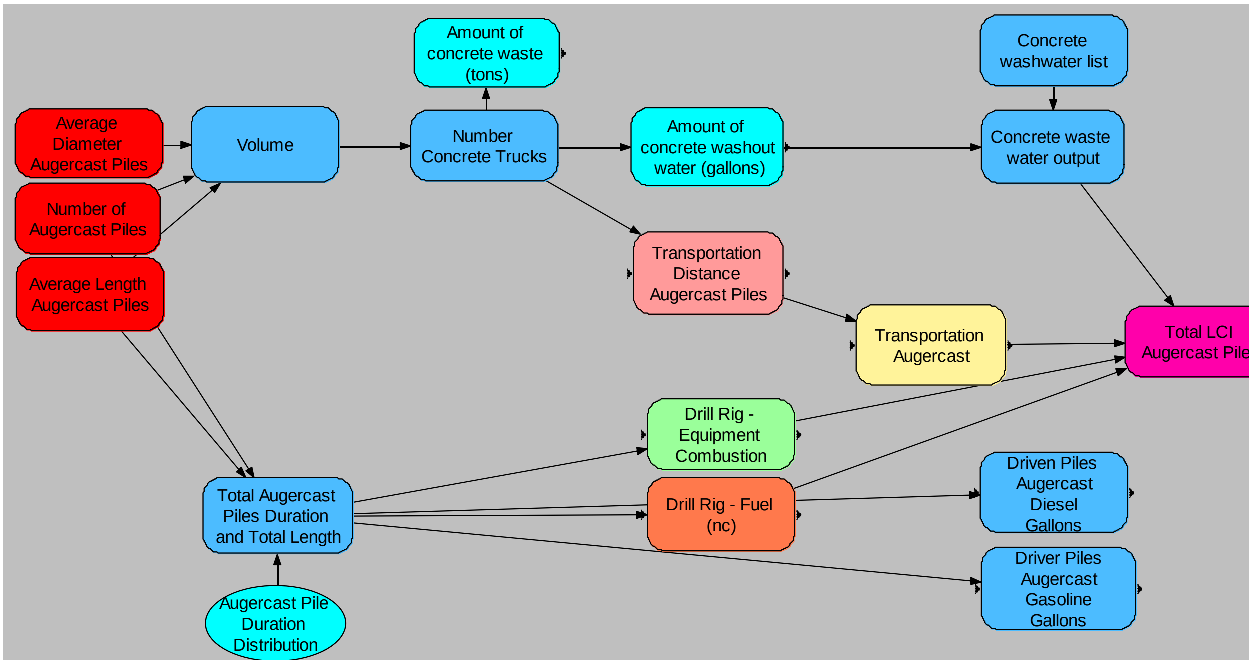


Figure 21. Driven Augercast Piles - Detailed Model

While modeling aspects of driven augercast piles are similar to excavation, some elements are unique. The first step incorporates the user input of “Average diameter augercast piles,” “Number of augercast piles,” and “Average length of augercast piles” to calculate the total volume in cubic yards. Next the “Number of concrete trucks” required to transport the concrete is calculated dividing the total volume of concrete by 10, the average amount of concrete in one truck. The ceiling function is used to account for rounding. The total number of concrete trucks is used to calculate the results of “Amount of concrete waste,” “Concrete wastewater output”, and “Transportation augercast.”

“Amount of concrete waste” is calculated by multiplying the number of trucks and amount of concrete waste per truck. The node, “Amount of concrete washout wastewater,” multiplies the number of concrete trucks and number of gallons of water to clean the truck; the result of “Concrete wastewater output” is the multiplication of the number of gallons of water washout and the vector from the node “Concrete wastewater list.”

“Transportation distance augercast piles” calculates the total distance traveled by the concrete trucks by multiplying the number of trucks, input from the user on the distance from the concrete plant to the site, and the number two to account for the round trip. “Transportation augercast” takes the concrete distance traveled information and multiplies this information by weight classification of Heavy Class 7, load factor distribution, 2 (to account for round trip), and diesel and gasoline ratio. “Total augercast pile duration and total length” first calculates the total vertical feet from the user input, and then draws from information from the node, “Augercast pile duration distribution.” The data for this distribution duration node was from R.S. Means (see Table 16) and is in units of labor hours per vertical linear feet (VLF).

The results from “Total augercast pile duration and total length” is multiplied by the equipment combustion data from Nonroad output and allocated according to the diesel and gasoline ratio in the node “Drill rig – equipment combustion,” providing the results for equipment combustion.

The results from the node, “Drill rig – Fuel (nc)” include the inventories for gasoline and diesel generation and distribution and the total gallons of fuel used. Within this node is the result from the duration in hours multiplied by the Nonroad fuel usage data in gallons per hour, and the diesel and gasoline ratio.

“Driven augercast piles diesel gallons” and “Driven augercast piles gasoline gallons” also draws upon the Nonroad fuel usage data in gallons per hour and total hours of operations to calculate total gallons of gasoline and diesel for the front end loader to calculate total fuel usage for driven augercast piles. Finally, all the information is summated in “Total LCI augercast piles.” It is assumed that the piles are not reinforced.

Table 16. Augercast Piles, Duration Distribution

Cast in Place Concrete Piles - Augercast Concrete Piles	Diameter (in)	Labor Hours/VLF	Min	Median	Max
RS Means 02455-100-0050 through 0080 Page 44 Cast in Place, Augered Piles, no casing or reinforcing 8" to 18" Diameter	8	0.089	0.089	0.1235	0.2
	10	0.1			
	12	0.114			
	14	0.133			
	16	0.16			
	18	0.2			

4.3.6.3 Concrete

Since concrete operations are fairly different dependent upon the final product, several concrete construction processes were developed, namely: concrete columns, concrete beams, elevated slabs, spread footings, pile caps, retaining walls, grade walls, and slab on grade. Form delivery is also included as a process. While the list of concrete processes is extensive, it does not account for all concrete construction processes. This section describes concrete beams, as shown in Figure 22. The process diagrams and R.S. Means data for concrete columns, concrete beams, elevated slabs, spread footings, pile caps, retaining walls, grade walls, and slab on grade are shown in Appendix C, Figure 114 through Figure 120, and Appendix D, Table 30 through Table 49.

The node, “Total concrete (CY),” multiplies the user input of “Number of concrete beams,” “Average area of concrete beams,” and “Average length of each concrete beam span” to calculate the total beam amount of concrete. Similar to augercast piles, the total concrete is used to calculate the “Number of concrete trucks” required to transport the concrete. The total number of concrete trucks is then used to calculate the results of “Amount of concrete waste,” “Concrete wastewater output”, and “Transportation concrete.”

The transportation of the reinforcement is computed in four nodes, “Pounds of steel,” “Reinf distribution,” “Trip number rebar,” and “Rebar distance.” “Pounds of steel” is calculated from “Reinf distribution” and user input of number of beams and average length of the beams. Information from R.S. Means is used to determine the distribution in the node, “Reinf distribution.” “Trip number rebar” was calculated by dividing the total pounds of rebar by 26,000. “Rebar distance” multiplies the number of trips and the user input on the rebar delivery distance. Finally, “Transportation rebar” multiplies the rebar distance, load factor distribution, two (round trip), weight classification of Heavy Class 7, and the diesel and gasoline ratio.

“Placement, pouring, and finishing duration” node draws from quantity of concrete and the node, “Beam distribution,” which contains distribution information on the amount of required installation time as shown in Appendix D, Table 37. The results from “Placement, pouring, and finishing duration” is multiplied by the equipment combustion data from Nonroad output and allocated according to the diesel and gasoline ratio in the nodes “Concrete pump equipment combustion” and “Gas engine vibrator equipment combustion” providing the results for equipment combustion.

The results from the nodes, “Concrete pump fuel (nc)” and “Gas engine vibrator (nc)” include the inventories for gasoline and diesel generation and distribution and the total gallons of fuel used. Within this node is the result from the duration in hours multiplied by the Nonroad fuel usage data in gallons per hour, and the diesel and gasoline ratio. Similar to the previously mentioned processes, the concrete pump and gas engine vibrators draw upon the Nonroad fuel usage data in gallons per hour and total hours of operations to calculate total gallons of gasoline and diesel. Within the module, “Concrete beams,” is the sub-module “Forms,” as shown in Figure 22. The user selects the number of times the forms will be used from one to four. The selection allocates the percentage of emissions that applies to the project under consideration. The percentage is not strictly based on the number of uses. Instead, information is based on averages from R.S. Means based on cost. Allocation based on cost was selected over direct use ratios because the cost allocations are eventually used in the node, “Plywood Form Results,” which also uses cost information.

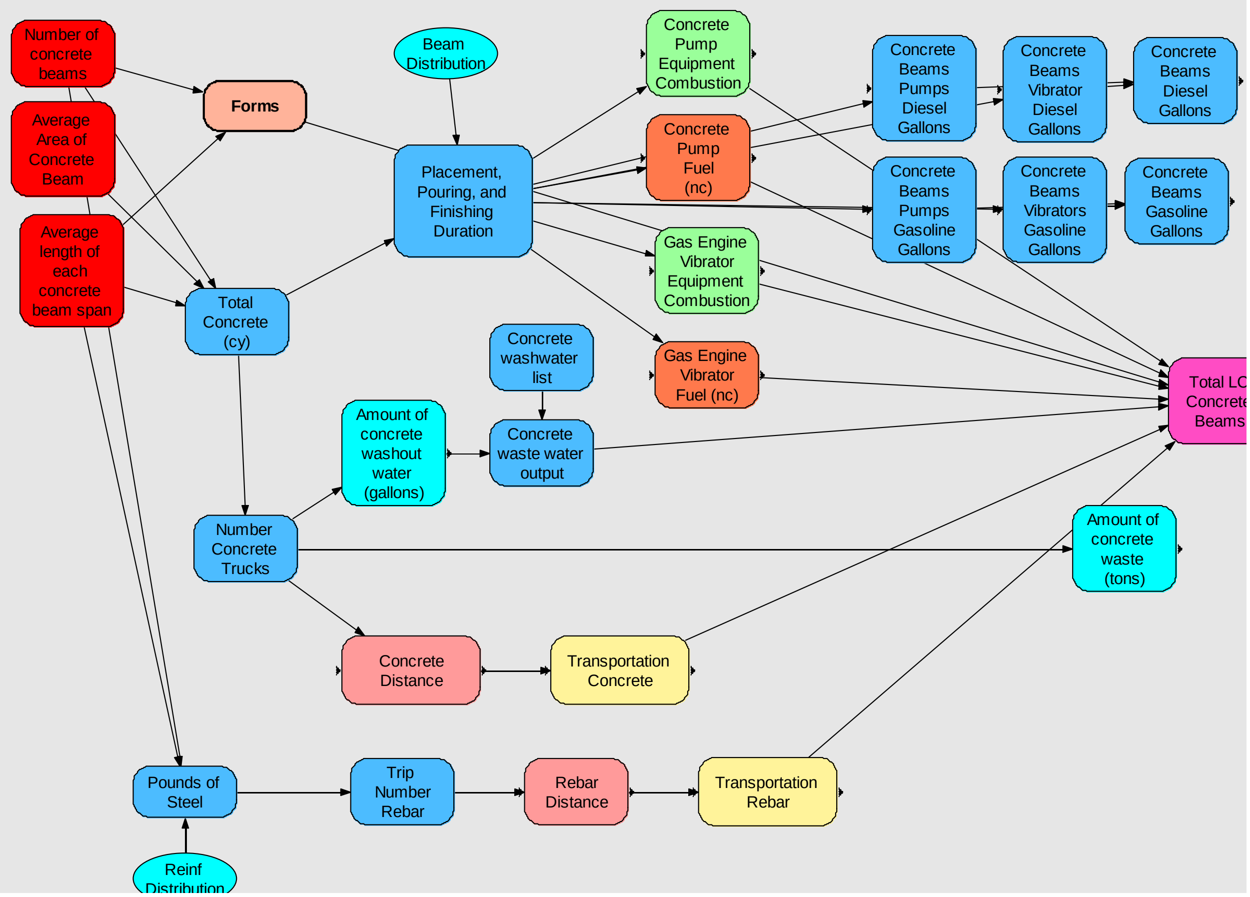


Figure 22. Concrete Beams - Detailed Model

The “Form plywood calculation” node draws from the nodes “Form installation distribution,” “Form cost distribution,” and the number of uses. “Form installation distribution” was also established from R.S. Means’ information and is shown in Appendix D, Table 35. “Form Cost Distribution” nodes contains information related to the material cost per square foot contact area (SFCA) shown in Appendix D, Table 36.

"Form plywood calculation" multiplies the form cost distribution information, form installation distribution information, concrete quantity, and number of uses with results in dollars. The information from this node then enters into the node, "Plywood form results," where the results are multiplied by EIO-LCA wood sector (Veneer and Plywood) results. Finally, all information is summed in "Total LCI Concrete Beams."

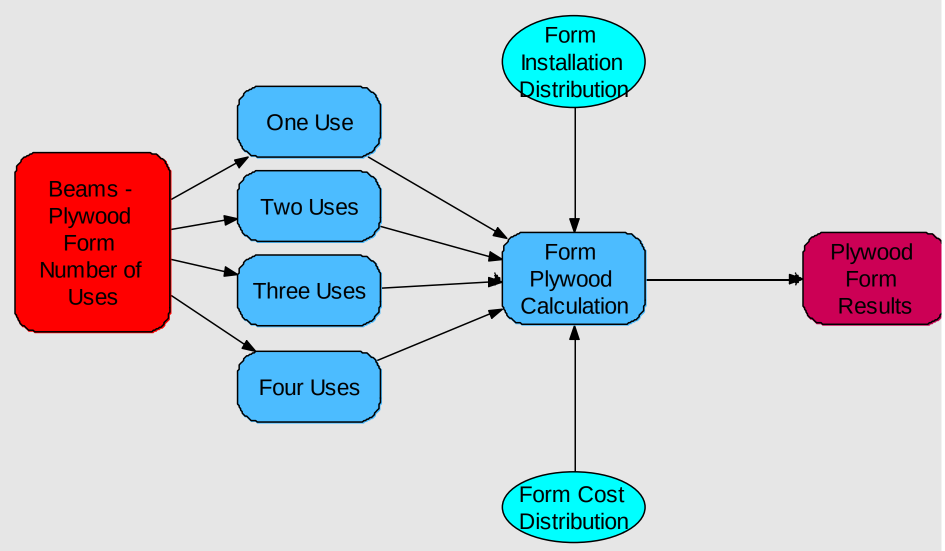


Figure 23. Forms, Concrete Beams - Detailed Model

4.3.6.4 Masonry

The masonry category of the detailed model includes brick and block installation. Since both processes are fairly similar, this section describes the brick construction process as illustrated in Figure 24. The process diagram for block is shown in Appendix C, Figure 121, with R.S Means related data also in Appendix D, Table 50 through Table 53.

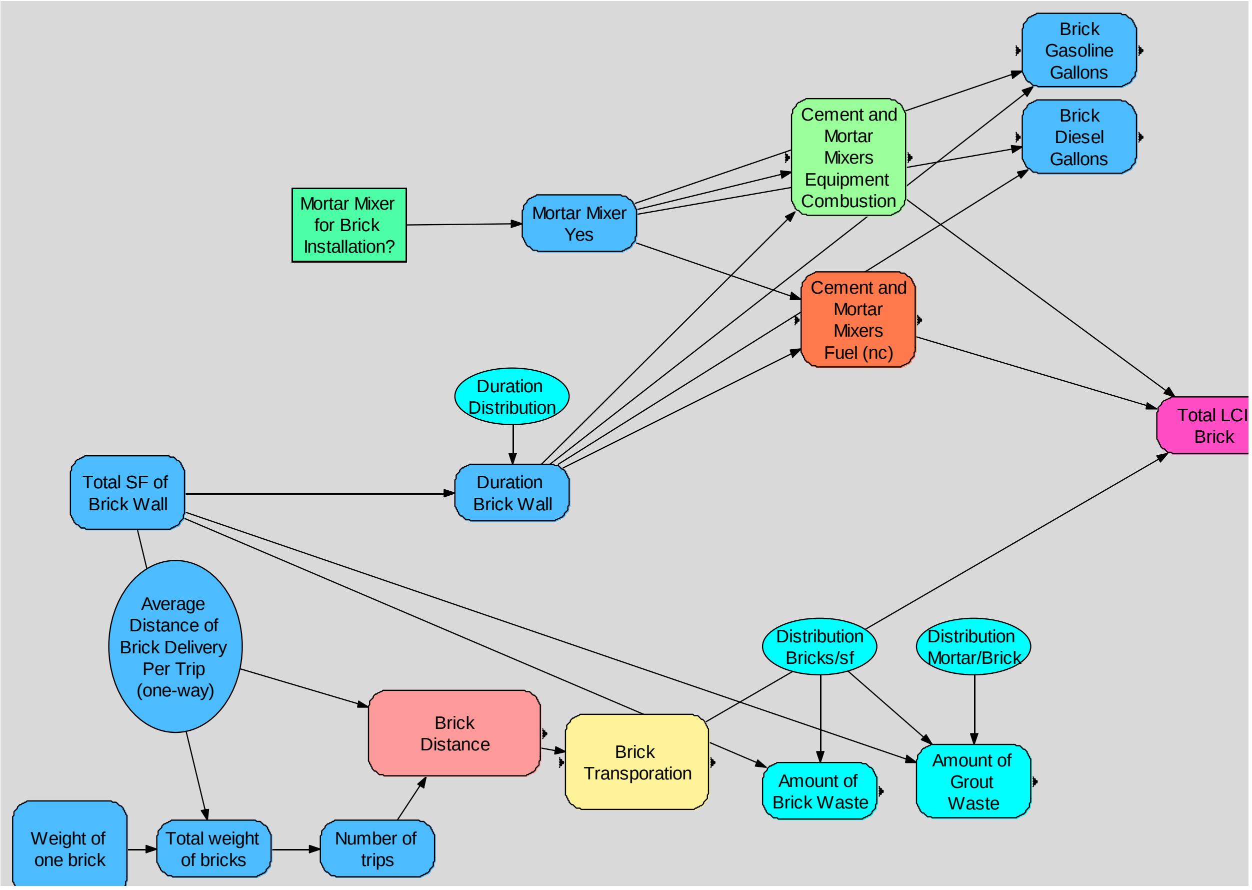


Figure 24. Brick - Detailed Model

The user provides information on “Total SF of Brick Wall,” which is used in several subsequent processes. For example, quantity of brick is used to calculate the “Total weight of bricks,” along with the assumptions related to the brick’s weight and surface area.

The “Number of trips” is calculated by dividing the total weight of the bricks by the assumed maximum load the vehicle can carry. “Brick distance” multiplies information from “Average distance of brick delivery per trip (one-way)” and “Number of trips.” Information on the distance of brick delivery per trip is provided by the user and can be entered as a distribution if the precise information is not known. “Brick Transportation” node contains the formula for multiplying brick distance, two (round trip), light heavy class 6 truck information, load factor, and the diesel and gasoline ratio. The amount of waste during brick installation includes both brick waste and grout waste. The node, “Amount of brick waste,” is calculated by multiplying the total amount of brick by an assumed three percent waste factor. The weight of bricks and the “Amount of grout waste” is calculated in a similar manner but with the percent waste factor, based on information from R.S. Means, as shown in Table 53.

In terms of equipment combustion, the user enters “yes” if a mortar mixer will be used, and if the answer is positive, then the inventory from equipment combustion is generated in first node, “Duration brick wall.” Information from “Duration distribution” and “Total sf of brick wall” is processed in the node “Duration brick wall” to obtain the total hours. It is assumed that labor hours/cy parallels the same amount of time the equipment will be used, which is consistent with Nonroad data and modeling. The results from “Duration distribution” is multiplied by the equipment combustion data from Nonroad output and allocated according to the diesel and gasoline ratio in the nodes “Cement and mortar mixers equipment combustion” providing the results for equipment combustion.

The results from the node, “Cement and mortar mixer fuel (nc)” include the inventory for gasoline and diesel generation and distribution and the total gallons of fuel used. Within this node is the result from the duration in hours multiplied by the Nonroad fuel usage data in gallons per hour, and the diesel and gasoline ratio. Similar to the previously mentioned processes, the mixer draws upon the Nonroad fuel usage data in gallons per hour and total hours of operation to calculate total gallons of gasoline and diesel for the front end loader to calculate total fuel usage. All results are summed in the node, ‘Total LCI brick.”

4.3.6.5 Steel

The construction process for steel is different than the previously mentioned processes. The steel process is broken into three main sub-modules of “Equipment,” “Transportation,” and “Welding,” (see Figure 25). The user enters the total weight of steel and this information is used in all three sub-modules. The first sub-module, “Equipment,” relies on user input in terms of equipment selection. The user selects from three pieces of equipment of crane, gas welding machine, and air compressor. The selection of the pieces of equipment used to develop the steel construction process is consistent with crew information from R.S. Means. The modeling of equipment combustion and fuel usage parallels the previously described processes, see Appendix C, Figure 122. In terms of steel erection duration, a distribution was established that assumes that 2 to 3 tons of steel per hour, consistent with R.S. Means information, specifically, R051223-20 Steel Estimating Quantities. “Transportation” is also calculated in a similar manner as the other processes as shown in Appendix C, Figure 123. The user provides information on the average steel delivery distance, which then is used in the node, “Steel distances,” along with estimating the number of steel trips. Final transportation information is calculated in the "Steel transportation" node by multiplying the one previous node, two (return trip), load factor, and diesel and gasoline ratio. The third sub-module, "Welding," relies on user input to select the type of welding method. The process model is shown in Appendix C, Figure 124. The welding process model relies on AP-42 information, as described in Section 4.3.1.4. The information in the module is not related to equipment combustion, only emissions from the welding process. The node, "Steel waste," estimates the amount of steel waste, based on an estimate of steel waste at 0.25% (R.S. Means 2006).

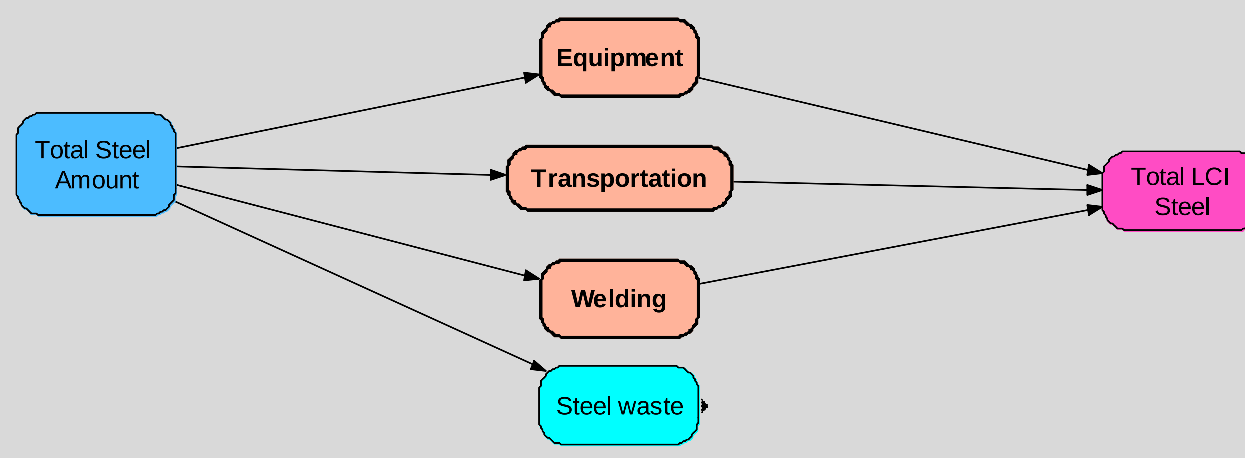


Figure 25. Steel - Detailed Model

4.3.6.6 Paints and Sealants

Surface applications, such as paints and sealants rely heavily on information provided by the user. The process diagram for this category is shown in Figure 26. The user enters both the gallons of paint and the average volatile organic compounds (VOCs) found in one gallon. If the user is unsure of average VOCs, default values are listed in the node "Average lb of VOC/gallon of coating." The node, "VOC coatings," multiplies the gallons of coatings and VOCs with the final summation in "Total LCI VOC." The amount of paint waste is calculated by assuming one gallon weighs about ten pounds with a two percent waste factor. The user can modify the average weight of one gallon, if more detailed information is known.

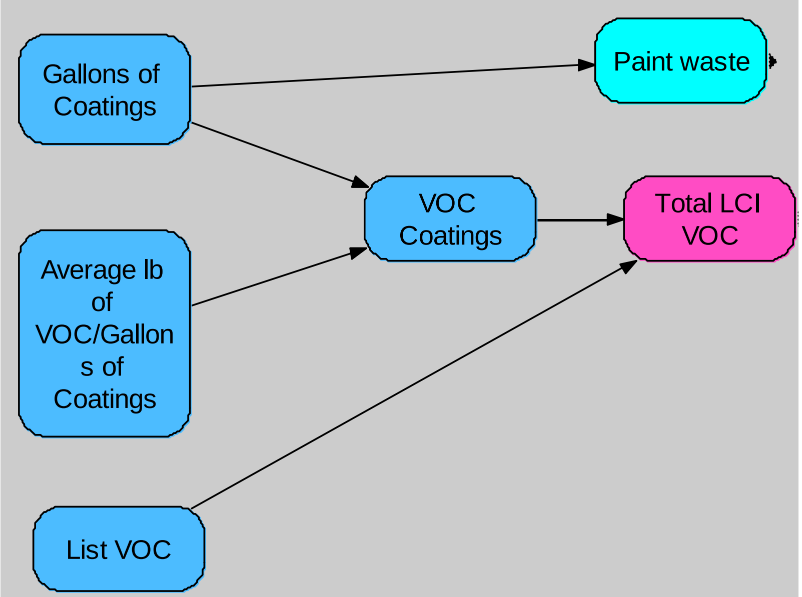


Figure 26. Surface Applications – Detailed Model

4.3.6.7 General Hauling and Material Handling

General hauling (see Figure 27) and material handling (see Figure 28) allows the user to capture transportation and material handling aspects that are not otherwise accounted for in the modeled construction processes. Transportation is modeled by taking user input distance information with respective vehicle classes, and then modeled in the same manner as transportation is modeled in the other construction processes.

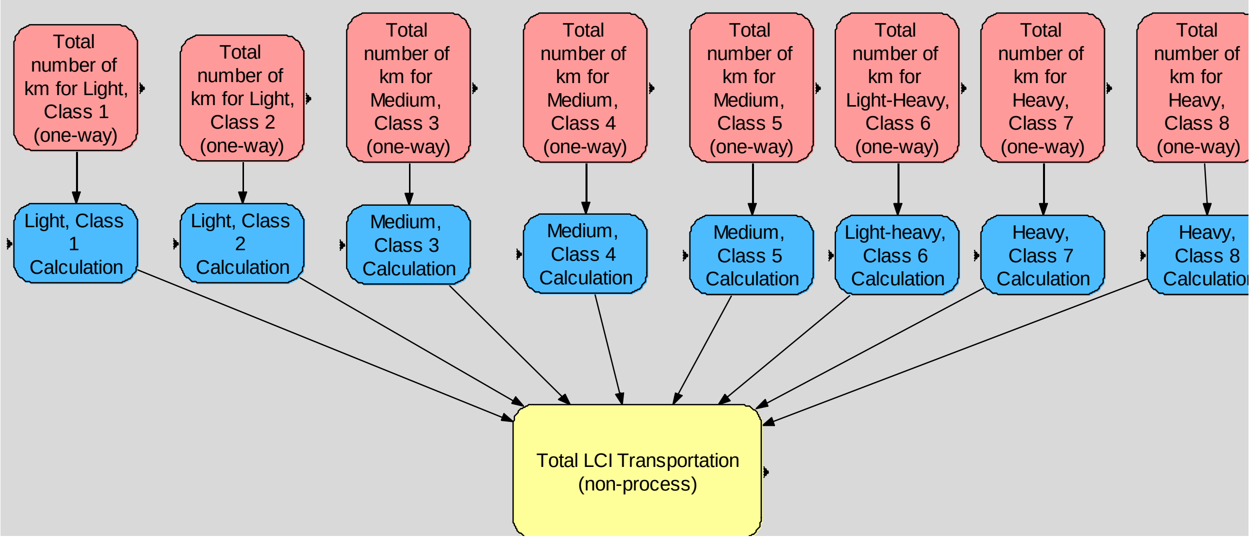


Figure 27. General Hauling - Detailed Model

Material handling also relies on input from the user in terms of hours of use for forklifts, aerial lifts, and cranes. This information only applies to equipment that is not accounted for in other construction processes. Equipment combustion, fuel (nc), and fuel usage is modeled similar to the other construction processes.

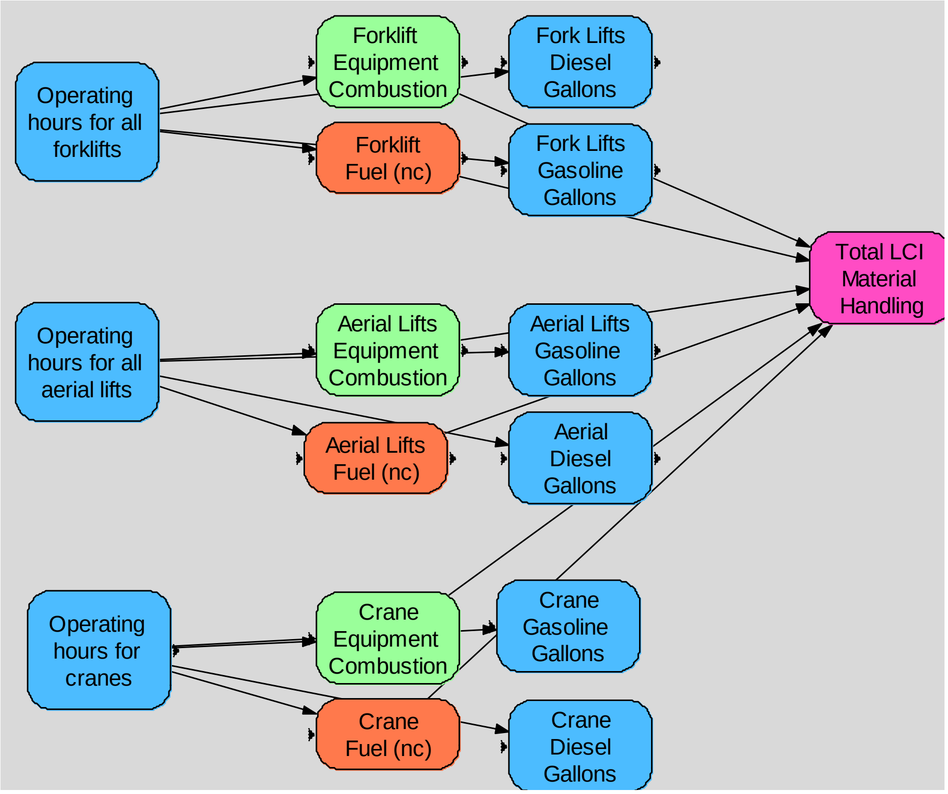


Figure 28. Material Handling – Detailed Model

4.3.6.8 Energy

The process diagrams for the energy include both on-site electricity and generators and are relatively simple diagrams. Both rely on user input and are illustrated in Appendix C, Figure 125 and Figure 126.

4.4 RESULTS

This section explains the options available for presenting and comparing results, both in terms of the life cycle inventory and life cycle impact assessment stages. The first screen the user encounters after the main screen is shown in Figure 29. The two modules direct the user in two different directions.

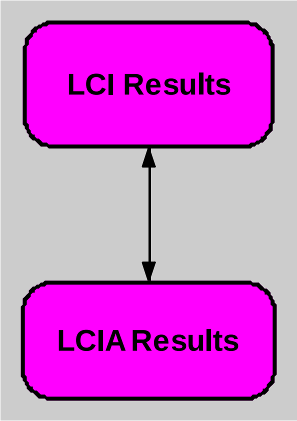


Figure 29. LCI and LCIA - Results

4.4.1 Life Cycle Inventory

The model has several options in the life cycle inventory stage represented in seven sub-modules as shown in Figure 30. The seven options are “Total LCI,” “Total LCI Broad Construction Impacts,” “Total LCI Aggregated Construction Processes,” “Total LCI Detailed Construction Processes,” “Total LCI Local and Regional Impacts,” “Selected LCI Construction Results,” and “Waste.”

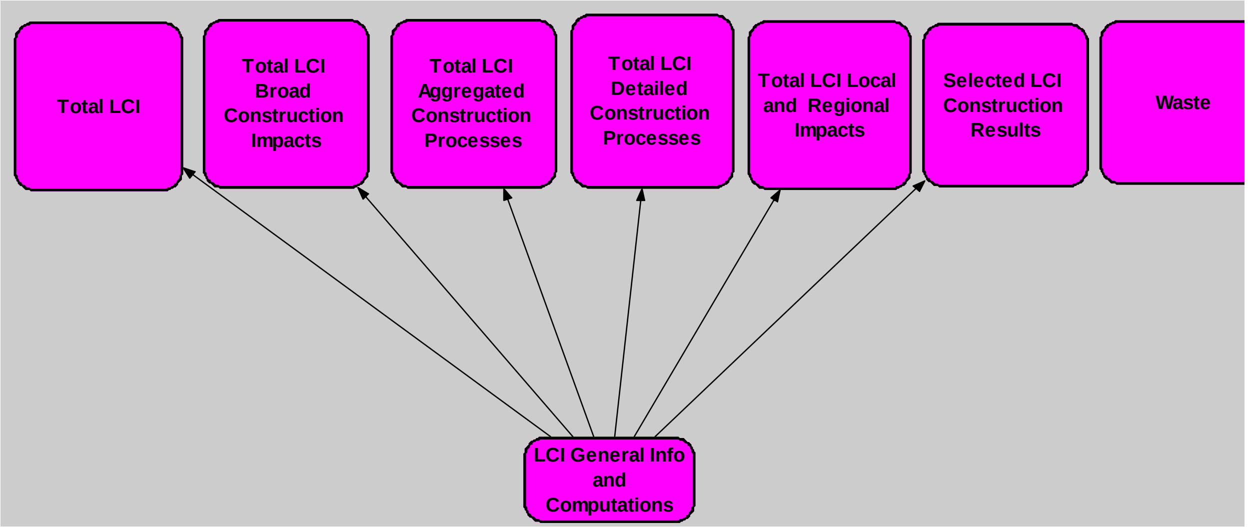


Figure 30. LCI – Results

"Total LCI" sums all the information from the user model and detailed model. The screen of Total LCI results is shown in Appendix C, Figure 127, and the results consist of 292 life cycle inventory items organized according to "Raw," "Air," "Water," "Solid," and "Soil." Analytica allows for easy manipulation of the results; for example, the results can be presented in the form of median or mean results, statistics, probability bands, probability density, cumulative probability, and sample population. The output screen is a vector with an abbreviated vector shown in Table 17 for inventory items 51 through 150 for the mean values.

Table 17. Example Total LCI - Results

51, Raw, wood/wood wastes FAL, kg	48.94	101, Air, Fe, kg	0.1123
52, Raw, zinc (in ore), kg	2.36E-03	102, Air, formaldehyde, kg	1.56E-03
53, Air, acetaldehyde, kg	1.03E-06	103, Air, H2S, kg	2.87E-05
54, Air, acetic acid, kg	4.79E-06	104, Air, HALON-1301, kg	2.08E-06
55, Air, acetone, kg	1.05E-06	105, Air, HCFC-21, kg	1.24E-05
56, Air, acrolein, kg	4.53E-04	106, Air, HCFC-22, kg	2.51E-09
57, Air, Al, kg	3.44E-05	107, Air, HCl, kg	2.306
58, Air, aldehydes, kg	6.431	108, Air, He, kg	3.69E-04
59, Air, alkanes, kg	0.01201	109, Air, heptane, kg	1.01E-04
60, Air, alkenes, kg	1.45E-03	110, Air, hexachlorobenzene, kg	8.03E-12
61, Air, ammonia, kg	0.4091	111, Air, hexane, kg	2.11E-04
62, Air, As, kg	2.05E-03	112, Air, HF, kg	0.3158
63, Air, B, kg	1.82E-05	113, Air, HFC-134a, kg	-5.33E-18
64, Air, Ba, kg	5.01E-07	114, Air, Hg, kg	9.91E-04
65, Air, Be, kg	2.13E-04	115, Air, I, kg	8.72E-07
66, Air, benzaldehyde, kg	2.72E-09	116, Air, K, kg	8.72E-05
67, Air, benzene, kg	4.96E-03	117, Air, kerosene, kg	0.01146
68, Air, benzo(a)pyrene, kg	2.44E-07	118, Air, La, kg	1.48E-08
69, Air, Br, kg	2.07E-06	119, Air, metals, kg	0.02457
70, Air, butane, kg	4.33E-04	120, Air, methane, kg	2.14E+04
71, Air, butene, kg	5.42E-05	121, Air, methanol, kg	2.53E-06
72, Air, Ca, kg	4.64E-05	122, Air, Mg, kg	1.29E-05
73, Air, Cd, kg	1.19E-03	123, Air, Mn, kg	144.3
74, Air, CFC-11, kg	0.01533	124, Air, Mo, kg	3.41E-07
75, Air, CFC-114, kg	2.69E-07	125, Air, MTBE, kg	3.97E-04
76, Air, CFC-116, kg	6.81E-07	126, Air, n-nitrodimethylamine, kg	9.57E-05
77, Air, CFC-12, kg	4.83E-03	127, Air, N2, kg	5.48E-05
78, Air, CFC-13, kg	1.37E-09	128, Air, N2O, kg	0.2836
79, Air, CFC-14, kg	6.12E-06	129, Air, Na, kg	1.00E-03
80, Air, Cl2, kg	0.01157	130, Air, naphthalene, kg	7.53E-05
81, Air, CO, kg	2.53E+05	131, Air, Ni, kg	10.56
82, Air, CO2, kg	1.62E+06	132, Air, non methane VOC, kg	3.85E+04
83, Air, CO2 (fossil), kg	7.34E+04	133, Air, NOx, kg	1.60E+04
84, Air, CO2 (non-fossil), kg	56.91	134, Air, NOx (as NO2), kg	1.13E+04
85, Air, cobalt, kg	1.34E-03	135, Air, organic substances, kg	131.3
86, Air, Cr, kg	3.03E-03	136, Air, P-tot, kg	6.47E-07
87, Air, Cu, kg	8.03E-06	137, Air, PAHÕs, kg	1.08E-06
88, Air, CxHy aromatic, kg	1.03E+04	138, Air, PM10, kg	1.55E+05
89, Air, cyanides, kg	1.44E-07	139, Air, PM2.5, kg	2.57E+04
90, Air, dichloroethane, kg	2.54E-07	140, Air, Pb, kg	1.84
91, Air, dichloromethane, kg	1.94E-03	141, Air, pentachlorobenzene, kg	2.14E-11
92, Air, dioxin (TEQ), kg	2.47E-09	142, Air, pentachlorophenol, kg	3.46E-12
93, Air, PM30, kg	7.95E+05	143, Air, pentane, kg	5.41E-04
94, Air, PM15, kg	1.86E+05	144, Air, phenol, kg	1.98E-03
95, Air, dust , kg	2628	145, Air, propane, kg	4.31E-04
96, Air, ethane, kg	1.44E-04	146, Air, propene, kg	2.75E-05
97, Air, ethanol, kg	2.05E-06	147, Air, propionic acid, kg	9.30E-08
98, Air, ethene, kg	1.46E-03	148, Air, Pt, kg	2.31E-05
99, Air, ethylbenzene, kg	1.21E-05	149, Air, Sb, kg	4.67E-04
100, Air, ethyne, kg	5.44E-07	150, Air, Sc, kg	5.10E-09

"Total LCI Broad Construction Impacts" includes the categories shown below and in Figure 31 with the goal of categorizing the inventory in order to compare results to published research and facilitate policy development.

- Total Services
    - Engineers, architects, surveyors, etc.
- Transportation
    - Worker and Truck fuel combustion, fuel production, and distribution
    - Manufacturing
- Total Equipment
    - Manufacturing, fuel combustion, fuel production, and distributions
- Driving on Roads
    - Paved and Unpaved
- Total Heavy Construction Operations (primarily dust generation)
- Paint and surface applications
- Energy
    - Process energy results
    - Equipment energy
    - I-O energy
    - On-site energy
    - Transportation

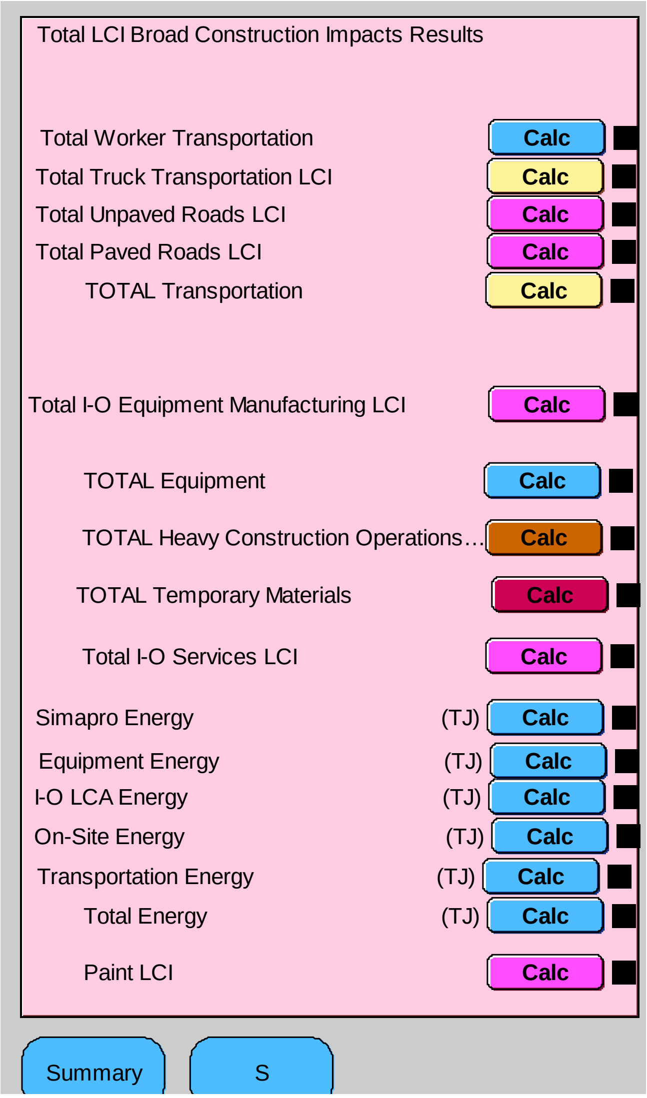


Figure 31. LCI Broad Construction Impacts – Results

“Total LCI Aggregated Construction Processes” allows the user to examine the specific higher-level construction activities and the associated emissions and resources. The categories include: deep foundations, concrete, masonry, steel, paint, transportation (not included in other categories), material handling, on-site electricity, generator, services, equipment manufacturing, unpaved roads, and paved roads. Transportation, when needed, is included in each of the categories; the separate category of transportation (non-process specific) allows the user to account for deliveries that are not explicitly accounted for in the modeled processes.

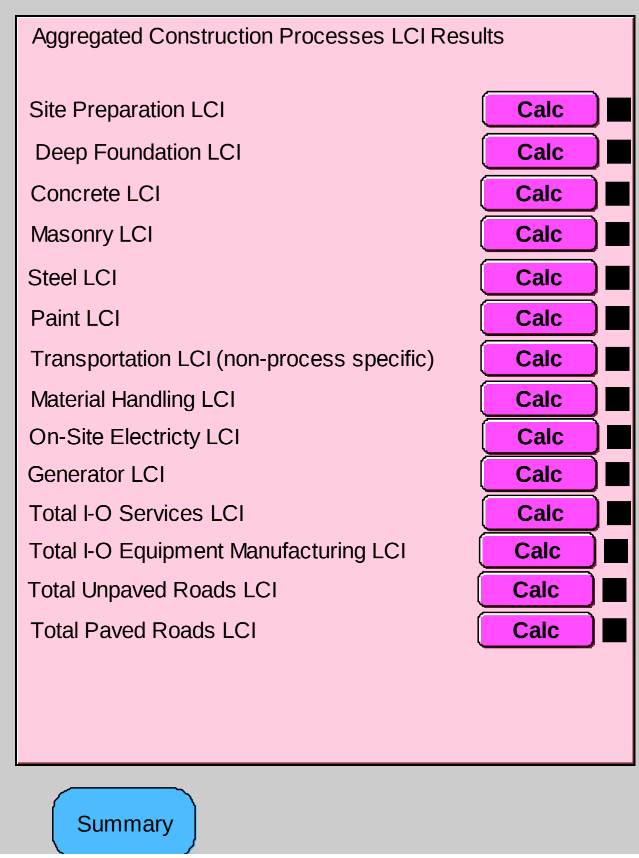


Figure 32. LCI Aggregated Construction Processes - Results

"Total LCI Detailed Construction Processes" results are provided to allow the user to disaggregate the construction process to delve deeper into understanding the relationship between their construction project and the associated environmental impacts and resource usage. The screenshot is shown in Appendix C, Figure 128 and the categories include: clearing and grubbing, excavation, backfilling, compaction, grading, augercast piles, steel piles, drilled caissons, concrete columns, concrete beams, elevated slabs, spread footings, pile caps, retaining walls, grade walls, slab on grade, bricks, blocks, steel, paint, electricity, transportation (non-process), material handling, generator usage, services, equipment manufacturing, unpaved roads, and paved roads.

"Total LCI Local and Regional Results" allow the user to focus on local and regional impacts for the construction project. Local impacts include the areas of equipment combustion, heavy construction operations (dust), and unpaved roads. Regional impacts accounts for transportation and paved roads.

"Selected LCI Construction Results" essentially disaggregates the entire total LCI results of 292 items into a shortened list of 20 items to provide the user with a snapshot of the most relevant construction life cycle inventory items. "Waste" sums both the solid waste and liquid waste associated with the construction project.

4.4.2 Life Cycle Impact Assessment

While the LCI results have seven distinct modules, the LCIA results are available in three options of "Total LCIA," "Total Broad Construction Impacts," and "LCIA Aggregated Processes Results," see Figure 33.

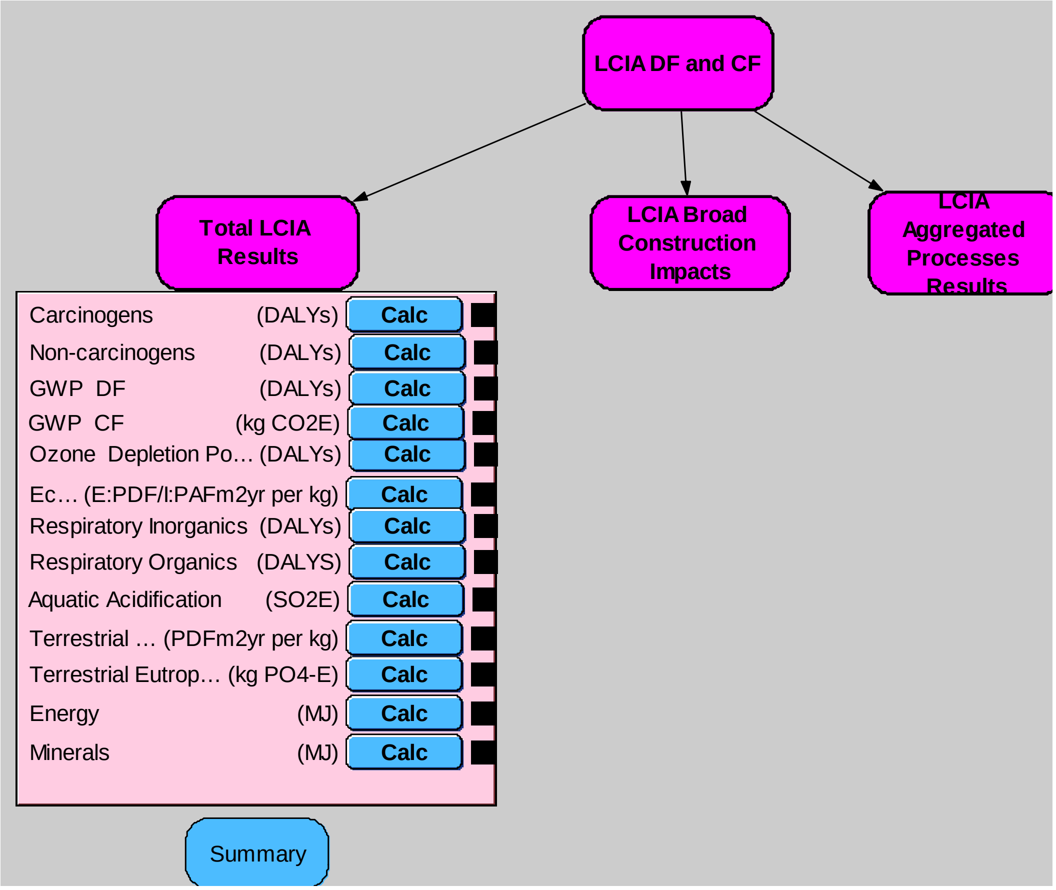


Figure 33. LCIA – Results

The first element in modeling the LCIA stage is calculated in the module "LCIA DF and CF," where DF is damage factor and CF is characterization factor. The impact assessment categories included in the model are carcinogens, noncarcinogens, global warming potential in terms of damage, global warming potential in terms of carbon dioxide equivalents, ecotoxicity, respiratory inorganics, respiratory organics, terrestrial acidification and nitrification, aquatic acidification, terrestrial eutrophication, energy, and minerals, as shown in Figure 34. LCIA results are given for both Eco-Indicator 99 and Impact 2002+ when available. More detailed information on LCIA and impact categories can be found in Chapter 3.0

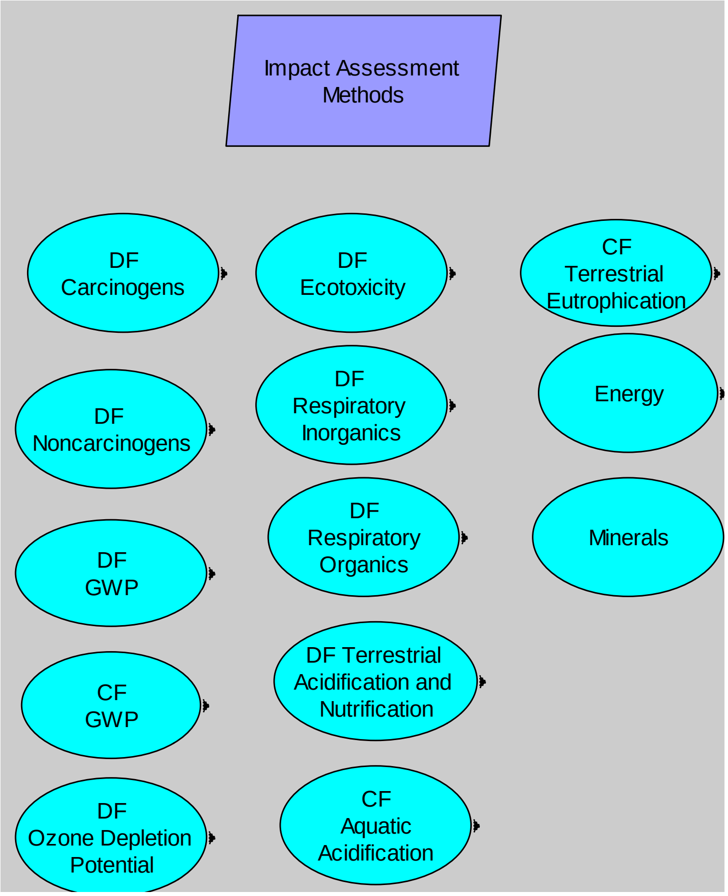


Figure 34. LCIA DF and CF Modeling – Results

The first module of “Total LCIA Results” multiplies the life cycle inventory vector result and each of the respective impact category’s DF or CF vector. The user has the option of either individually calculating each impact category results by selecting the “Calc” button, or obtaining all the results in the “Summary” node as shown on the left side of Figure 33.

The second module, “LCIA Broad Construction Impacts,” multiplies the respective life cycle inventory vector for each category (transportation, equipment, paint, heavy equipment operations, temporary materials, and services) and the impact category’s DF or CF vector. The user can either obtain LCIA results within the category by selecting the “Calc” button, or comparing results between the categories by analyzing the impact categories on the left side of Figure 35.

Figure 35. LCIA – Broad Construction Impacts – Results

Similar to "LCIA Broad Construction Impacts," the LCIA module of "LCIA Aggregated Construction Processes" multiplies the inventories of the construction categories and the LCIA vectors. The user can either obtain LCIA results within the construction category by selecting the "Calc" button, or comparing results between the categories by analyzing the impact categories.

4.5 SUMMARY

In summary, the hybrid life cycle assessment construction model is a complex model that draws from many data sources. Creating the structure of the model and finding and integrating the appropriate data sources was challenging from a larger scale in both framework and structure, and a smaller scale in terms of consistent units and unit conversions. While the model is unique to construction, the framework can translate to other applications of hybrid life cycle assessment models. The model basically is created by manipulating and modeling large vectors of the life cycle inventory and translating the LCI results into LCIA results. The processes created for individual construction activities are in some ways unique to each activity, but in other ways are very similar. Most of the construction processes involved the steps of calculating equipment combustion and associated fuel usage and emissions, determining transportation impacts, and estimating the amount of temporary materials.

4.6 VALIDITY

The model's structure and readability was validated through face validity, which is an assessment method for the relevance of the model by using knowledgeable opinions from individuals. Two meetings were held with a large, local construction company. The first meeting reviewed the model and asked questions about not only how the model was structured, but also about its applicability and use during the construction of a project. The reaction of the company's representative was positive and suggested a few changes, such as adding more detailed information on gallons of paint and square feet of painted surface area. The suggestions were incorporated into the final model. In terms of applicability and use, it was discussed with the company's representative that the model could be useful during the estimating phase if the project was concerned with life cycle assessment.

The second meeting reviewed the final results of the case studies to discuss the general impression and rationality of the results. The representative thought that the results were intuitive and well-represented the projects.

5.0 CASE STUDIES

Two case studies were completed in order to demonstrate how the model works and present conclusions regarding the environmental impacts of the construction phase. The first case, a steel frame structure, represents a typical office building. The results from the first case study, since the building type is common, can ultimately be used by other researchers in their own LCAs. The second case study, a precast parking garage, was also conducted as another common structural frame building constructed in the U.S. While the ultimate use of the projects is greatly different – office versus parking, the projects have some similarities. Both projects are located on the same remediated brownfield site, and both projects installed augercast piles. The material phase, except for temporary materials, is not included in the boundary of these LCAs. The construction method of erecting the steel and precast structure is similar, both requiring cranes for erection. Additionally, due to the increase in mixed-use development, which limits the amount of surface parking, steel buildings and precast concrete parking garages are often built in tandem to support a development. This section describes both case studies, starting with the steel case study followed with the precast concrete. The user input is first discussed, then results are presented. For comparative purposes, selected results from both case studies were also plotted on the same graphs and listed in Appendix I, Figure 149 through Figure 182.

The results for both the steel and precast case studies are presented in the order of LCI and LCIA with sub-categories of (Total LCI, Broad Construction Impacts, and Aggregated Construction Processes). The LCI focused primarily on total energy, air emissions, solid waste, and liquid waste. The presented results for the air emissions focus on $PM_{2.5}$, PM_{10}, PM_{15}, PM_{30}, CO_2 , CH_4, N_2O, CFCs and HCFs, CO, NO_x, SO_x, Pb, and NMVOC because these emission values were the most prevalent in the entire inventory.

5.1 STEEL STRUCTURE

The steel framed 186,000 square foot structure, is an office building located on a brownfield site. This private project is a core and shell office building completed in 2005. The six-story, steel structure with brick and curtain wall exterior, and exposed architectural and structural steel. The primary data source was construction drawings.

5.1.1 Assumptions – Steel Structure

The following list details the following modeling assumptions:

- Once the steel member was delivered to the site, the member was moved off the trailer bed by a crane and was erected. It is assumed that the steel member was not stored in a staging area on-site.

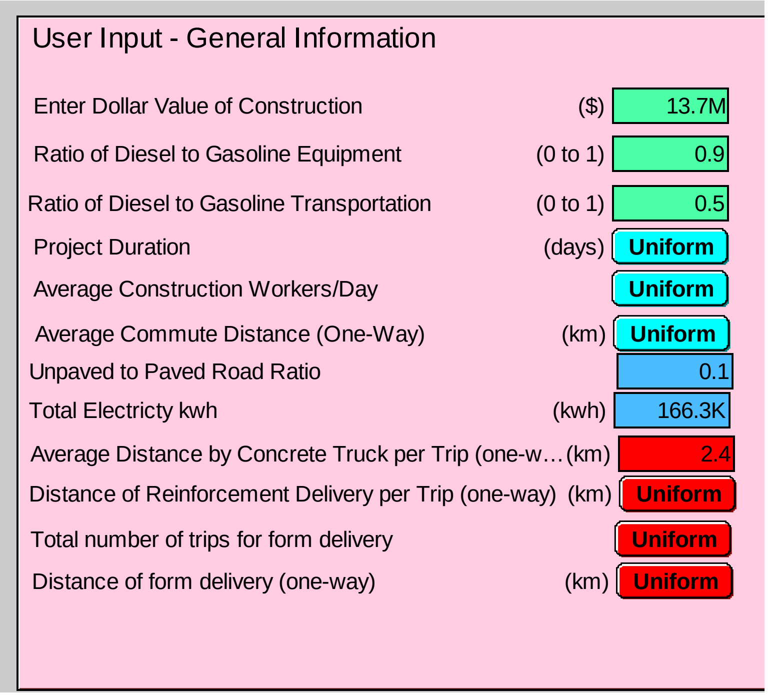
- The adjacent courtyard is not considered a part of the core and shell office building.

- The electric switch gear and transformer were not included because this equipment was shared with adjacent buildings.

- Storm water run-off quantity and quality were not included in this analysis since a management plan was implemented. The storm water management plan was approved by the County Conservation District and included elements such as inlet basins covers, silt fencing, and rock construction entrances.

5.1.2 Input – Steel Structure

General information input into the hybrid construction model for the steel structure is shown in Figure 36. Uniform distributions were established for project duration (300 to 315 days); average construction workers per day (30 to 40 workers); and average commute distance one-way (10 to 20 miles); average distance for reinforcement delivery per trip one-way (5 to 10 miles); total number of trips for form delivery (5 to 20); and average distance for form delivery (5 to 10 miles).



User Input - General Information

Enter Dollar Value of Construction	($)	13.7M
Ratio of Diesel to Gasoline Equipment	(0 to 1)	0.9
Ratio of Diesel to Gasoline Transportation	(0 to 1)	0.5
Project Duration	(days)	Uniform
Average Construction Workers/Day		Uniform
Average Commute Distance (One-Way)	(km)	Uniform
Unpaved to Paved Road Ratio		0.1
Total Electricty kwh	(kwh)	166.3K
Average Distance by Concrete Truck per Trip (one-w…	(km)	2.4
Distance of Reinforcement Delivery per Trip (one-way)	(km)	Uniform
Total number of trips for form delivery		Uniform
Distance of form delivery (one-way)	(km)	Uniform

Figure 36. User Input – General Information – Steel Structure

Specific user input information on site preparation and foundations, concrete, masonry, surface applications, can be found in Appendix E, Figure 129 through Figure 136. A summary is listed below:

- Excavation
    - 2,623 BCY
- Backfilling
    - 1,425 LCY
- Compaction
    - 1,854 CCY
- Grading
    - 3,360 SY
- Augercast piles
    - 353 piles
    - Average length, 45 feet
    - Average diameter, 1.25 feet
- Elevated slab concrete
    - 139,800 sf

  - Average depth, 4.5”
- Spread footings
  - 148.7 CY
- Pile caps and grade beams
  - 656.4 CY
- Slab on grade
  - 377.5 CY
- Masonry
  - Brick
    - 34,9200 SF
- Steel
  - 832.9 tons
- Transportation (not otherwise included)
  - Class 1, 2, 3, 5, and 6
    - 100 km
  - Class 4
    - 1046 km
  - Class 7
    - 87.72 km
  - Class 8
    - 64.37 km
- Material handling
  - Fork lifts
    - 80 hours
  - Aerial lifts
    - 80 hours
  - Crane
    - 80 hours
- Generator
  - 1000 hours

5.1.2.1 LCI – Steel Case Study

PM Emissions for Total LCI, Broad Construction Impacts, and Aggregated Construction Processes as shown in Figure 37, Figure 38, and Figure 39. GWP emissions for the same respective categories are shown in Figure 40, Figure 41, and Figure 42. The remaining emissions are shown in Figure 43, Figure 44, and Figure 45. Additional results are also located in Appendix F, Figure 137, Figure 138, and Figure 139.

As a reminder, for the graphs associated with broad construction impacts, definitions are located in Section 4.4.1.

PM Emissions – Steel Case Study

PM emissions are due to several of the broad construction processes - services, equipment, and heavy construction dust operations - as shown in Figure 38, but primarily due to emissions in the unpaved and paved road category. The importance of including unpaved and paved roads emissions is also visually shown in Figure 39. Due to the high emission values for PMs from paved roads, including this element is considered very important in future LCAs. The heavy construction operations from equipment movement are primarily accounted for during the site preparation activities of excavation, grading, compaction, and backfilling. For this case study, a limited amount of site preparation work was performed. The transportation category for PM emissions is somewhat lower than expected because the PM from driving on paved and unpaved road is in a separate category.

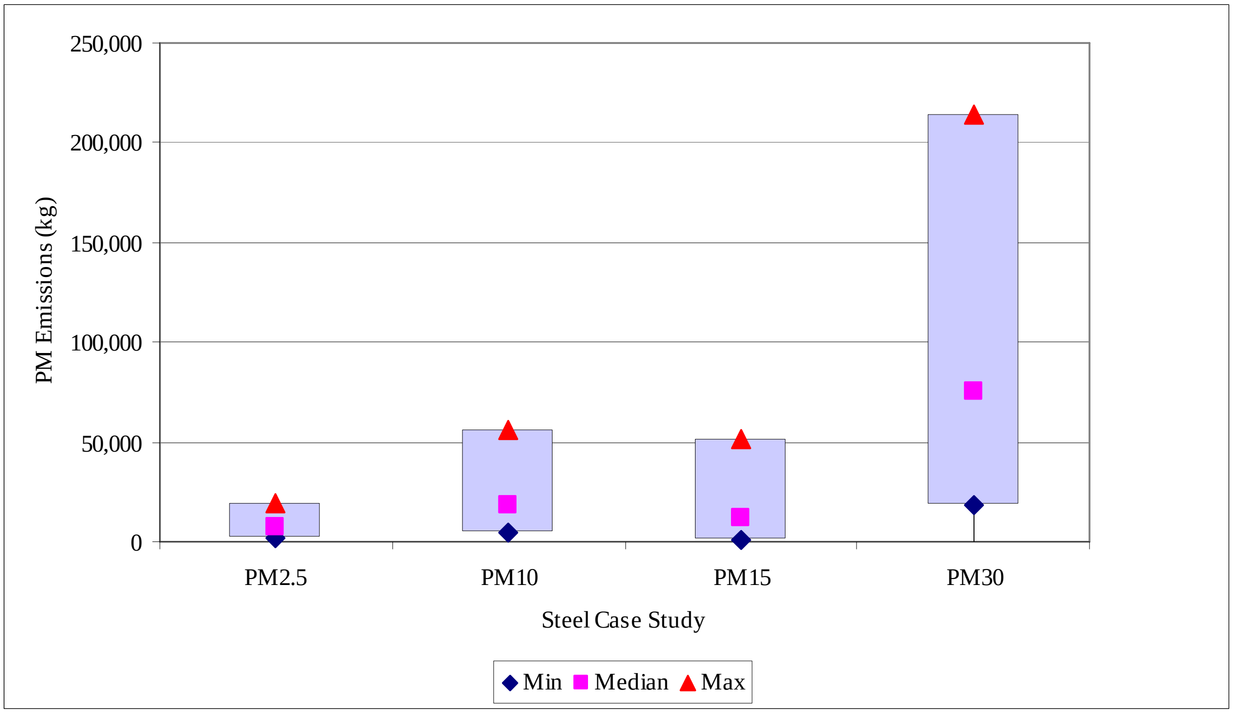


Figure 37. LCI PM Emissions – Total LCI – Steel Case Study

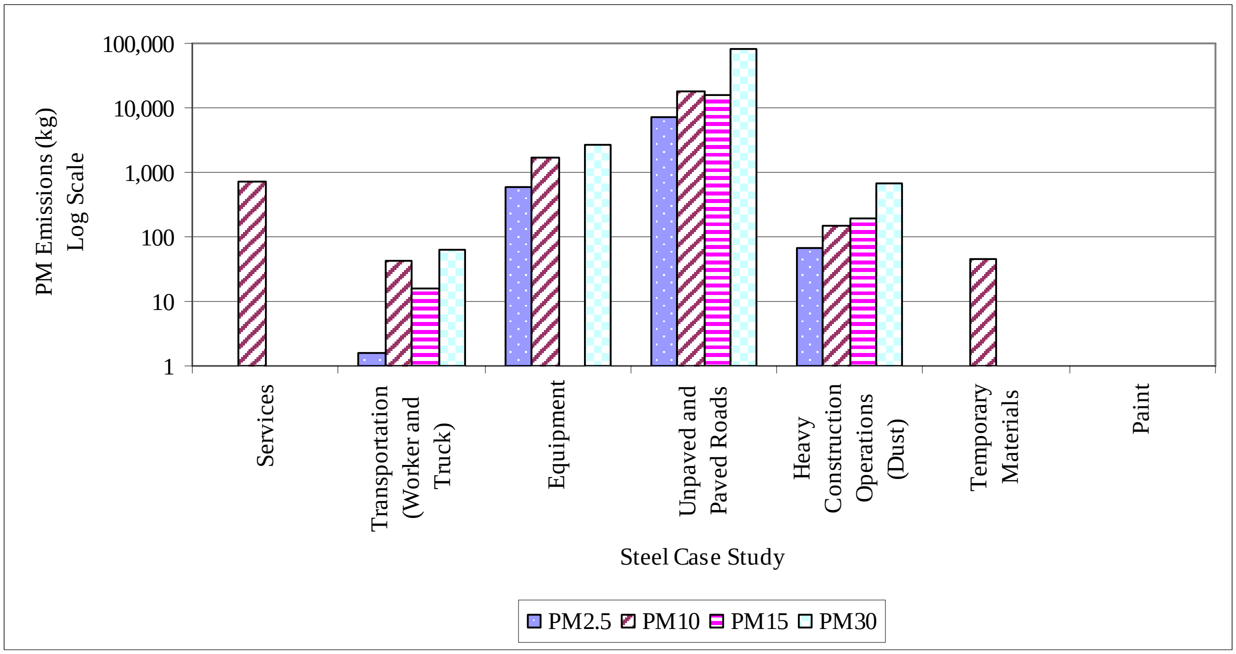


Figure 38. LCI PM Emissions – Broad Construction Impacts – Steel (Mean Value)

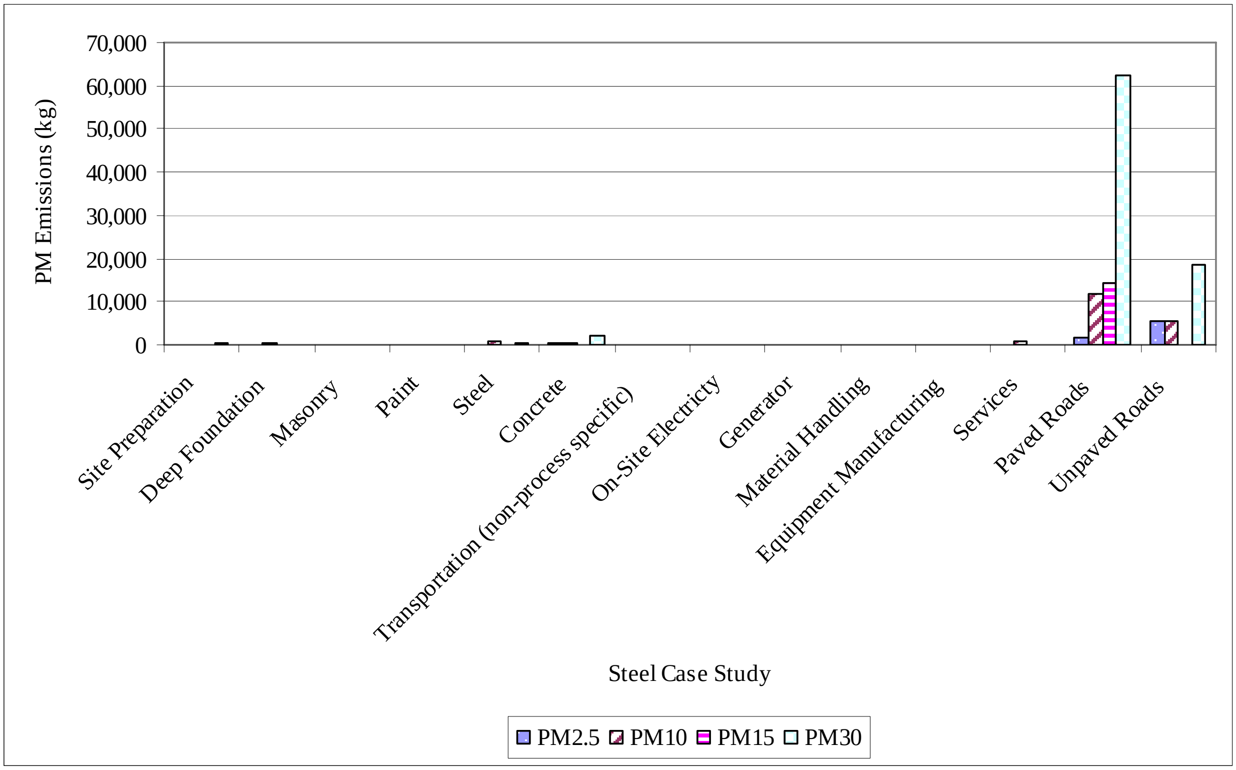


Figure 39. LCI PM Emissions –Aggregated Construction Processes – Steel (Mean Value)

GWP Emissions – Steel Case Study

In terms of GWP emissions, CO_2 is the highest greenhouse gas emission when compared with the other greenhouse gas inventory items of CH_4, N_2O, and CFCs and HCFCs as shown in Figure 40. From the broad construction perspective, the greatest contributors of CO_2E are equipment, services, and transportation in order of highest to lowest, see Figure 41. Equipment manufacturing and services are often not included in LCAs, but these results show that including equipment manufacturing and services are important processes to consider when conducting a construction LCA. Additionally, Nonroad output information for equipment combustion emissions indicates the CO_2 values are higher than the other engine combustion emissions, such as transportation engines. The aggregated construction processes results show that the concrete, services, and steel are the construction elements that contribute the most to CO_2E emissions.

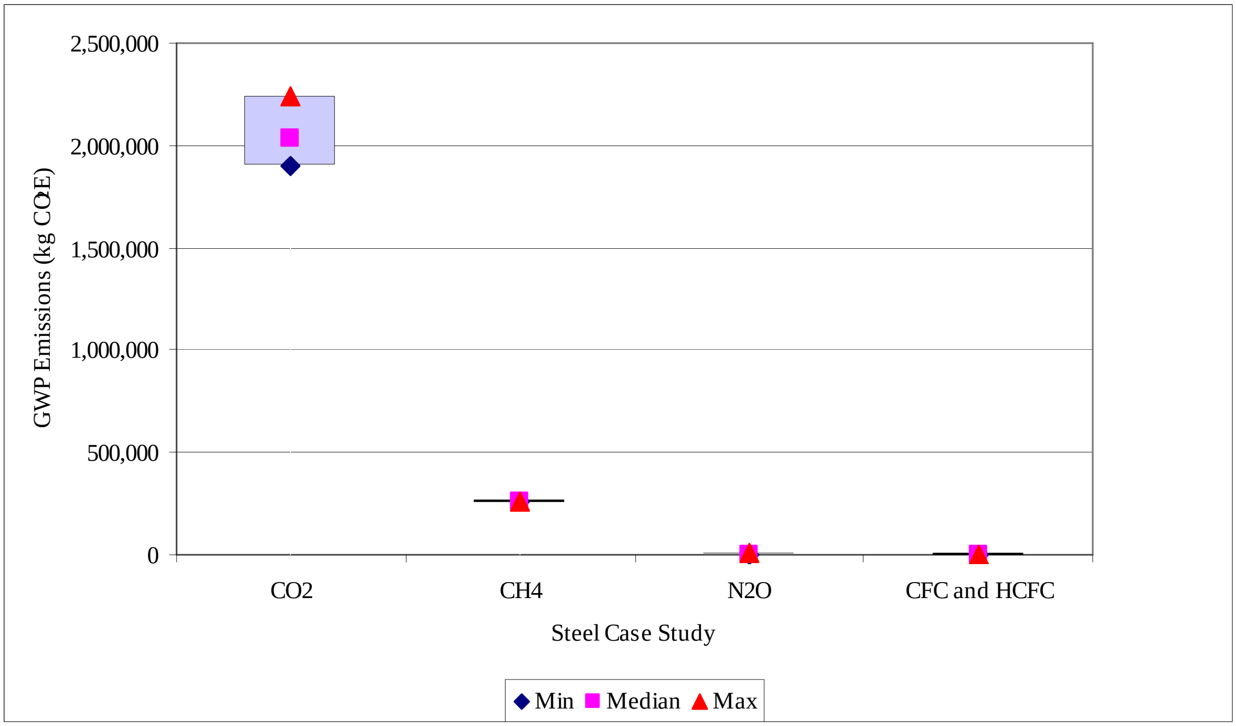


Figure 40. LCI GWP Emissions – Total LCI – Steel

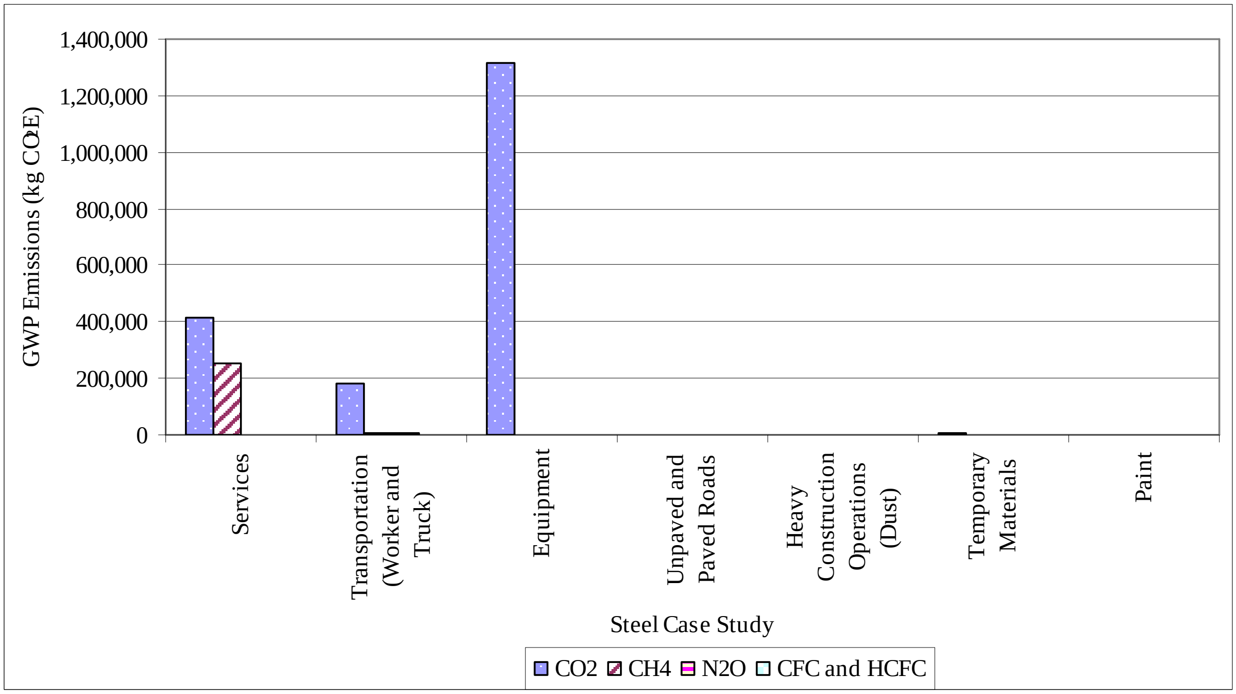


Figure 41. LCI GWP Emissions – Broad Construction Impacts – Steel (Mean Value)

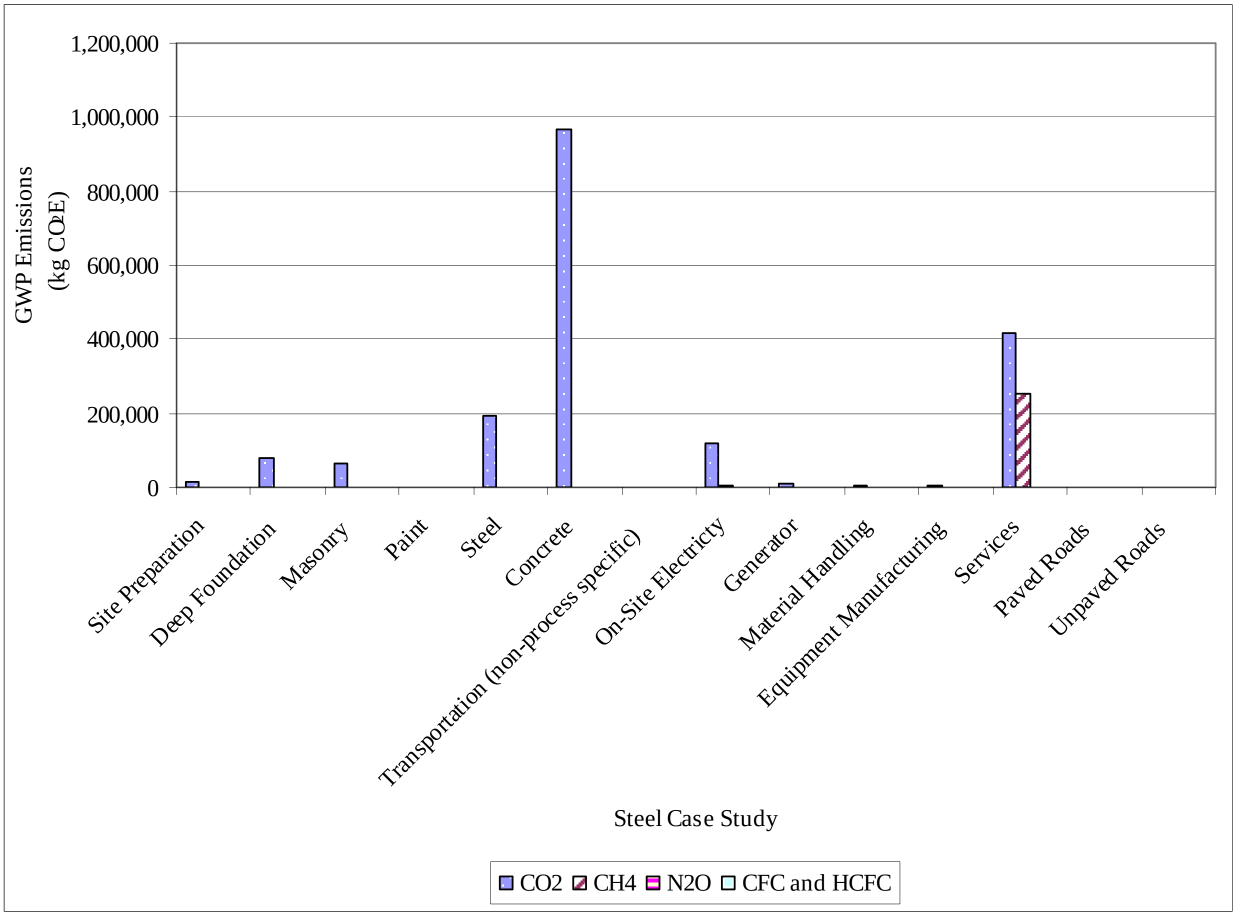


Figure 42. LCI GWP Emissions –Aggregated Construction Processes – Steel (Mean Value)

Emissions – Steel Case Study

Figure 43, Figure 44, and Figure 45 show data related to the emissions of CO, NO_x, SO_x, Pb, and non-methane VOCs (NMVOCs). In terms of broad construction impacts, the largest CO contributor is from the equipment category (Figure 44), primarily due to the concrete process (Figure 45). Since steel is the primary structural material, it would be more intuitive to expect that the steel process would be higher, but the amount of concrete for the office building is significant in terms of the augercast piles, pile caps, grade beams, slab on grade, and elevated slabs.

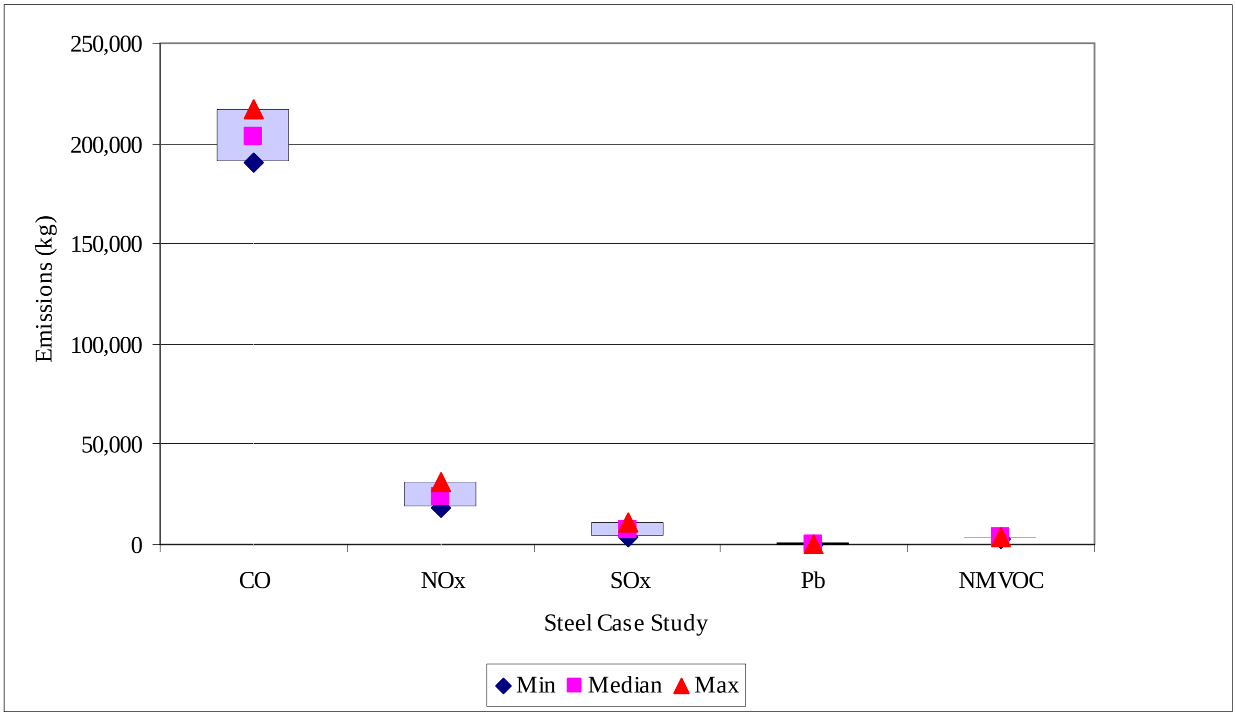


Figure 43. LCI Emissions – Total LCI – Steel

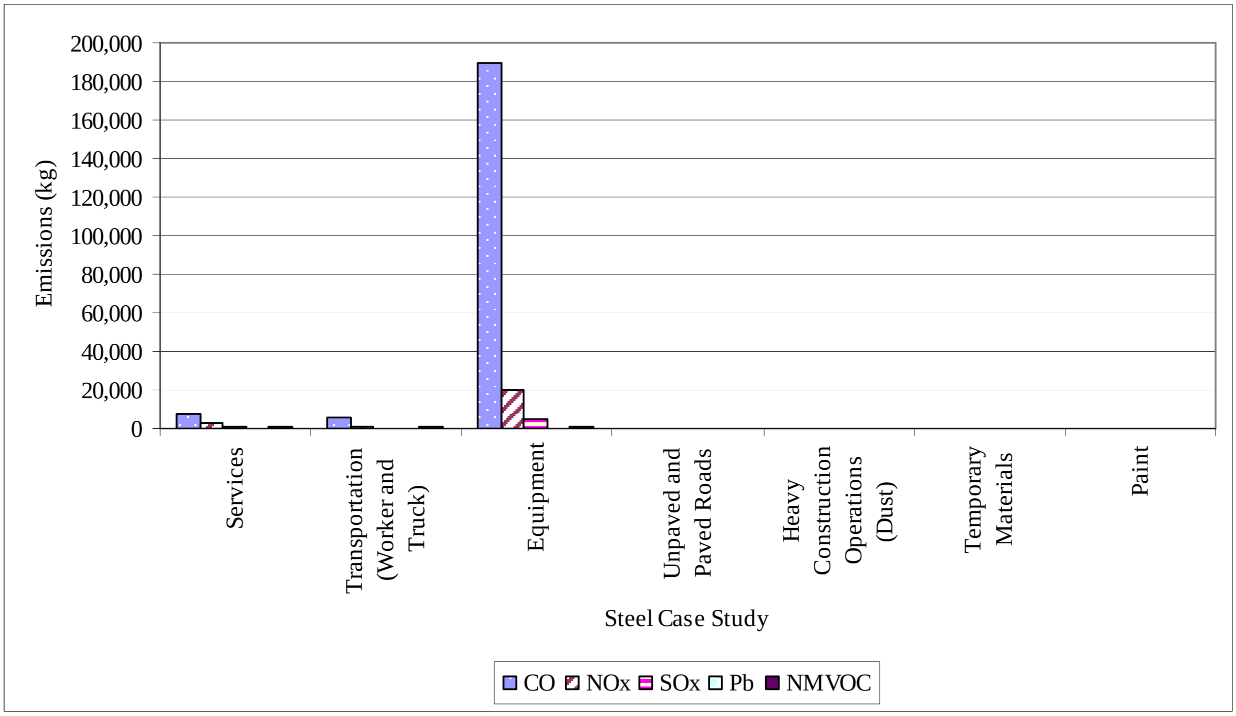


Figure 44. LCI Emissions – Broad Construction Impacts – Steel (Mean Value)

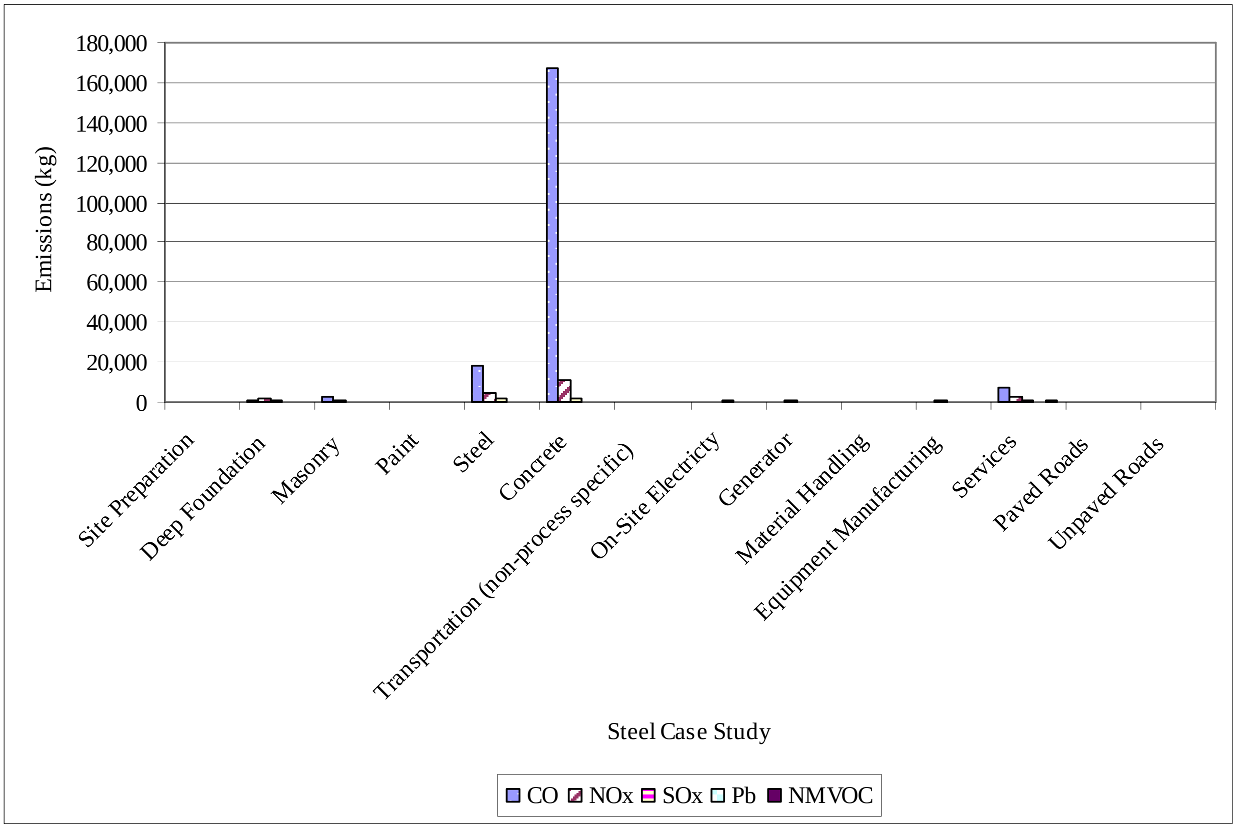


Figure 45. LCI Emissions –Aggregated Construction Processes – Steel (Mean Value)

5.1.2.2 Energy and Waste Results

The total mean value for energy usage during in the construction phase was about 20 TJ. The results for solid and liquids waste were 91 tons and 2,709 gallons respectively (see Table 18).

Table 18. Energy and Waste Results – Steel Case Study (Mean Value)

	Energy (TJ)	Solid Waste (tons)	Liquid Waste (gallons)
Steel	20	91	2,709

5.1.2.3 LCIA – Steel Case Study

The LCIA steel case study results are displayed in the same manner as the LCI results of "Total LCIA," "Broad Construction LCIA," and "Aggregated Construction Processes LCIA." However, this section focuses on the "Broad Construction LCIA" results in Figure 46 through Figure 56. "Total LCIA" results for both the steel and precast case studies are shown in Appendix I, Figure 149 through Figure 159. "Aggregated Construction Processes LCIA" results are also shown in Appendix I, Figure 172 through Figure 182.

The impact categories include carcinogens, noncarcinogens, GWP damage factors, GWP characterization factors, ozone depletion potential, ecotoxicity, respiratory inorganics, respiratory organics, aquatic acidification, terrestrial acidification and nitrification, and terrestrial eutrophication. In all the impact categories except respiratory inorganics, the first three categories of services, transportation, and equipment have the most significant impacts, illustrating that services and equipment are important because of two reasons. First, services are often not included in LCAs; and not including services can result in significantly different LCIA results. Second, since the equipment category has proven to be important in all the impact categories, this research focused on improving and focusing on equipment combustion through using data from Nonroad results. Other LCA construction research such as Guggemos and Horvath (2005), focused on a limited range of construction equipment with limited data on horsepower ranges.

It is important to take note that the scale of the some of the results is very small, for example, carcinogens. While it is worthwhile to report the results, the small variation between transportation (slightly greater than 0.03 DALYs) and equipment (about 0.005 DALYs) cannot lead to conclusive results with respect to carcinogens.

Differences between the two LCIA methods and LCIA modeling will be discussed in subsequent sections.

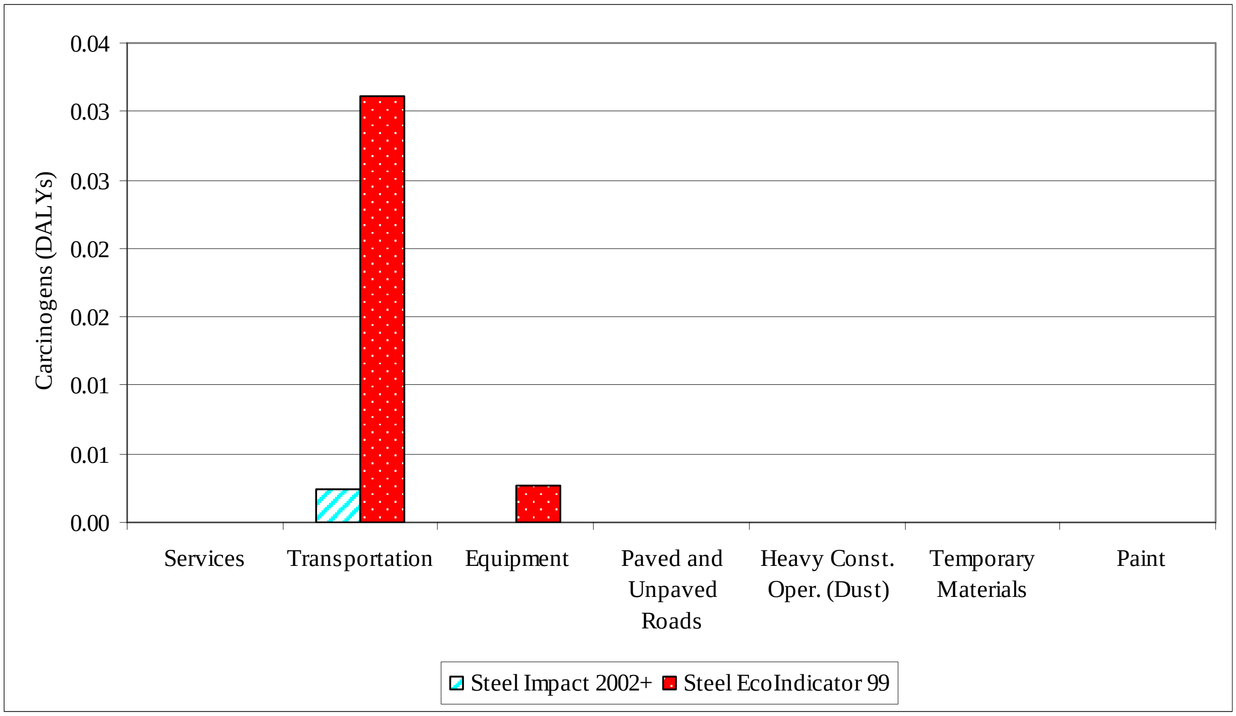


Figure 46. LCIA Carcinogens – Broad Construction Impacts – Steel (Mean Value)

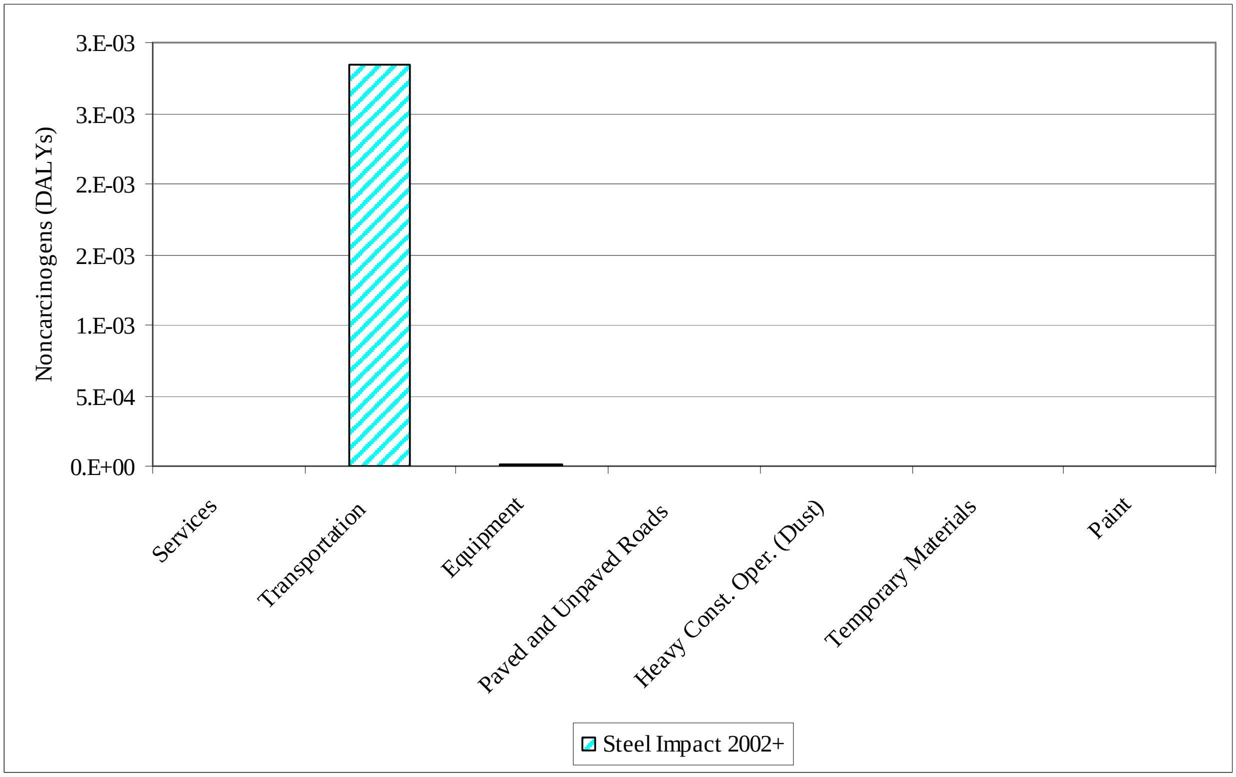


Figure 47. LCIA Noncarcinogens – Broad Construction Impacts – Steel (Mean Value)

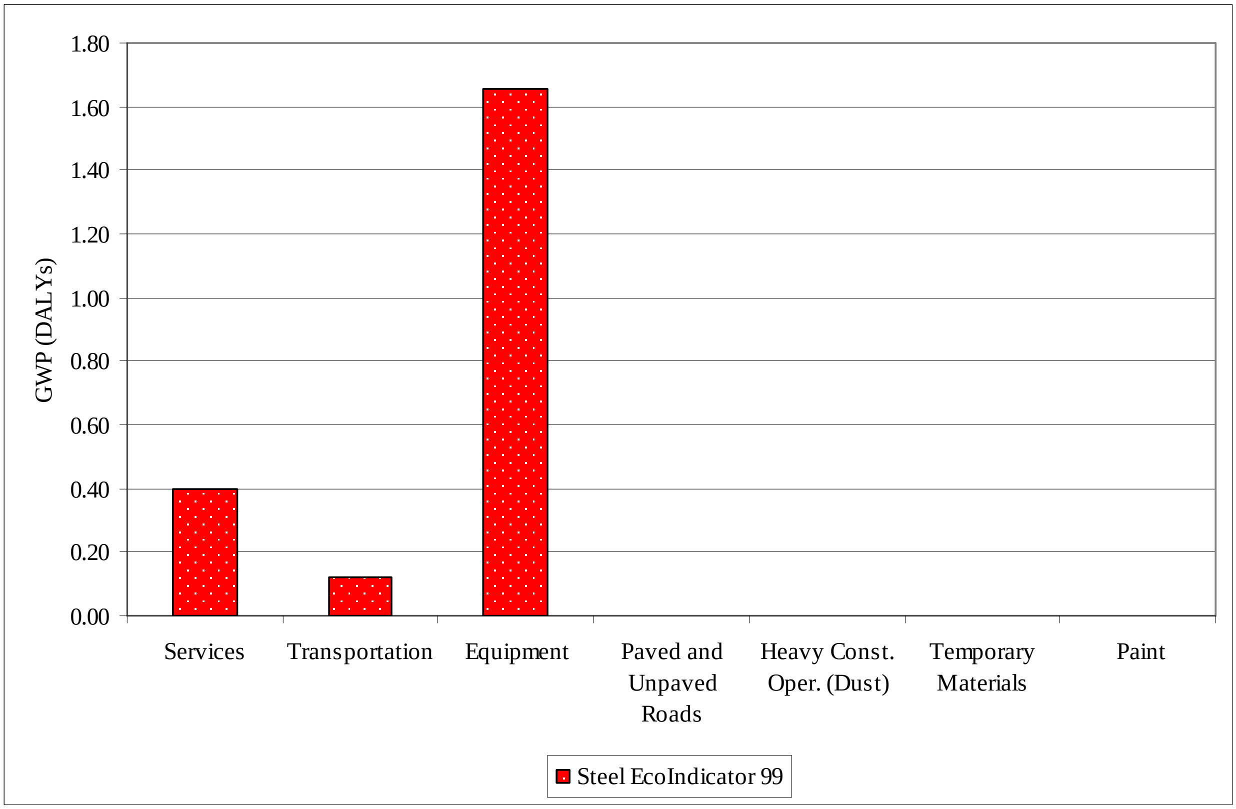


Figure 48. LCIA GWP DF – Broad Construction Impacts – Steel (Mean Value)

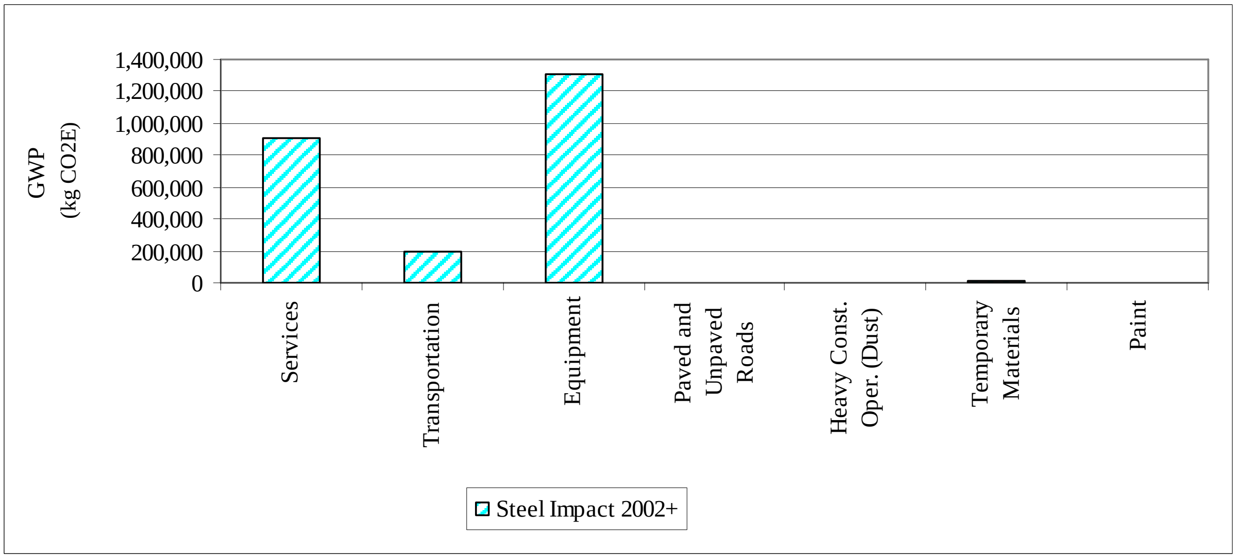


Figure 49. LCIA GWP CF – Broad Construction Impacts – Steel (Mean Value)

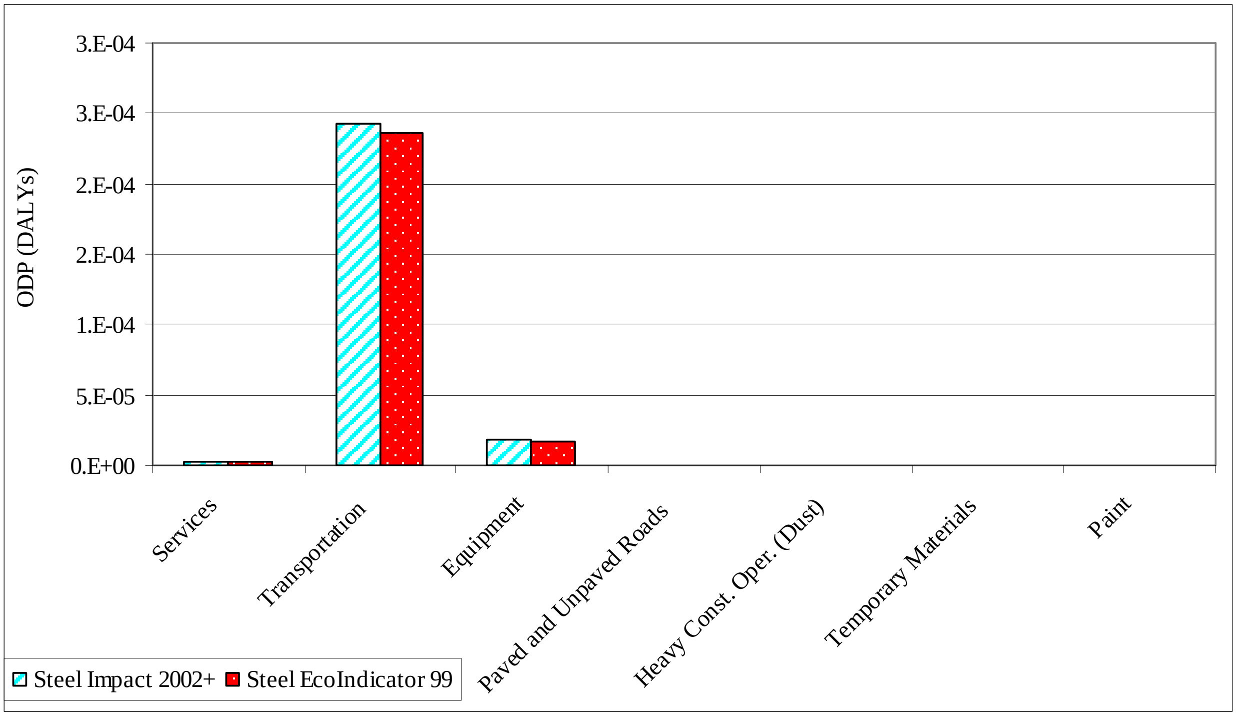


Figure 50. LCIA ODP – Broad Construction Impacts – Steel (Mean Value)

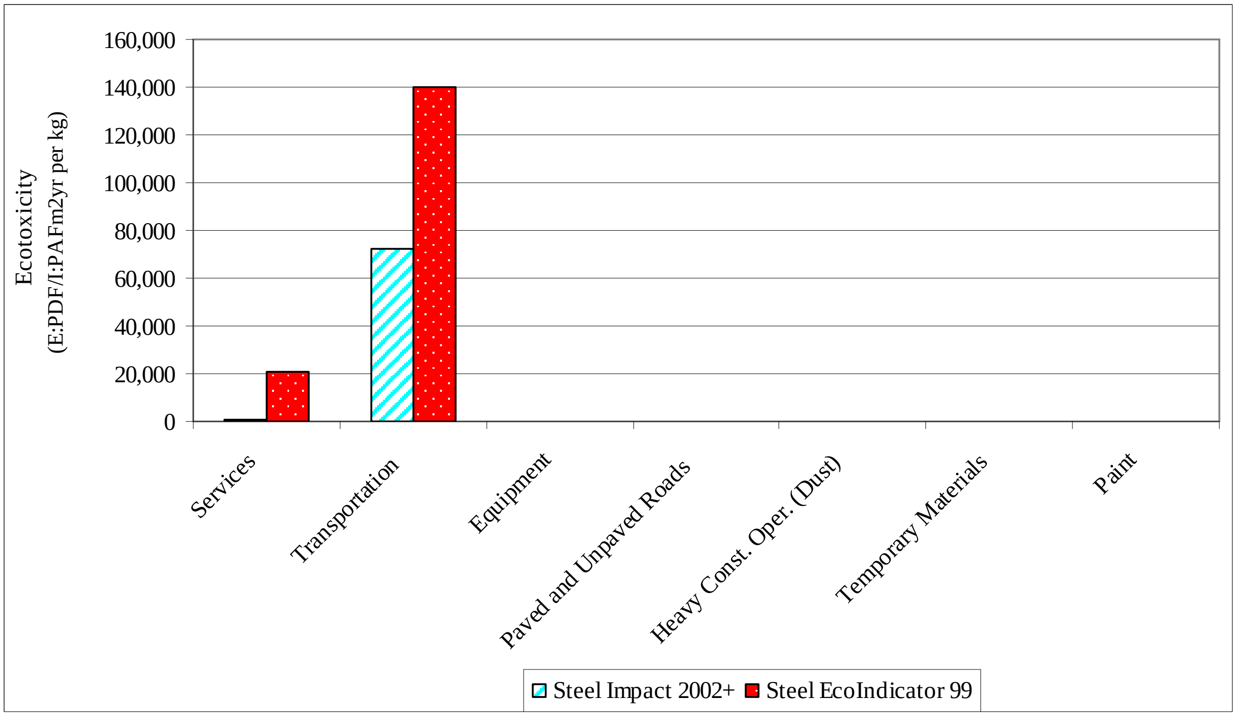


Figure 51. LCIA Ecotoxicity – Broad Construction Impacts – Steel (Mean Value)

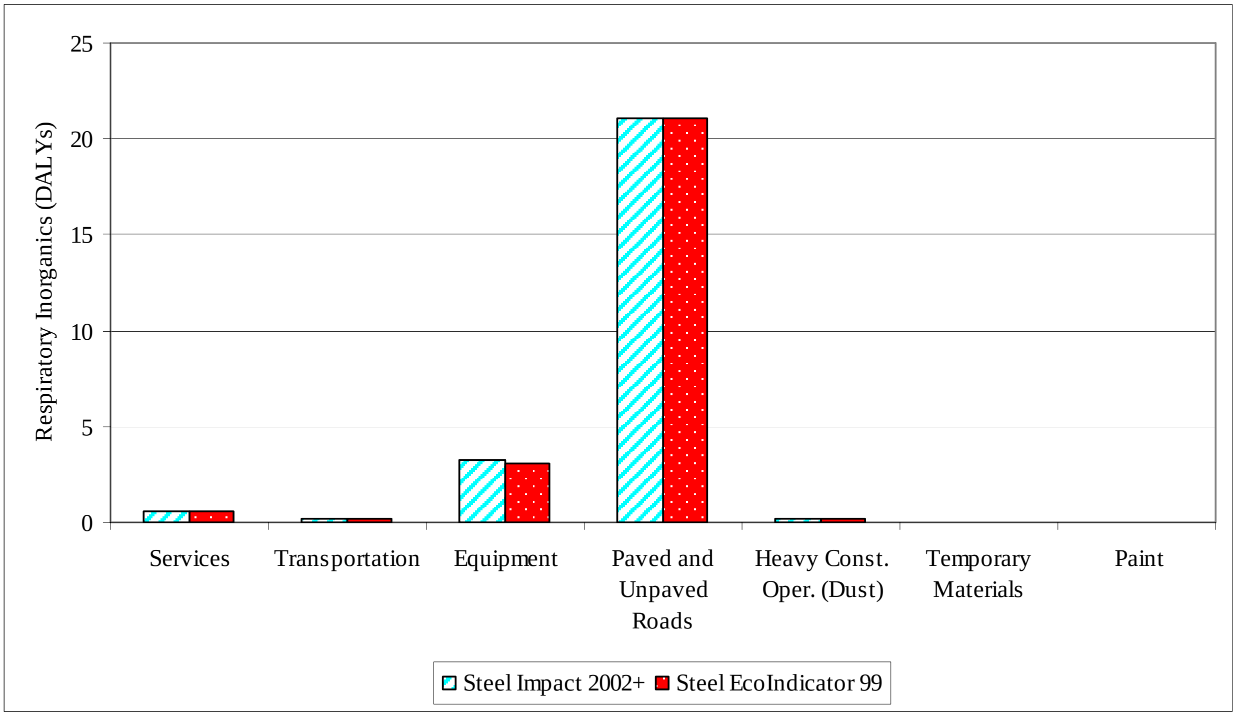


Figure 52. LCIA Respiratory Inorganics – Broad Construction Impacts – Steel (Mean Value)

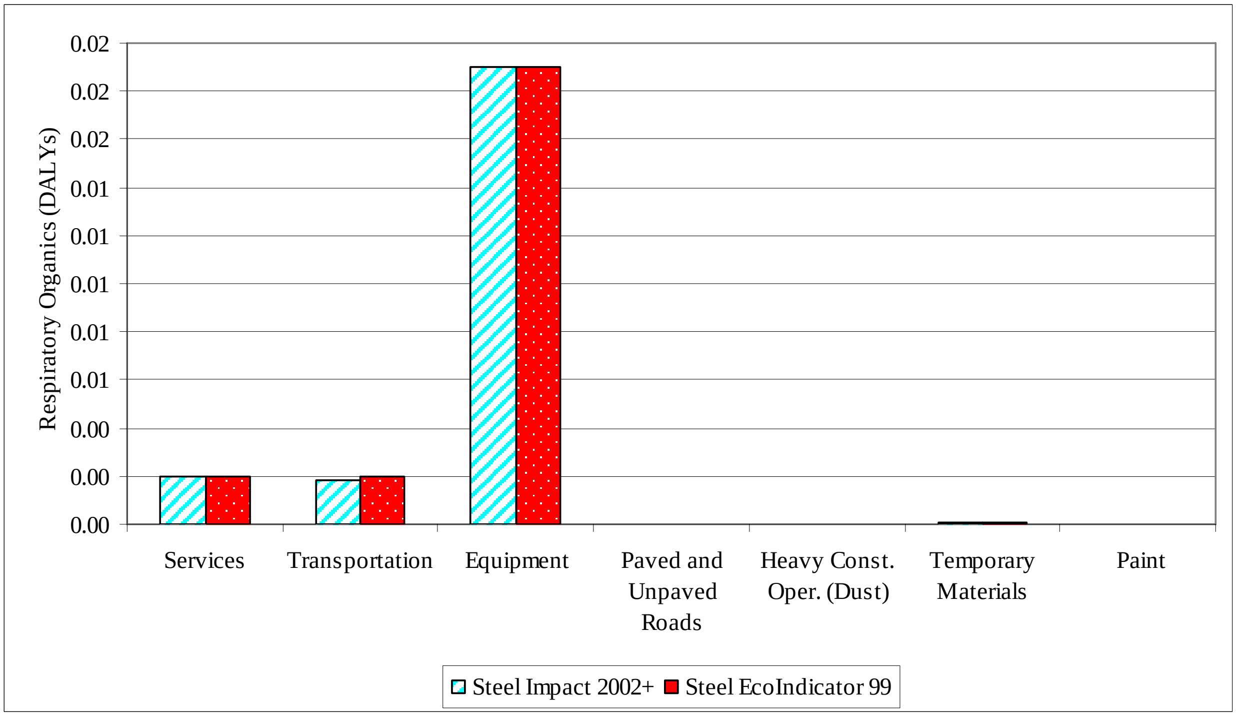


Figure 53. LCIA Respiratory Organics – Broad Construction Impacts – Steel (Mean Value)

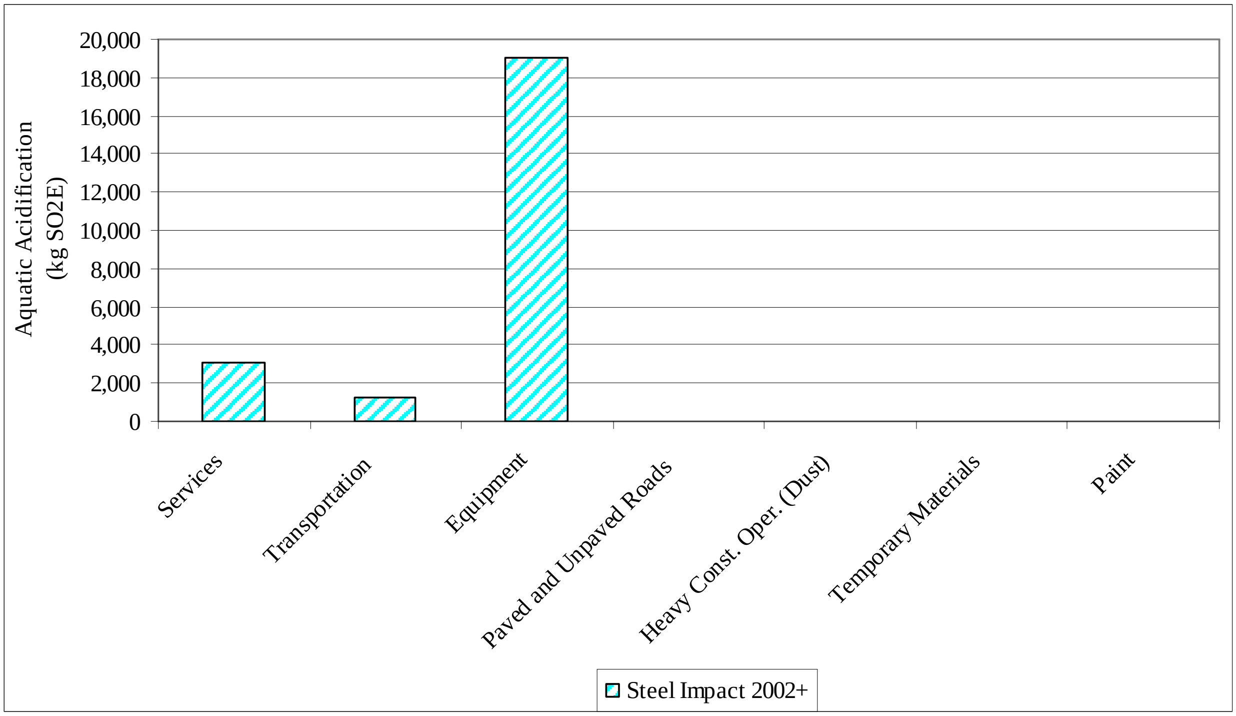


Figure 54. LCIA Aquatic Acidification– Broad Construction Impacts – Steel (Mean Value)

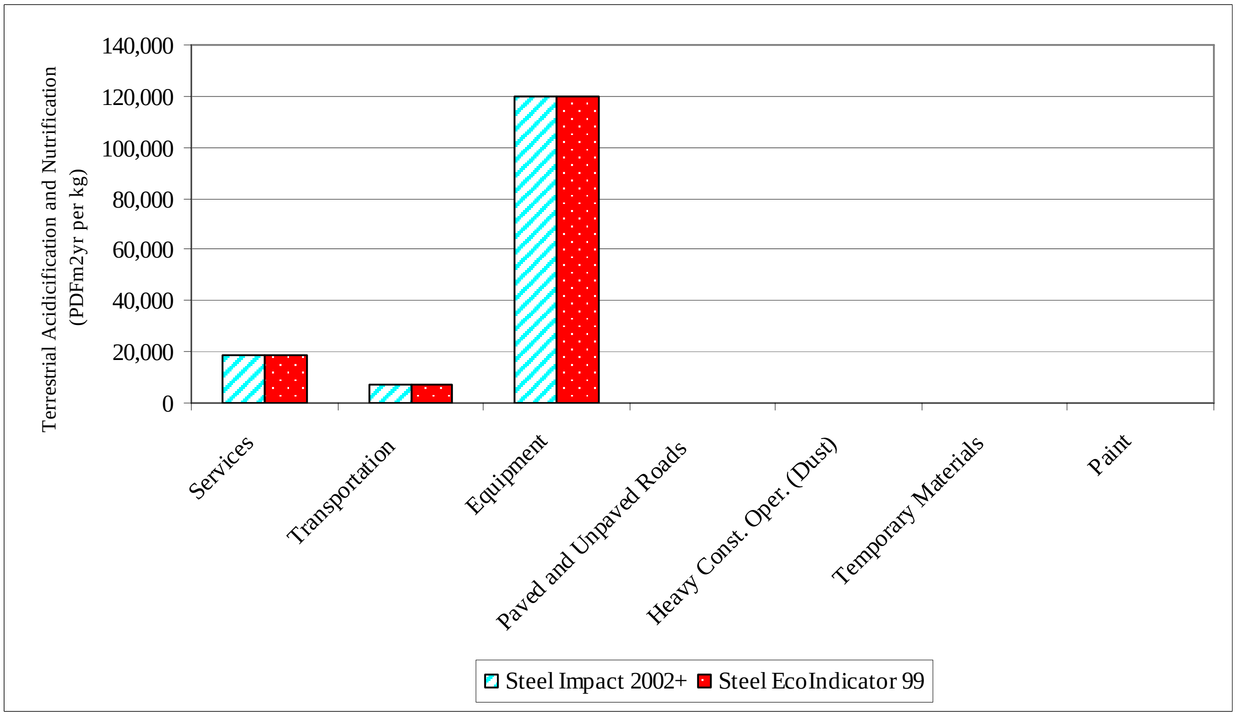


Figure 55. LCIA Terr. Acid. & Nutr.– Broad Construction Impacts – Steel (Mean Value)

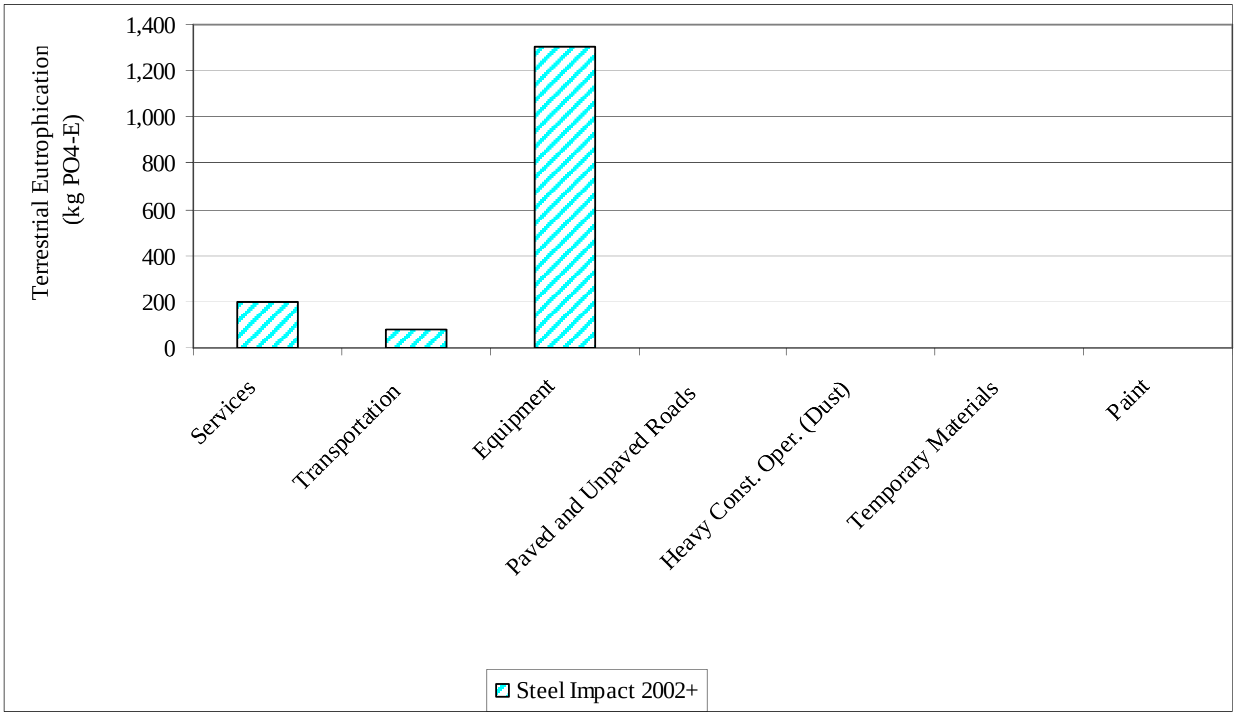


Figure 56. LCIA Terr. Eutr.– Broad Construction Impacts – Steel (Mean Value)

5.2 PRECAST STRUCTURE

5.2.1 Overview - Precast Structure

The precast parking structure is a 5-level parking structure located on a brownfield site. The design began in 2002, and the bid documents were issued on October 14, 2002. This was a publicly funded project with four prime contractors who were awarded the project based on the lowest responsible bid. The four primes were precast, general construction, electrical, and mechanical/heating and plumbing contractors. Pennsylvania state law requires separation of prime contractors for publicly funded projects. In addition to the four primes, an agency construction manager was hired by the owner to oversee daily construction activity. Construction began at the beginning of 2003 and was completed on time in October 2003. The parking facility has 377 spaces. The foundation system is a deep foundation with augercast piles, pile caps, and grade beams. The main structural system is precast concrete with the main components of pre-topped double tees, columns, lite walls, spandrels, panels, stairs, and hollowcore planks. There are two stair towers: a precast stair tower and a transparent stair tower with glazing and a curtainwall system. Other main features include one bank of elevators with two cabs; parking revenue equipment; fiberglass canopies; aluminum trellis work; poured concrete lobbies, islands, slab on grade, and pour strips; lights; generator; steel stairs; brick; and piping.

A comprehensive description of the parking garage construction process was developed through daily construction reports, drawings, specifications, and utility bills. Therefore, the data quality is better than average because assumptions regarding the construction process are limited.

5.2.2 Assumptions – Precast Structure

The following list details the following modeling assumptions:

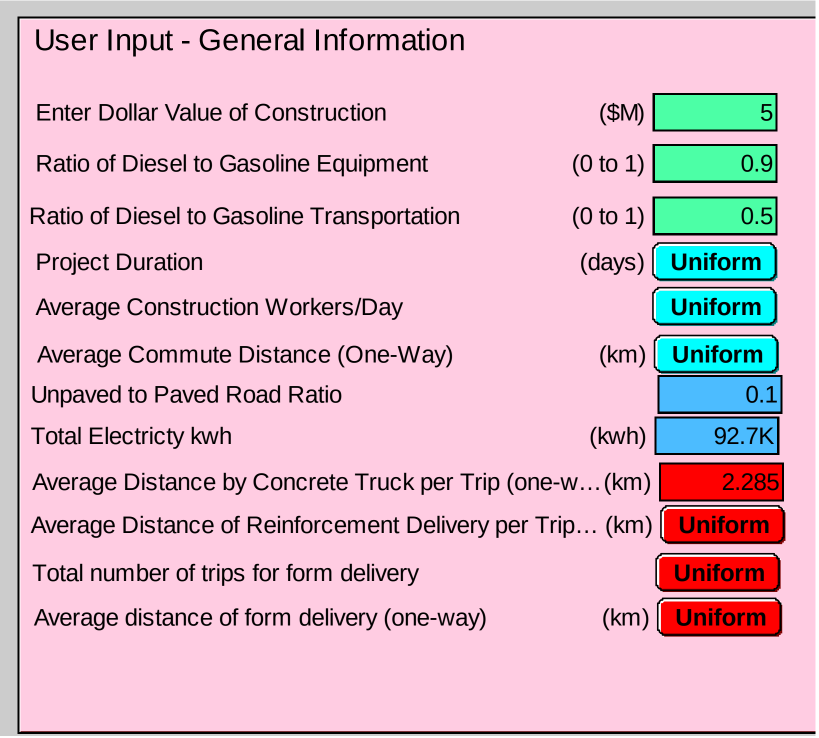
- Once the precast member was delivered to the site, the member was moved off the trailer bed by a crane and was erected. It is assumed that the precast member was not stored in a staging area on-site.

- The electric switch gear and transformer were not included because this equipment was shared with adjacent buildings.

- Storm water run-off quantity and quality were not included in this analysis since a management plan was implemented. The storm water management plan was approved by the County Conservation District and included elements such as inlet basin covers, silt fencing, and rock construction entrances.

5.2.3 Input – Precast Structure

General information input into the hybrid construction model for the precast structure is shown in Figure 57. Uniform distributions were established for project duration (270 and 300 days); average construction workers per day (8 and 9 workers) based on construction daily reports; and average commute distance one-way (5 to 10 miles); average distance for reinforcement delivery per trip one-way (5 to 10 miles); total number of trips for form delivery (1 to 5). The electricity usage is based on actual utility bills from the owner and contractors.


User Input - General Information

Enter Dollar Value of Construction	($M)	5
Ratio of Diesel to Gasoline Equipment	(0 to 1)	0.9
Ratio of Diesel to Gasoline Transportation	(0 to 1)	0.5
Project Duration	(days)	Uniform
Average Construction Workers/Day		Uniform
Average Commute Distance (One-Way)	(km)	Uniform
Unpaved to Paved Road Ratio		0.1
Total Electricty kwh	(kwh)	92.7K
Average Distance by Concrete Truck per Trip (one-w…	(km)	2.285
Average Distance of Reinforcement Delivery per Trip…	(km)	Uniform
Total number of trips for form delivery		Uniform
Average distance of form delivery (one-way)	(km)	Uniform

Figure 57. User Input - General Information - Precast Structure

Specific user input information on site preparation and foundations, concrete, masonry, surface applications, can be found in Appendix G, Figure 140 through Figure 145. A summary is listed below:

- Excavation
    - 6,500 BCY
- Backfilling
    - 821 LCY
- Compaction
    - 1068 CCY
- Grading
    - 3,698 BCY
- Augercast piles
    - 141 piles
    - Average length, 80 feet
    - Average diameter, 1.33 feet
- Pile caps and grade beams

    - 1,382 CY
- Masonry
    - Brick
        - 3893 SF
    - Block
        - 1344 SF
- Surface Applications
    - Gallons, 42
- Transportation (not otherwise included)
    - Class 7
        - 80,000 km
- Material handling
    - Fork lifts
        - 40 hours
    - Aerial lifts
        - 40 hours
    - Crane
        - 280 hours

5.2.3.1 LCI –Precast Case Study

PM Emissions for Total LCI, Broad Construction Impacts, and Aggregated Construction Processes results are represented in Figure 58, Figure 59, and Figure 60. GWP emissions for the same respective categories are shown in Figure 61, Figure 62, and Figure 63. The remaining emissions are shown in Figure 64, Figure 65, and Figure 66. Additional results are also located in Appendix H, Figure 146, Figure 147, and Figure 148.

PM Emissions – Precast Case Study

Minimum, median, and maximum results for PM emissions $PM_{2.5}$, PM_{10}, PM_{15}, and PM_{30} are shown in Figure 58. Broad construction impacts results show that for this precast case study, heavy construction operations and paved and unpaved roads, are significant in terms of PM emissions (see Figure 59). The results for heavy construction operations are higher for this case study, as opposed to the steel case study, because the site preparation activities were relatively extensive for this project. Consistent with the steel case study, the paved and unpaved road category is an important category and should be included in all LCAs, not only building LCAs.

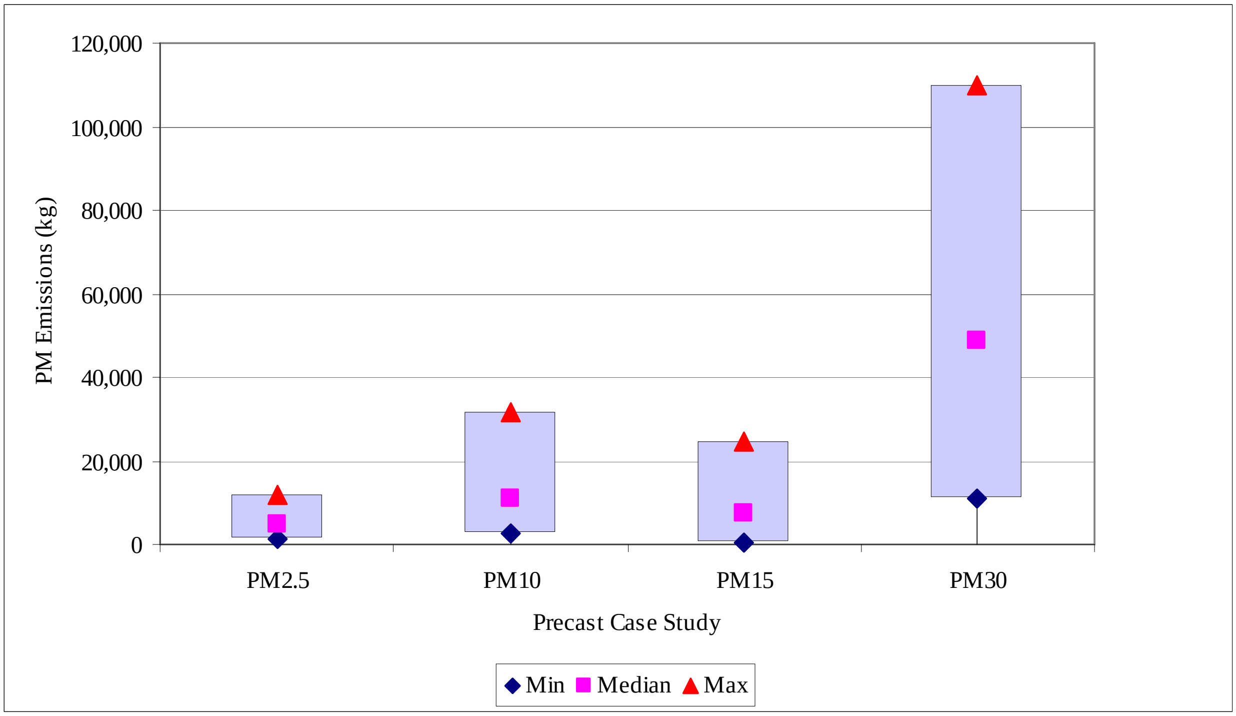


Figure 58. LCI PM Emissions – Total LCI – Precast

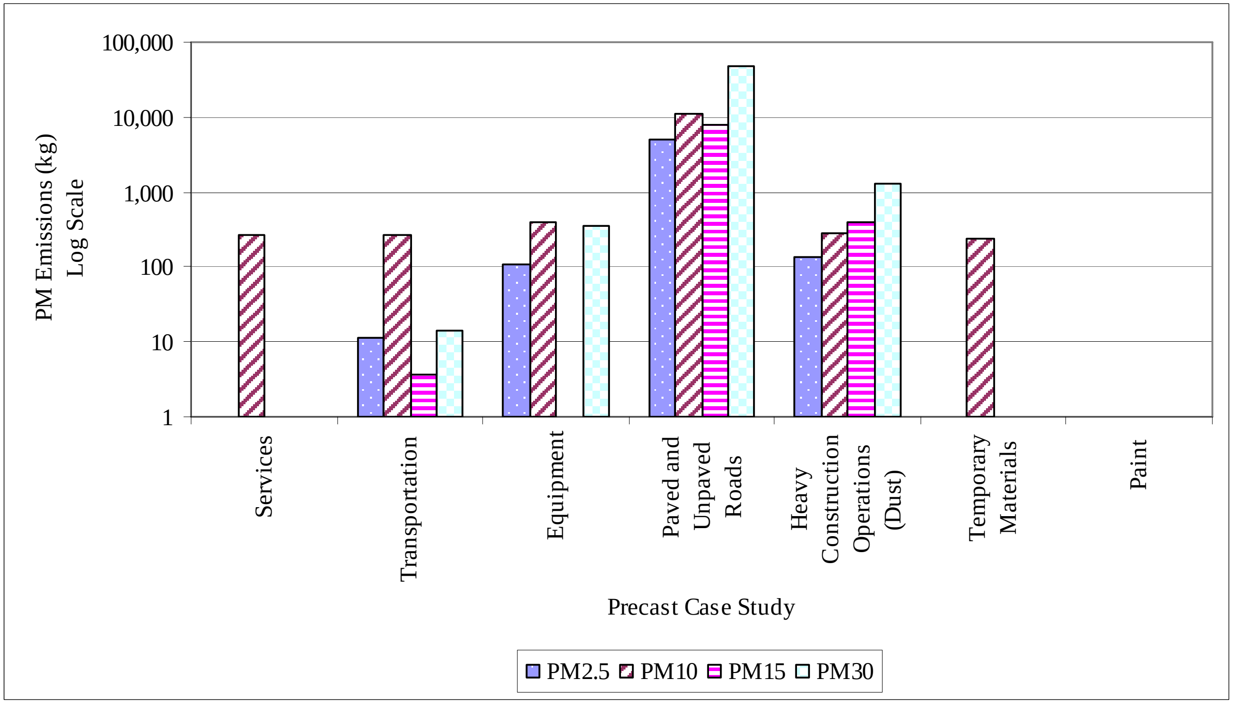


Figure 59. LCI PM Emissions – Broad Construction Impacts –Precast (Mean Value)

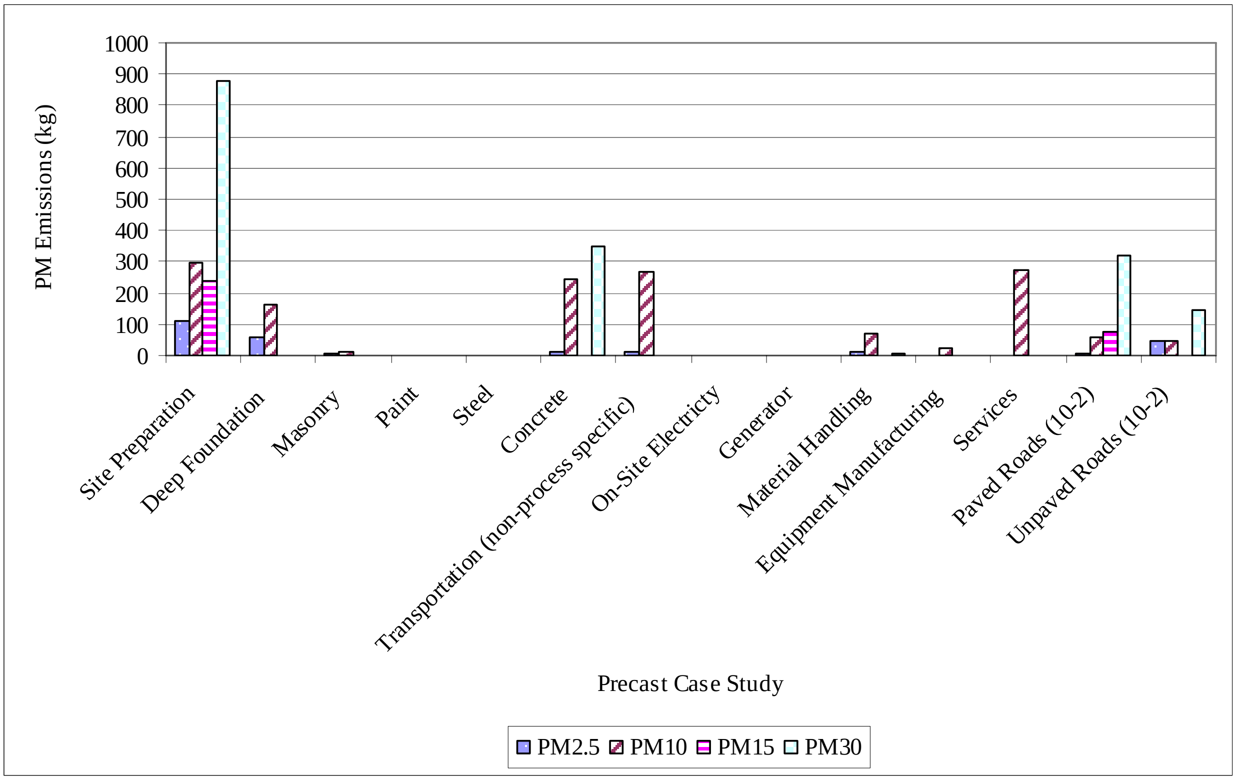


Figure 60. LCI PM Emissions –Aggregated Construction Processes –Precast (Mean Value)

GWP Emissions – Precast Case Study

In terms of GWP emissions, CO_2 is the highest when compared to CH_4, N_2O, and CFCs and HCFCs as shown in Figure 61. The most significant categories for CO_2 emissions are equipment, transportation, services, and temporary materials (Figure 62). One interesting result is that in terms of CH_4 emissions, the services category is the highest contributor. Figure 63 demonstrates that transportation is the second highest contributor of CO_2 emissions, which is due primarily to the transportation of the precast concrete.

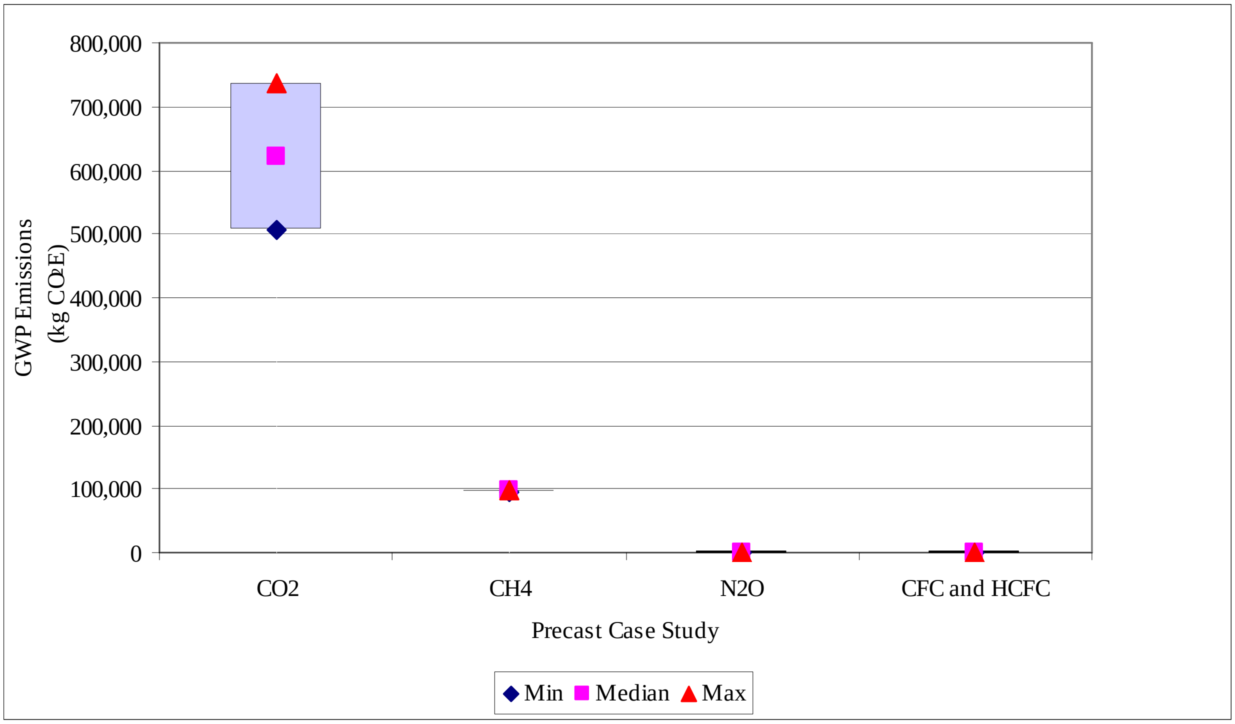


Figure 61. LCI GWP Emissions – Total LCI – Precast

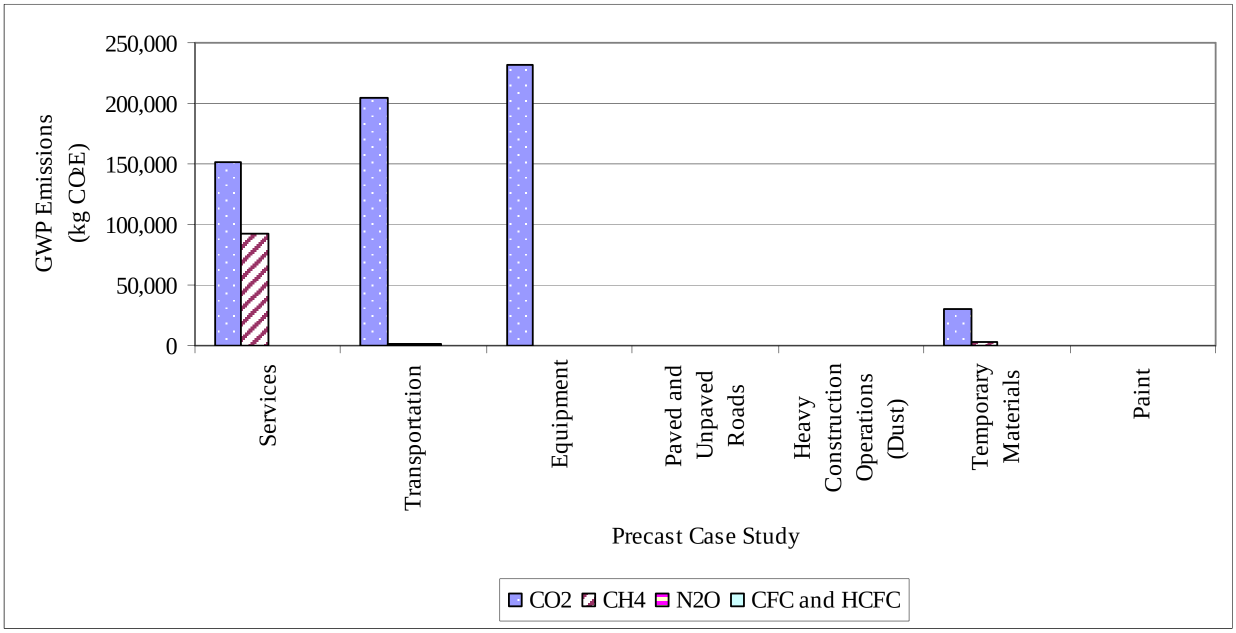


Figure 62. LCI GWP Emissions – Broad Construction Impacts – Precast

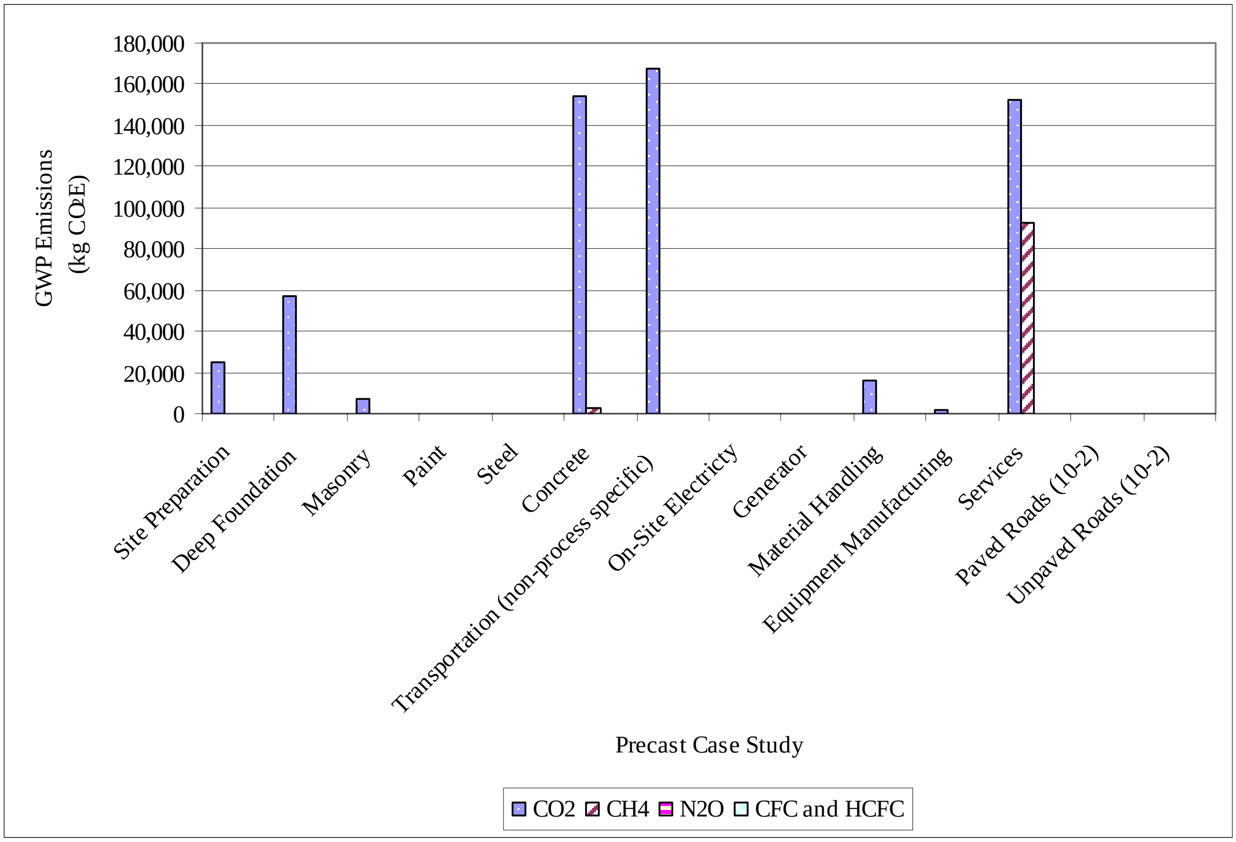


Figure 63. LCI GWP Emissions – Aggregated Construction Processes – Precast

Emissions – Precast Case Study

CO and NO_x emissions are the highest emissions as shown in Figure 64 with CO as the highest. The results for the precast case study are consistent with the results of the steel case study. The equipment category is the highest in terms of the emissions of CO, NO_x, and SO_x (Figure 65). Finally, the concrete process is the highest construction process, which is also consistent with the steel case study.

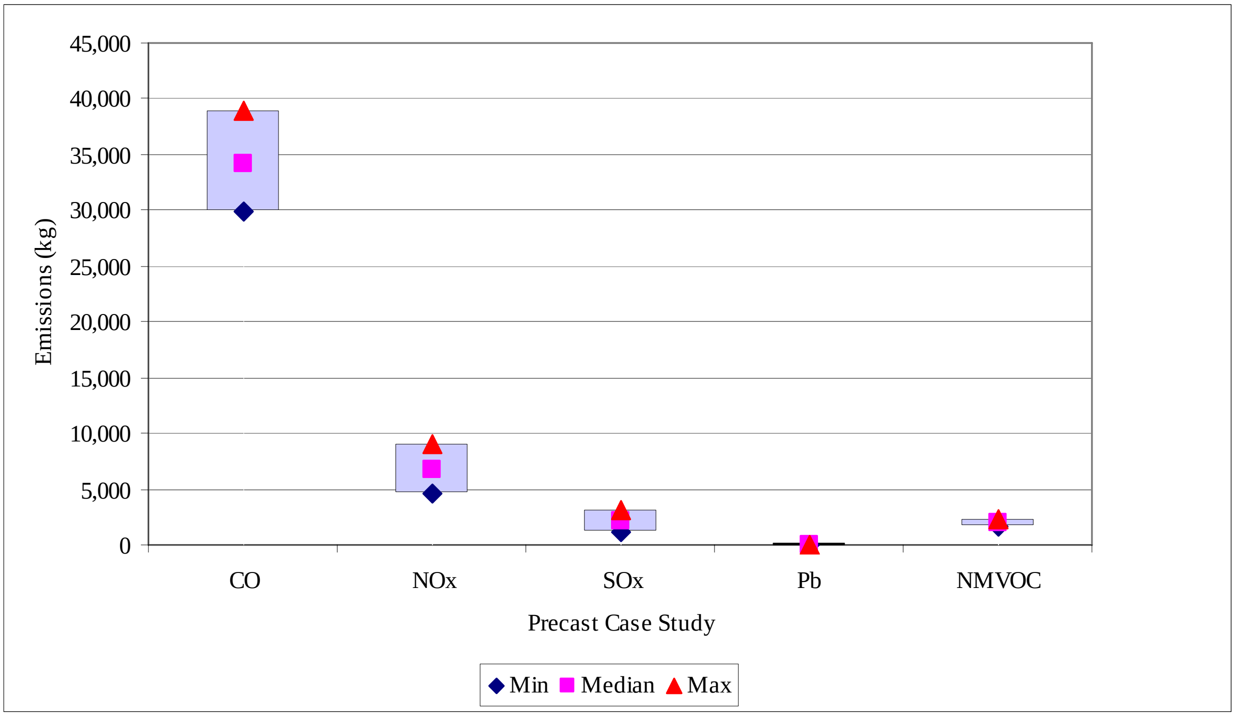


Figure 64. LCI Emissions – Total LCI – Precast

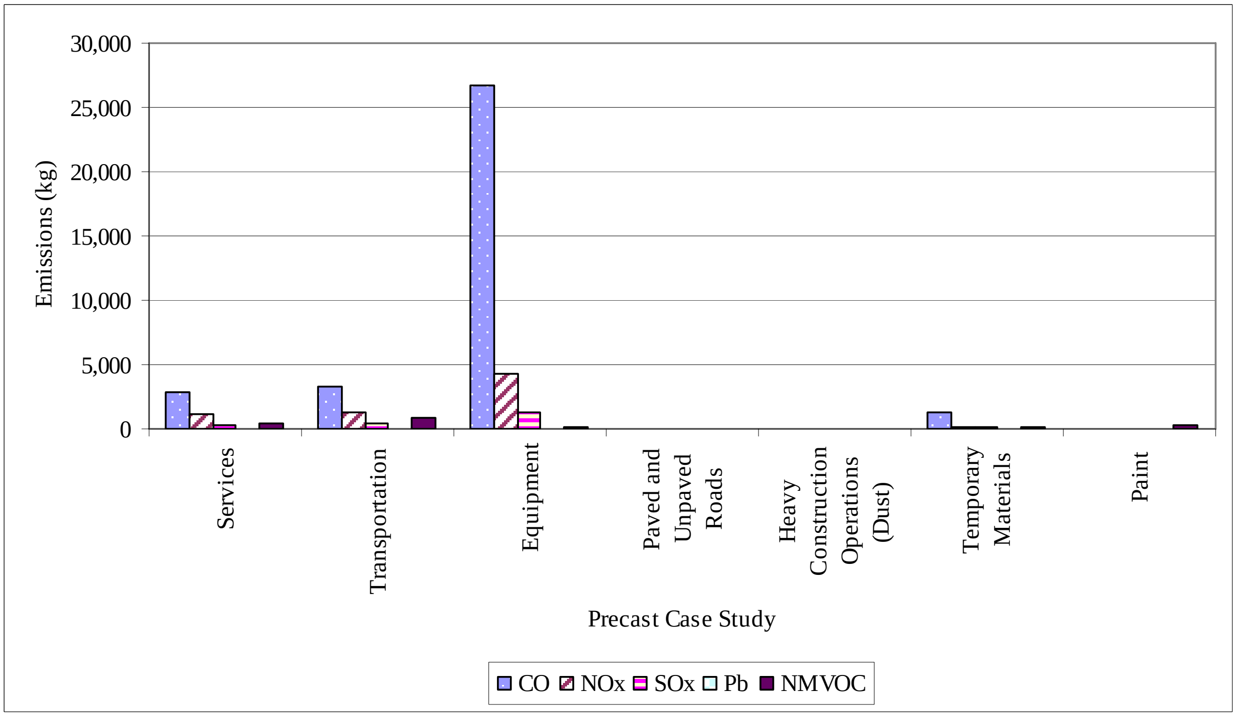


Figure 65. LCI Emissions – Broad Construction Impacts – Precast

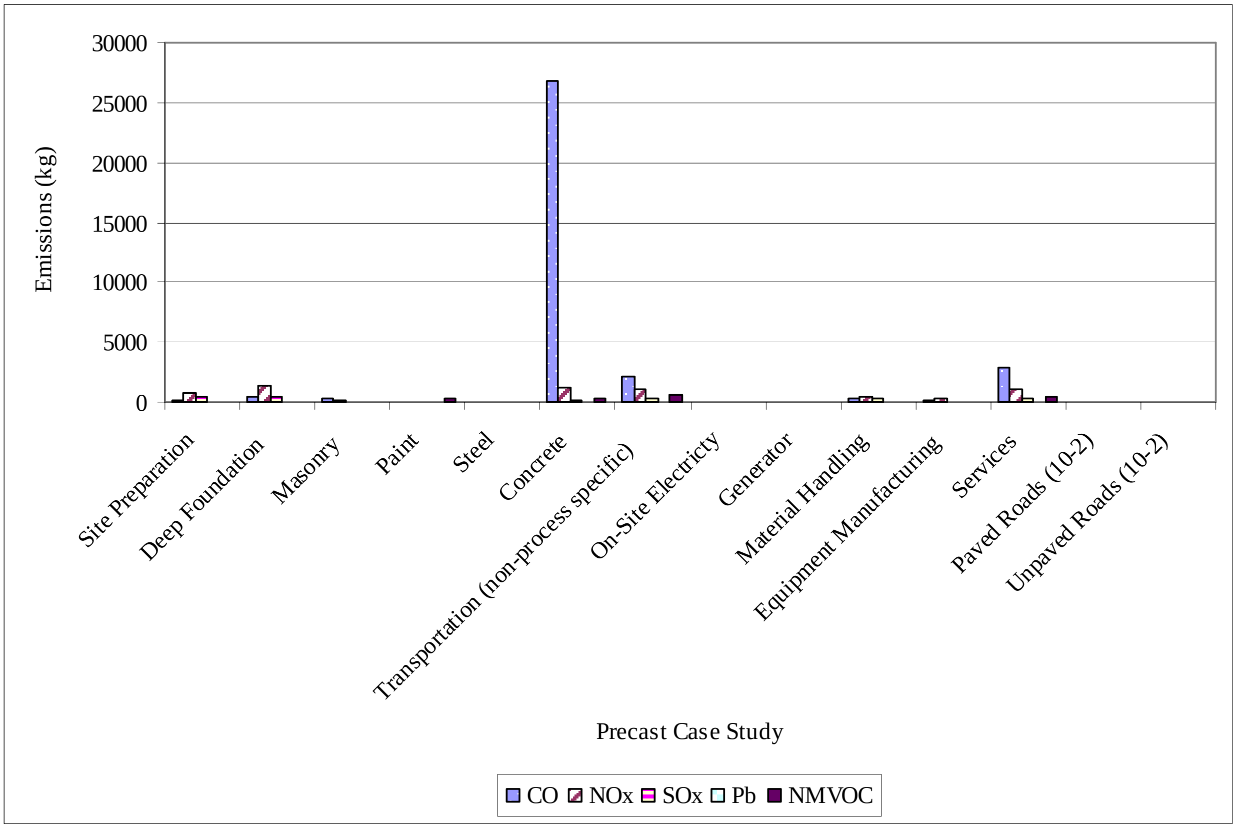


Figure 66. LCI Emissions – Aggregated Construction Processes – Precast

5.2.3.2 Energy and Waste Results – Precast Case Study

The total mean value for energy usage during in the construction phase was about 8TJ. The results for solid and liquids waste were 172 tons and 1,308 gallons respectively (see Table 19).

Table 19. Energy and Waste – Precast (Mean Values)

	Energy (TJ)	Solid Waste (tons)	Liquid Waste (gallons)
Precast	8	172	1386

5.2.3.3 LCIA – Precast Case Study

The LCIA precast case study results are displayed in the same manner as the steel case study LCIA results. This section focuses on the "Broad Construction LCIA" results in Figure 67 through Figure 77. "Total LCIA" results for both the steel and precast case studies are shown in Appendix I, Figure 149 through Figure 159. "Aggregated Construction Processes LCIA" results are also shown in Appendix I, Figure 172 through Figure 182.

Similar to the steel case study, services, transportation, and equipment are the prevalent construction categories in almost all of the impact categories. The temporary material category does appear to be more significant in the precast case study, as opposed to the steel case study.

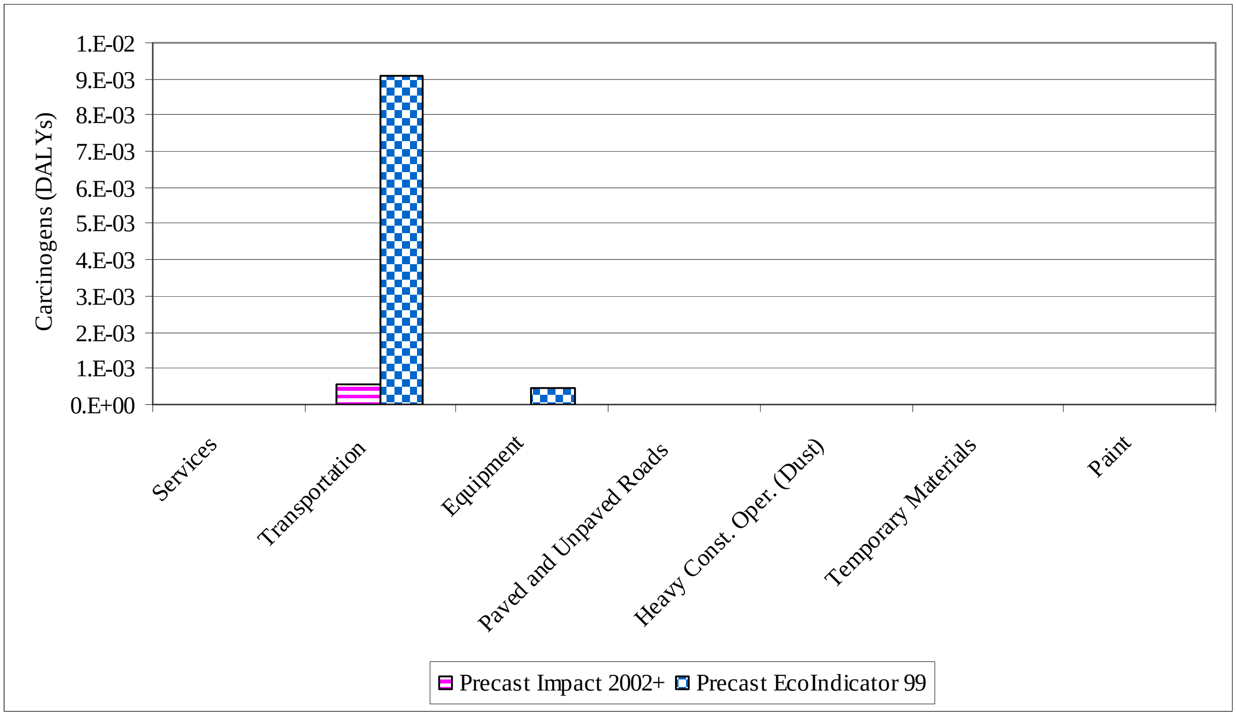


Figure 67. LCIA Carcinogens– Broad Construction Impacts – Precast

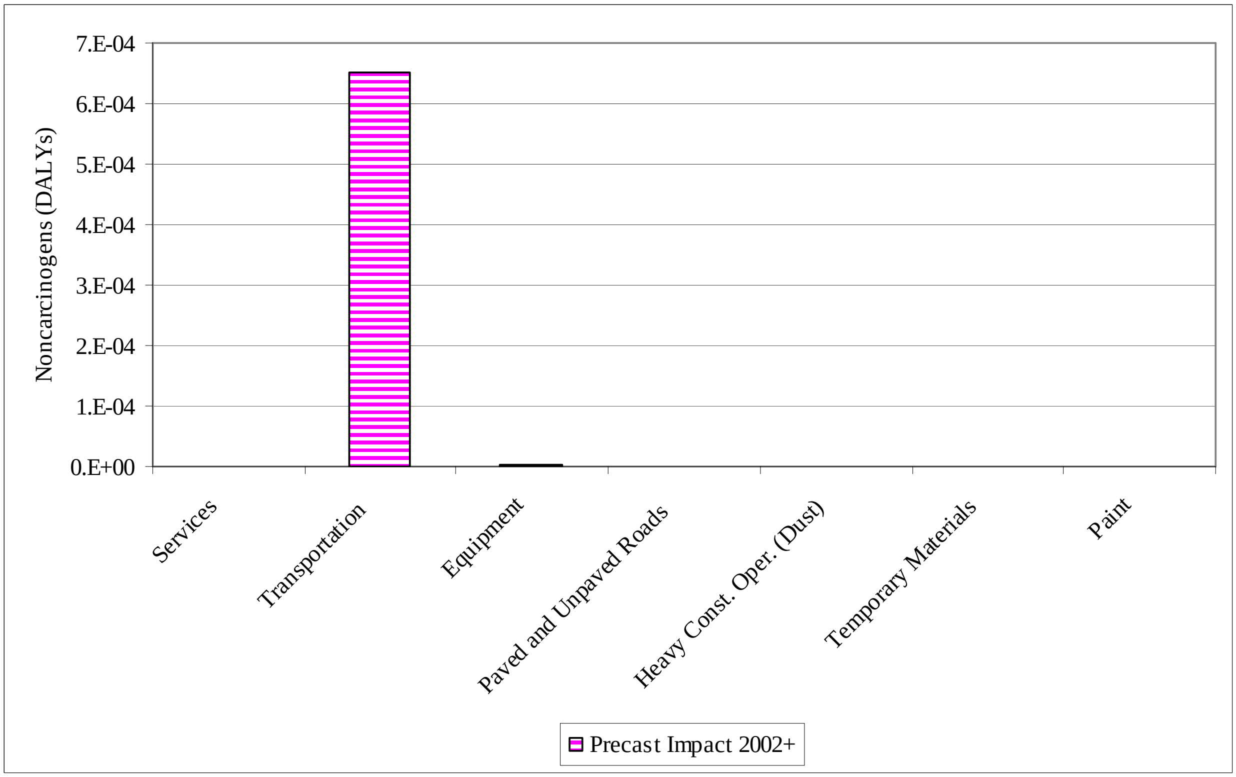


Figure 68. LCIA Noncarcinogens– Broad Construction Impacts – Precast

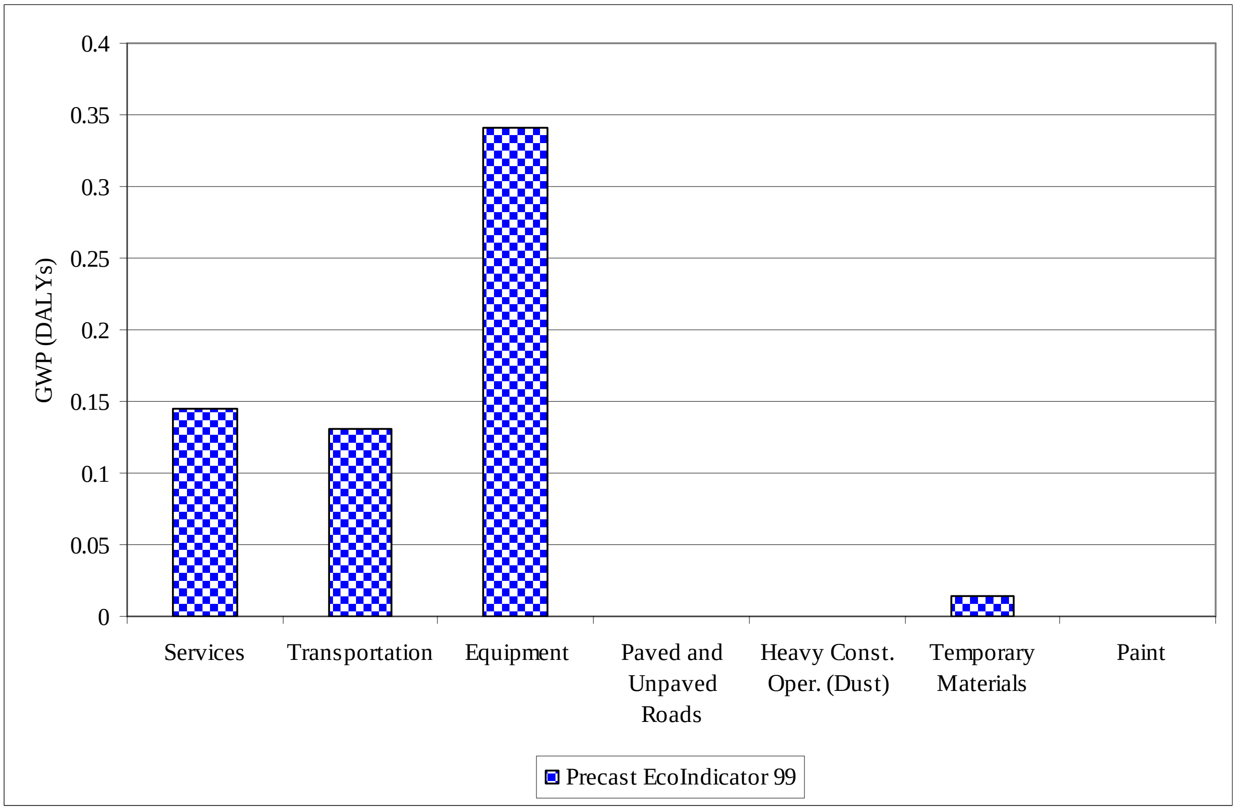


Figure 69. LCIA GWP DF– Broad Construction Impacts – Precast

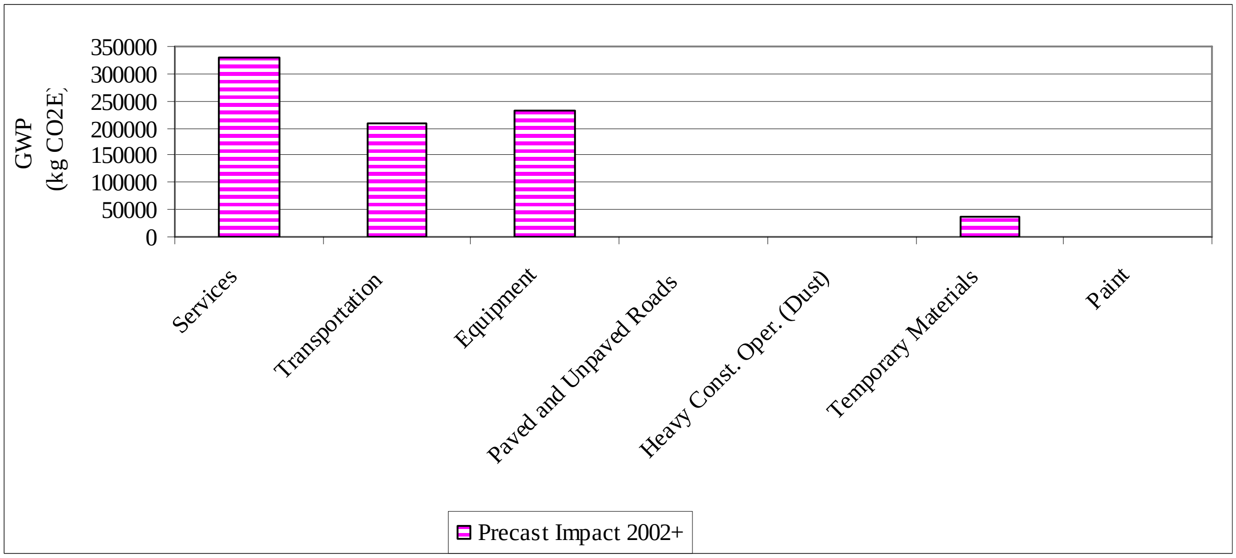


Figure 70. LCIA GWP CF– Broad Construction Impacts – Precast

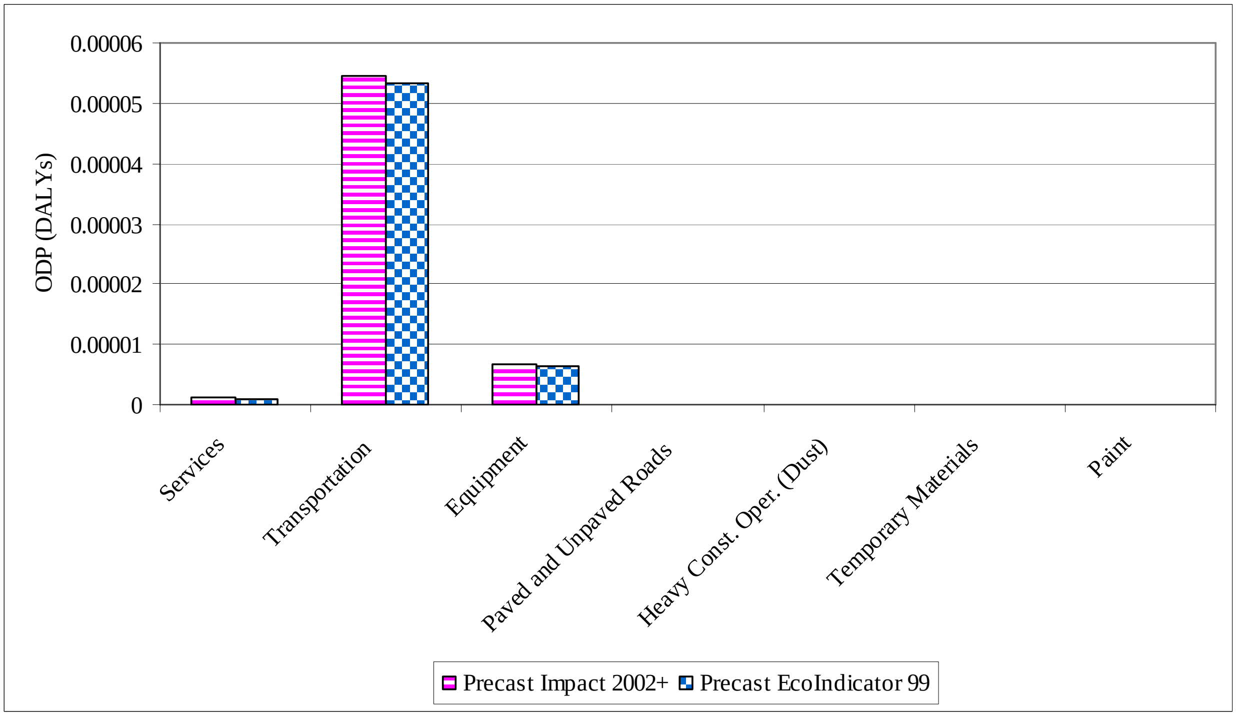


Figure 71. LCIA ODP– Broad Construction Impacts – Precast

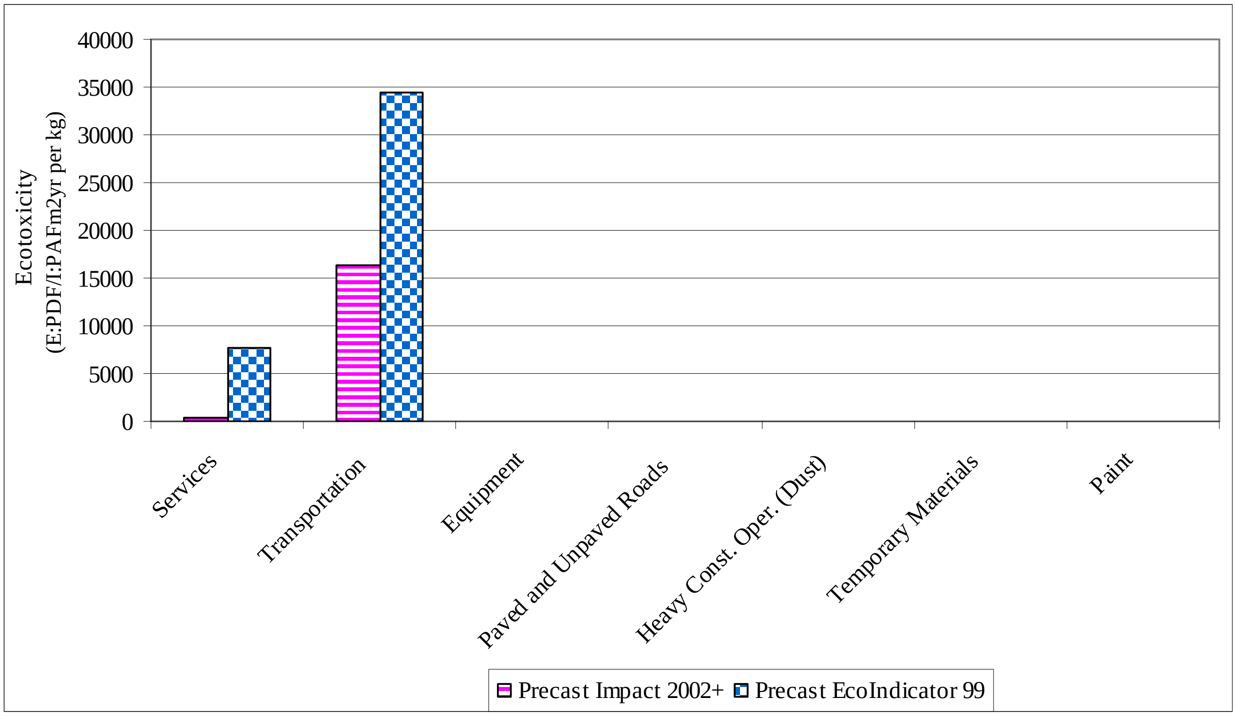


Figure 72. LCIA Ecotoxicity– Broad Construction Impacts – Precast

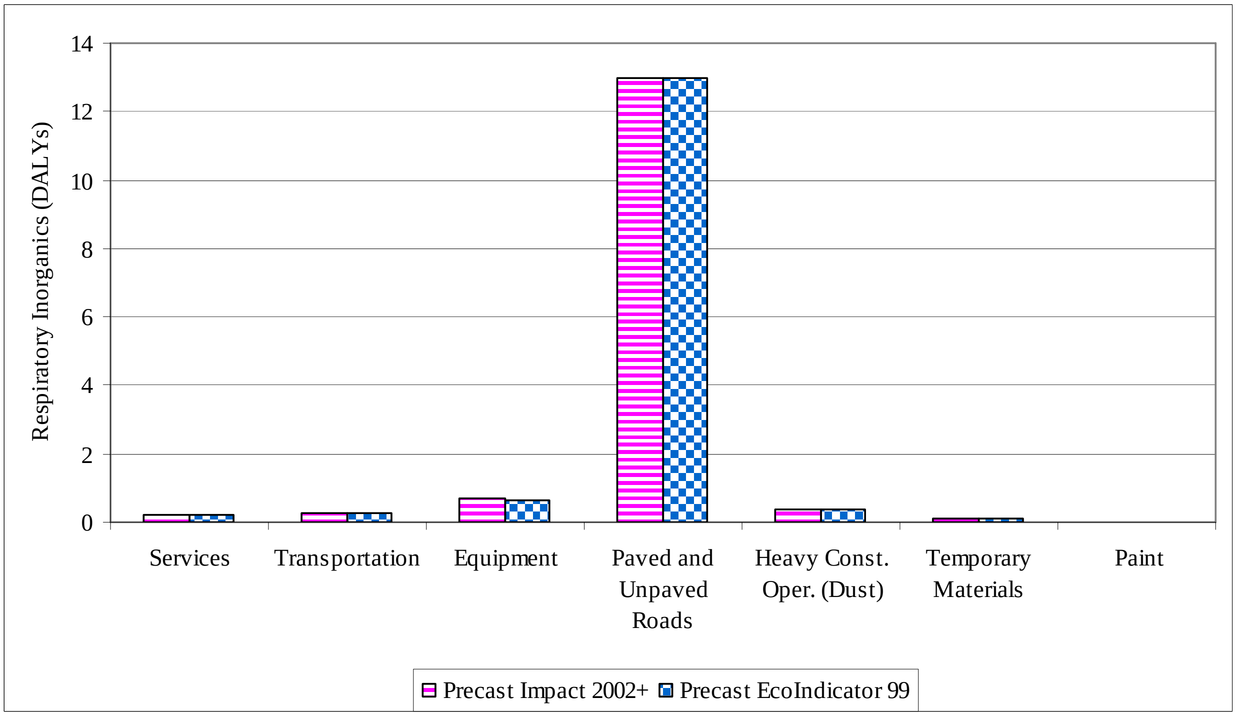


Figure 73. LCIA Respiratory Inorganics– Broad Construction Impacts – Precast

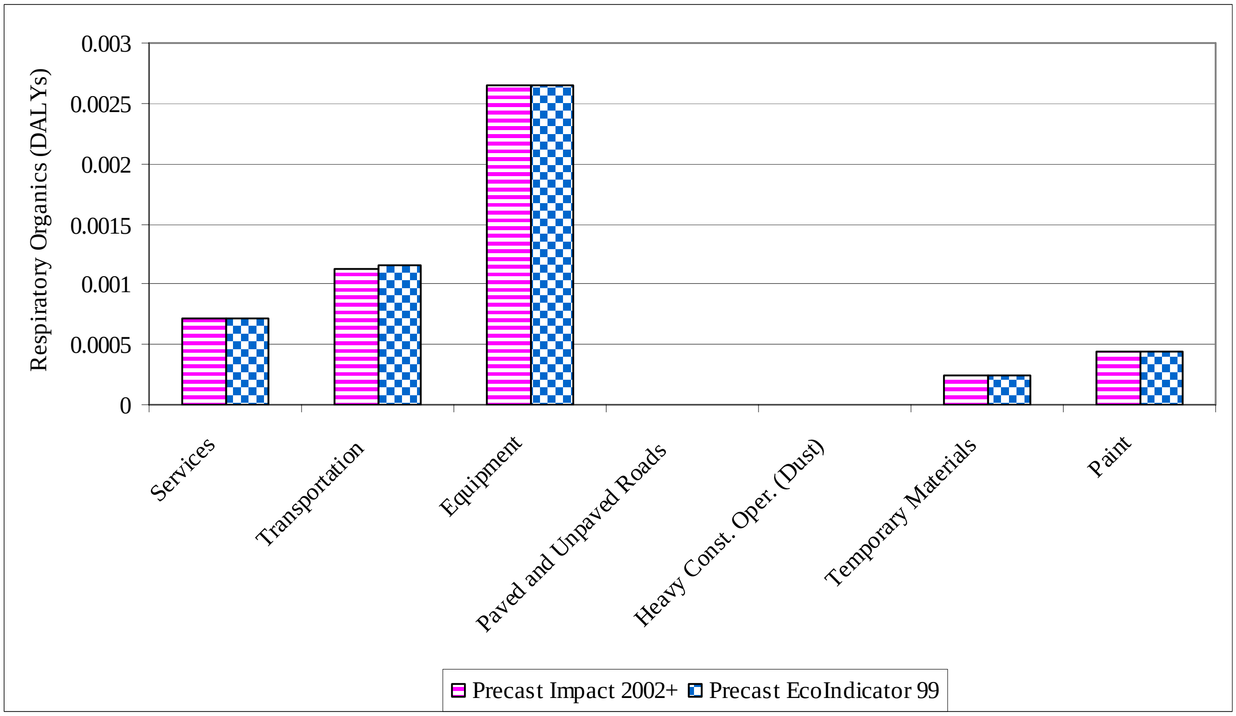


Figure 74. LCIA Respiratory Organics– Broad Construction Impacts – Precast

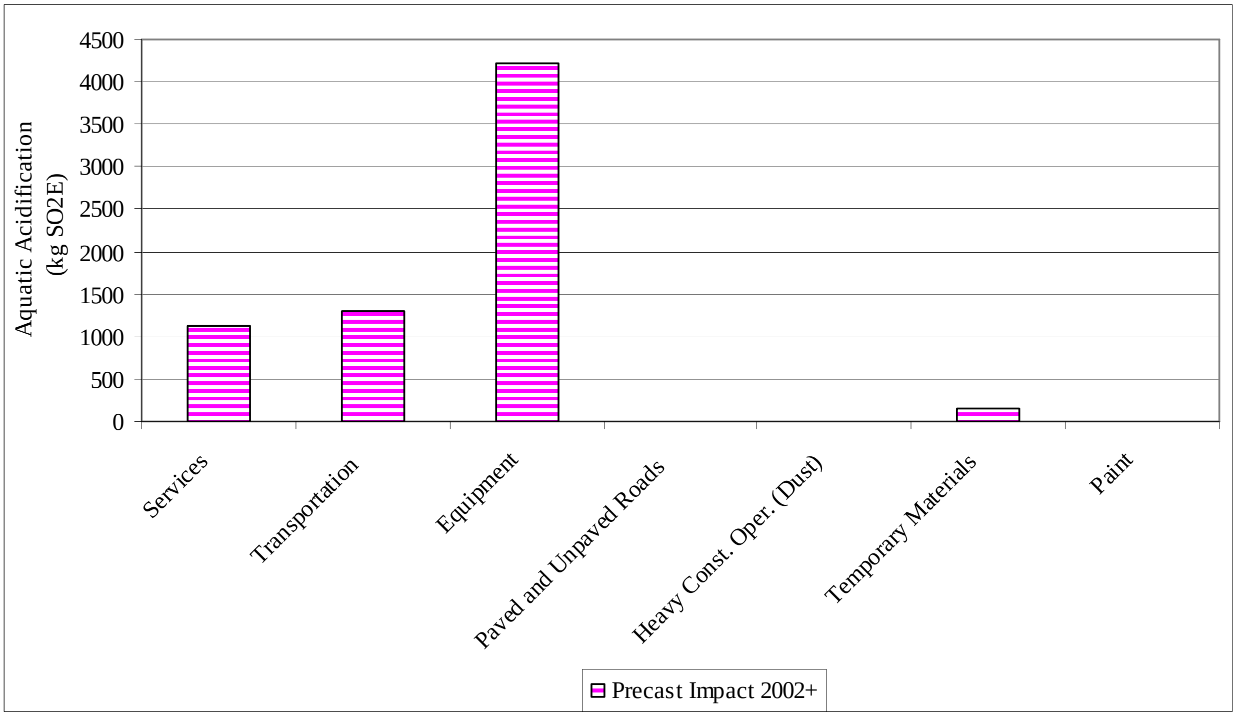


Figure 75. LCIA Aquatic Acidification– Broad Construction Impacts – Precast

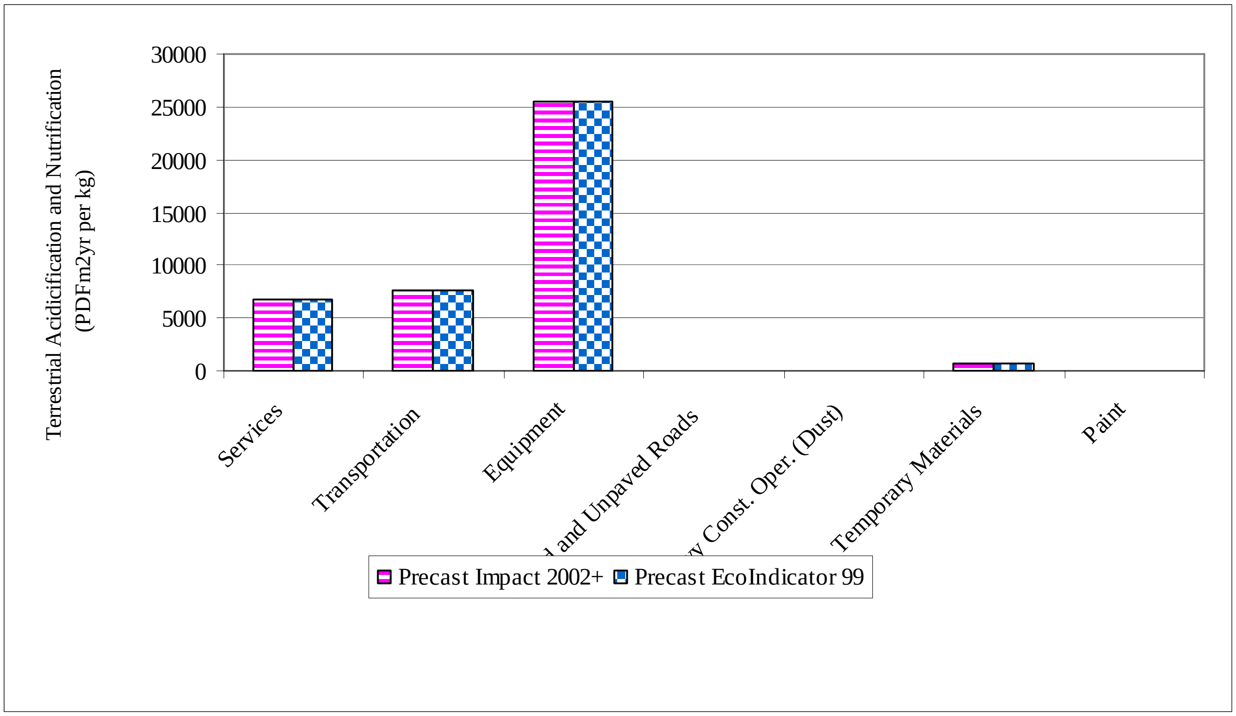


Figure 76. LCIA Terrestrial Acidification and Nutrification– Broad Construction Impacts

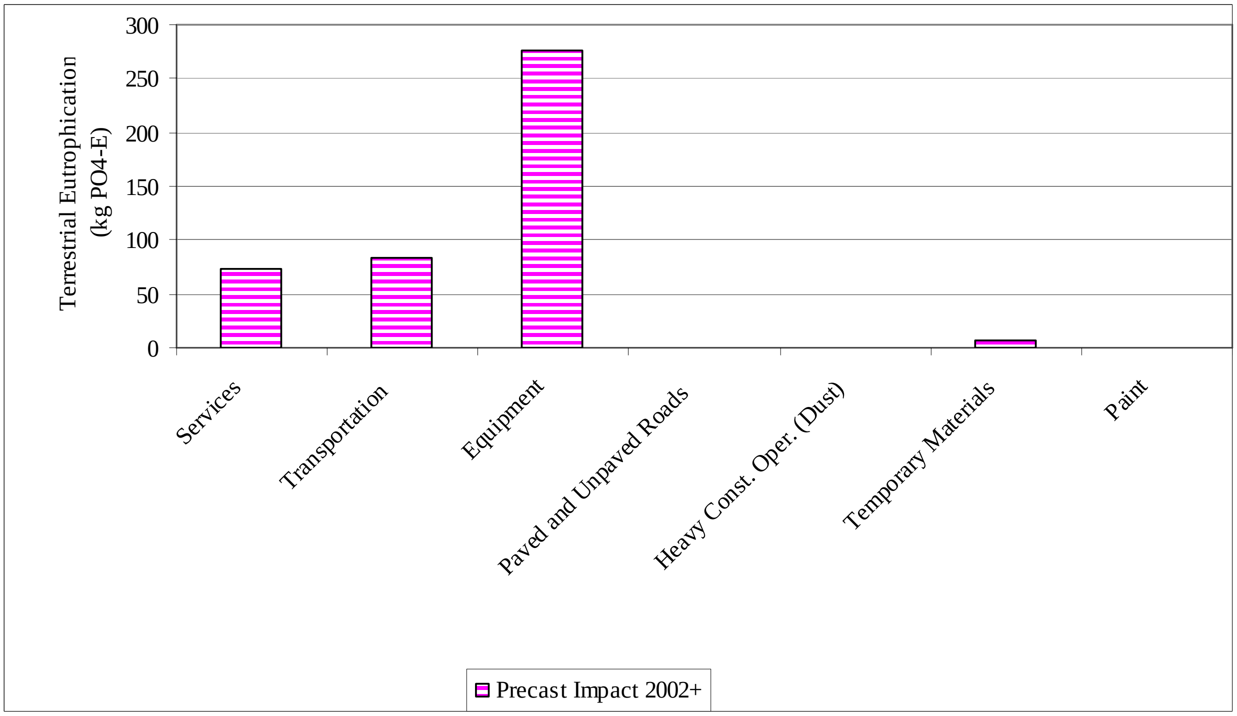


Figure 77. LCIA Terrestrial Eutrophication– Broad Construction Impacts – Precast

6.0 RESULTS DISCUSSION

This section examines and compares the results from the hybrid construction model with other published LCA case studies and other life cycle stages. This section discusses modeling LCIA and the different LCIA methods used in this research, examines construction from local and regional perspectives, and concludes with sensitivity analyses.

6.1 COMPARISON WITH EXISTING LITERATURE

The modeled results for the construction phase were compared with the other life cycle stages of materials, use and maintenance, and end of life. The comparisons were performed for the steel case study only, not the precast case study because an existing LCA did not exist for adequate comparisons. The values for materials, use and maintenance, and end of life phases for energy, CO_2, SO_2, NO_x, and PM_{10} as shown in Figure 78, Figure 80, and Figure 83 were obtained from Guggemos and Horvath (2005) for the steel framed building located in the United States. These results were selected because the case study was most similar to the modeled case study performed herein. The results were normalized on a square meter basis.

Figure 78 shows that the construction phase is greater than the materials and end of life phase, but considerable lower than the use phase. The energy result is somewhat inconsistent with the general notion that construction is less significant than the materials phase. Reasons why construction may be higher than expected is because construction worker transportation, service sectors, and equipment manufacturing was included in this analysis, but excluded from other analyses. To further validate the results, a comparison of the construction phase only was made between the steel framed case study from Guggemos and Horvath (2005), results from this research, and pure I-O results. $13 million representing the cost of construction was the demand in the Commercial and Institutional sector in EIO-LCA model. Since the EIO-LCA results contain both the material and construction phases, the results for the material phase were subtracted out using the averages from the material phases values from Junnila et. al (2006) and Guggemos and Horvath (2005). Figure 79 visually shows the comparison, noting that the Guggemos and Horvath results is considerably less than the EIO-LCA results with the results from this research falling in the middle.

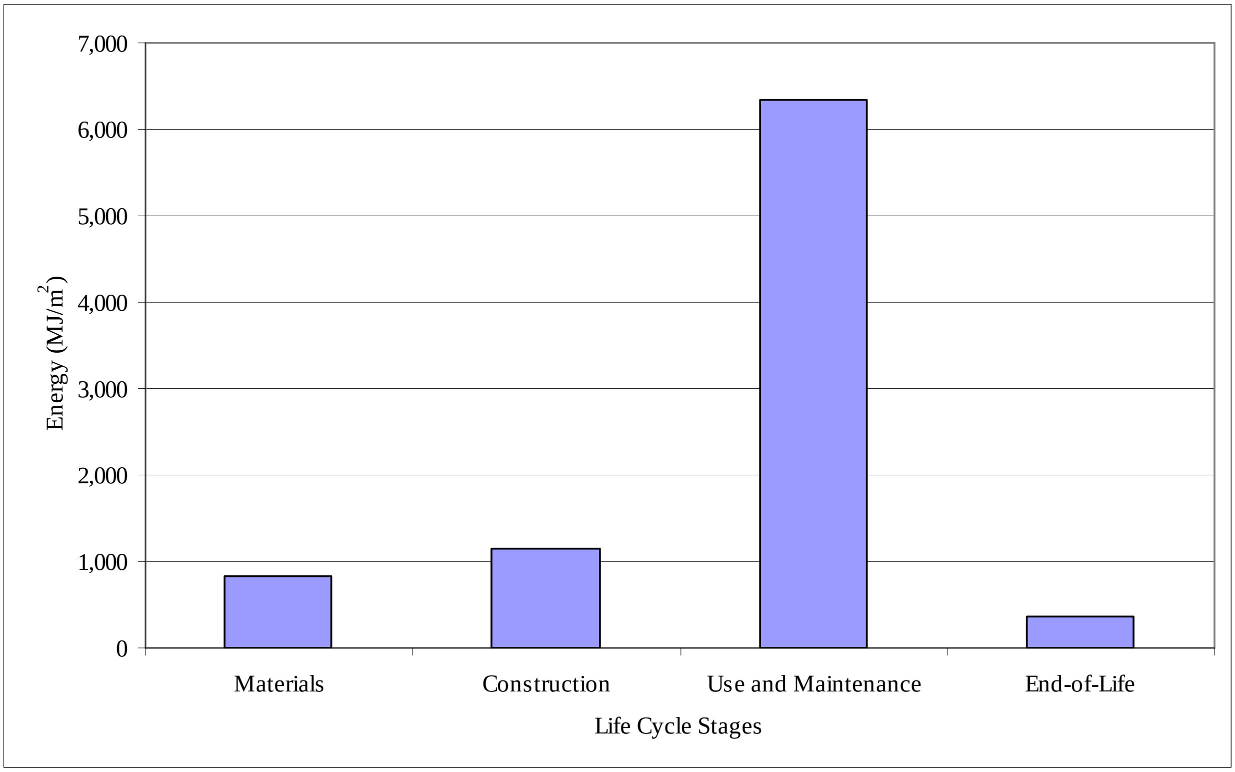


Figure 78. Energy Life Cycle Stage Comparison – Steel

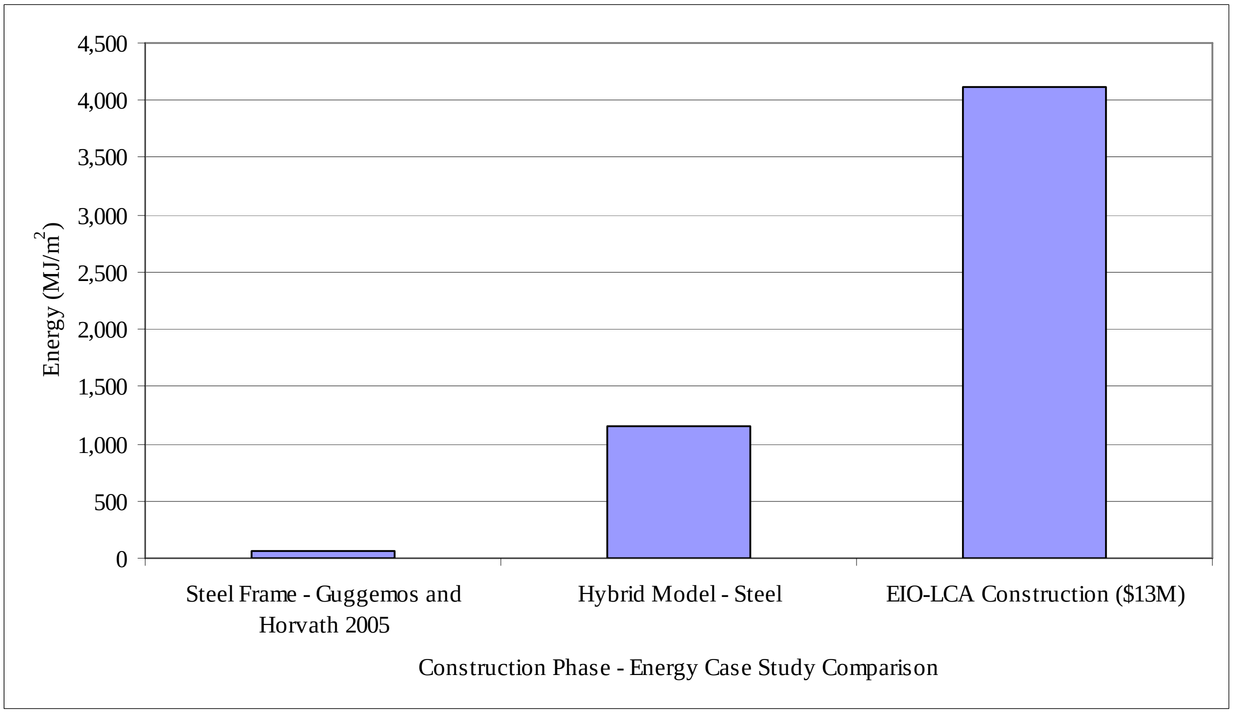


Figure 79. Energy – Construction – Case Study Comparison

In terms of CO_2 emissions, not total CO_2 equivalents, construction is lower than materials, see Figure 80. The results are somewhat counterintuitive, since the construction energy numbers were higher; although, CO_2 emissions were compared with three relevant case studies, and the results for the hybrid model fall between Guggemos and Horvath results and EIO-LCA results as shown in Figure 81. One reason for a smaller than expected increase in the CO_2 emissions is because about half of the construction energy expenditure is from equipment use (approximately 11 TJ of the total 20 TJ). Another reason for the disparity the results may be due to the fact that Guggemos and Horvath used the results from the 1992 version of EIO-LCA, and the 1997 environmental vector has changed considerably. In terms of CO_2 emissions from different sources, electricity is about 2.5 times higher than diesel fuels as shown in Table 20. Additionally, CO_2 emissions from Guggemos and Horvath (2005) are higher than expected when viewed in terms of kg of CO_2/MJ in the construction phase and illustrated in Figure 82.

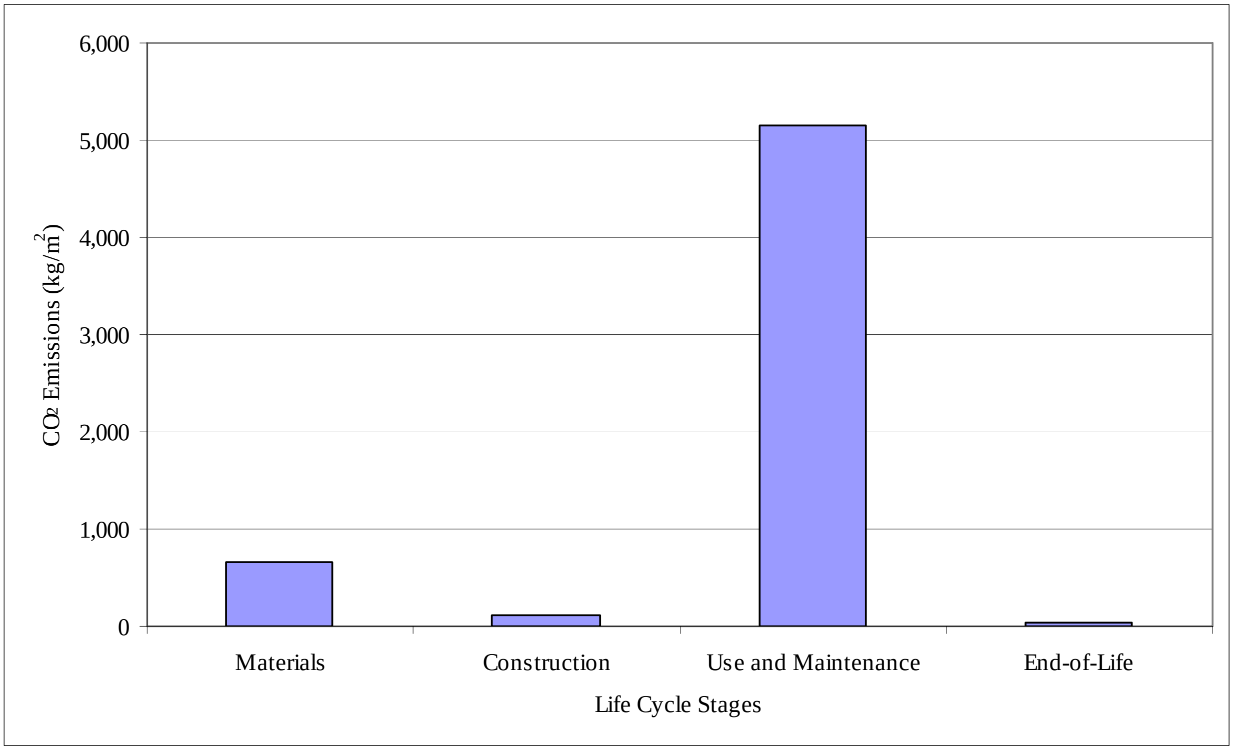


Figure 80. CO_2 Emissions Life Cycle Stage Comparison – Steel Case Study

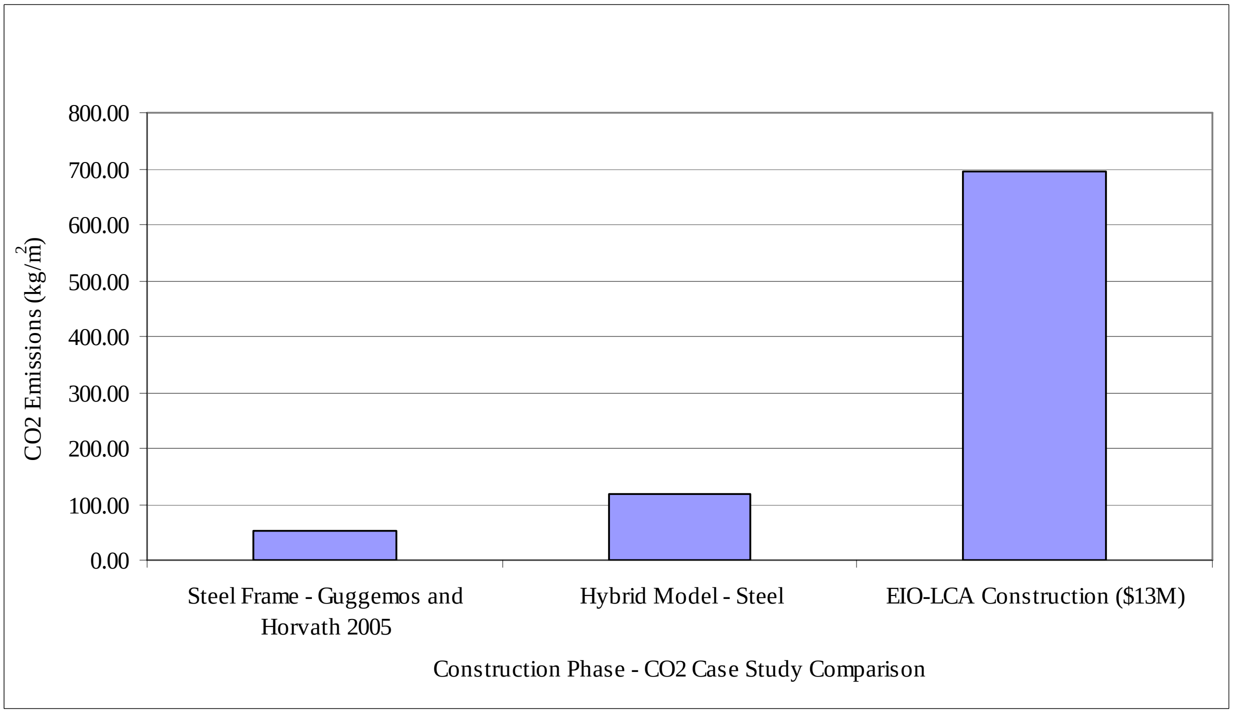


Figure 81. CO_2 – Construction – Case Study Comparison

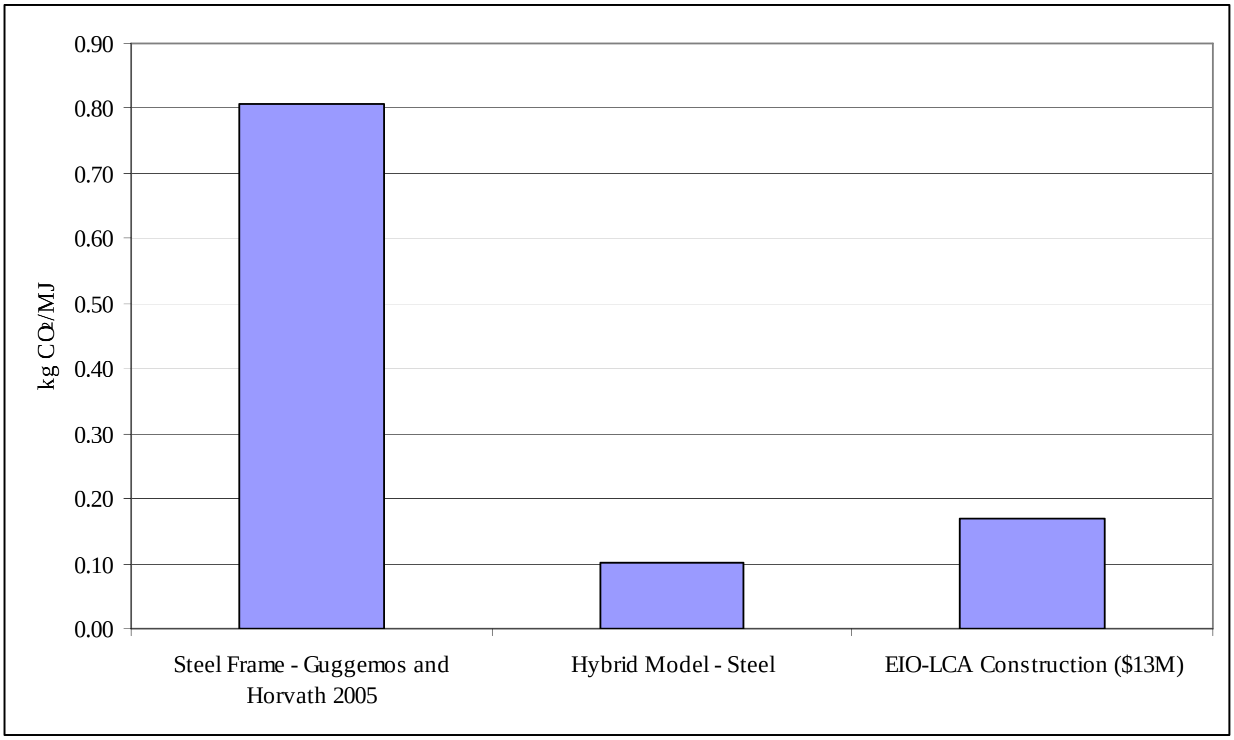


Figure 82. CO2 and Energy Ratio Case Study Comparisons

Table 20. Fuel with CO_2 Emission Factors

	kg CO2/MJ
Aviation Gasoline	6.58E-02
Distillate Fuel (No. 1, No. 2, No. 4 Fuel Oil and Diesel)	6.95E-02
Jet Fuel	6.73E-02
Kerosene	6.87E-02
Liquified Petroleum Gases (LPG)	5.99E-02
Motor Gasoline	6.74E-02
Petroleum Coke	9.70E-02
Residual Fuel (No. 5 and No. 6 Fuel Oil)	7.49E-02
Methane	4.97E-02
Landfill Gas	4.97E-02
Flare Gas	5.20E-02
Natural Gas (Pipeline)	5.05E-02
Propane	6.00E-02
Electricity - National Average	1.69E-01

The final comparison is made between the life cycle stages and other published LCAs for SO_2, NO_x, and PM_{10} (see Figure 83). For SO_2, construction is lower than the other phases, except end-of-life. For NO_x, construction is the lowest of all the phases. For PM_{10}, construction is the highest, except for the use and maintenance phase. PM_{10} is higher mainly due to including the emissions from traveling on unpaved and paved roads and the dust generated during construction activity.

Figure 84 compares the three studies, with all the emissions, except PM_{10}, the hybrid model falls in the middle. For PM_{10}, the hybrid model is higher than both studies; however, it is anticipated that the updated EIO-LCA model will increase the amount PM_{10}.

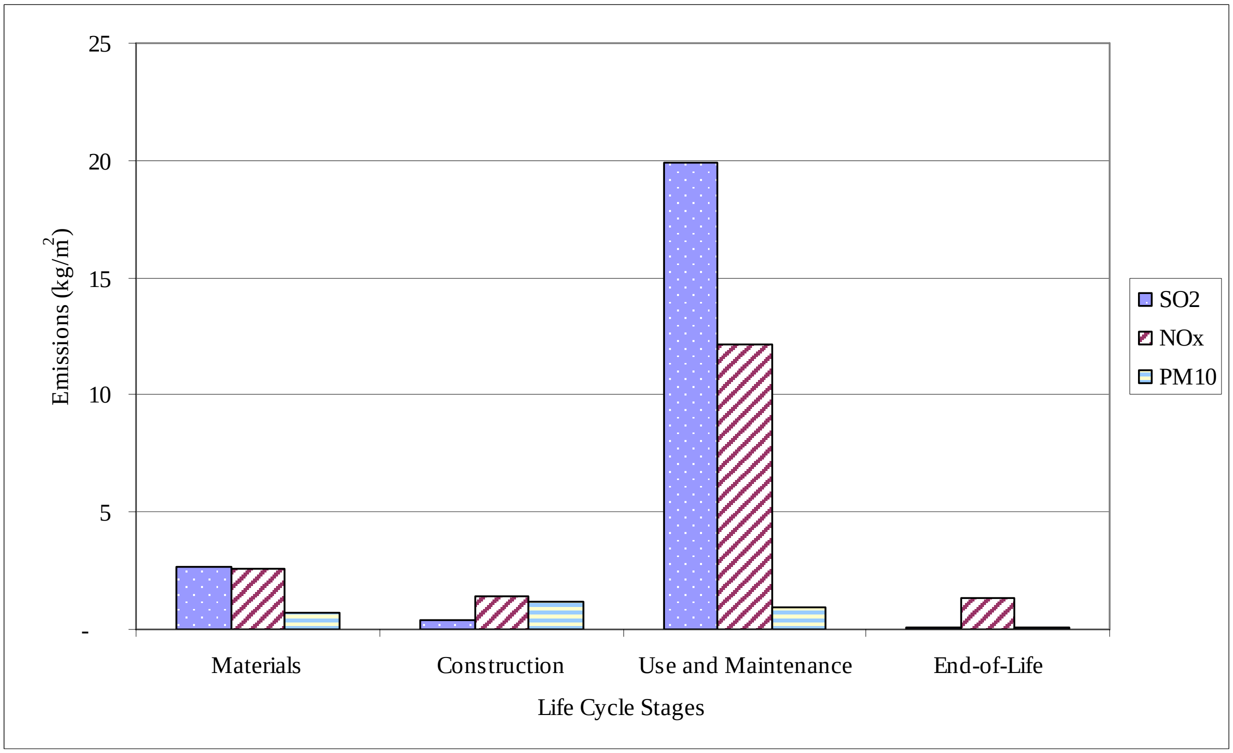


Figure 83. Emissions Life Cycle Stage Comparison – Steel Case Study

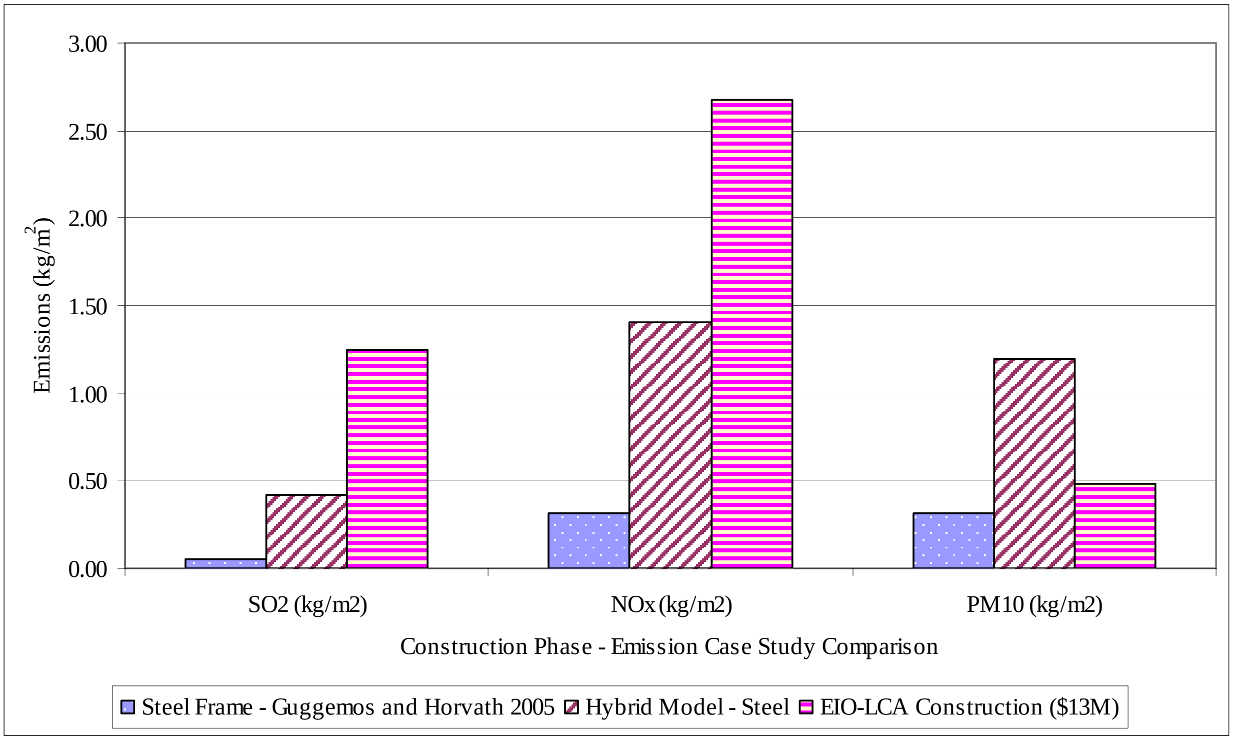


Figure 84. Emissions – Construction – Case Study Comparison

6.2 MODELING WITH LCIA METHODS

Eco-Indicator 99 and Impact 2002+ were the selected impact assessment methods used in this research. When the two impact methods have common impact categories, the results are similar and comparable. In most categories, Impact 2002+ slightly exceeds Eco-Indicator 99 with the exception of carcinogens where Eco-Indicator 99 exceeds Impact 2002+. Eco-Indicator 99's ecotoxicity results exceed Impact 2002+, but this is primarily due a difference in the units between the two impact categories.

6.3 LOCAL AND REGIONAL IMPACTS

Since construction has a local and regional impacts, analyses on the local and regional impacts are presented. Local includes impacts from equipment combustion, heavy construction operations (dust), and driving on unpaved roads. Regional includes impacts from transportation, driving on paved roads, and electricity generation. This section includes the results from the steel case studies in Figure 85, Figure 86, and Figure 87 with the results from the precast case study found in Figure 88, Figure 89, and Figure 90. The results can also be viewed in long-term and short-term impacts with GWP and representing long-term impacts; and PM, CO, and NMVOCs representing short-term impacts; SO_x and NO_x representing both short- and long- term perspectives.

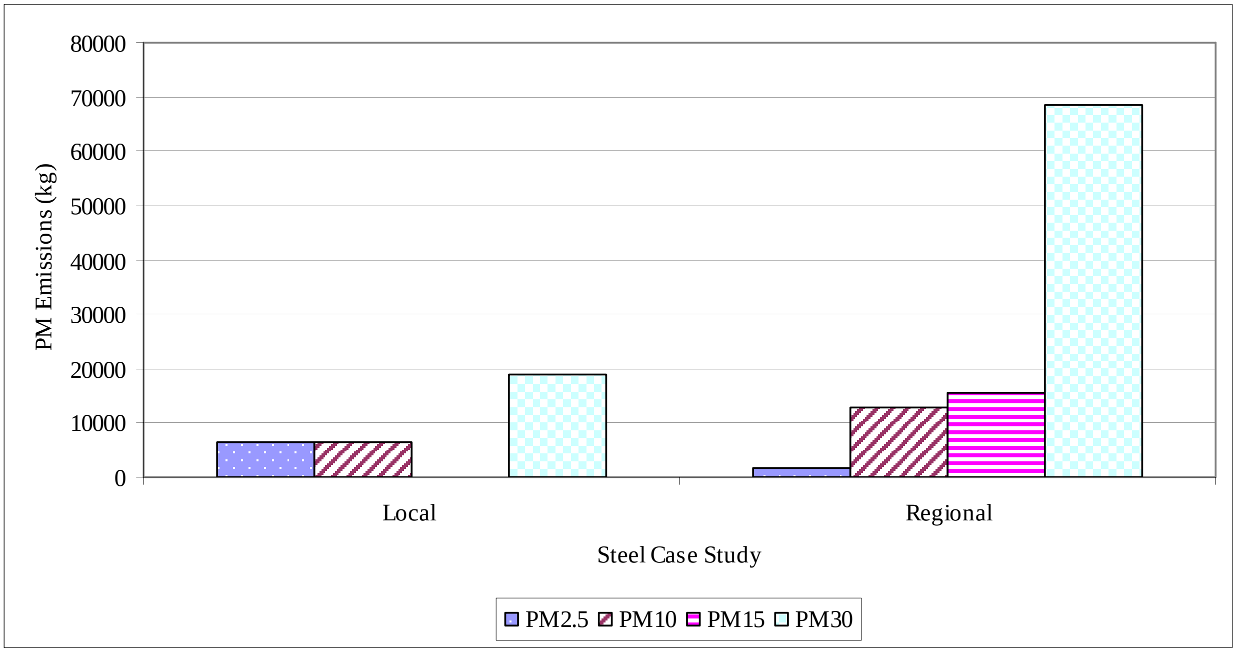


Figure 85. PM Emissions – Local and Regional Impacts – Steel Case Study

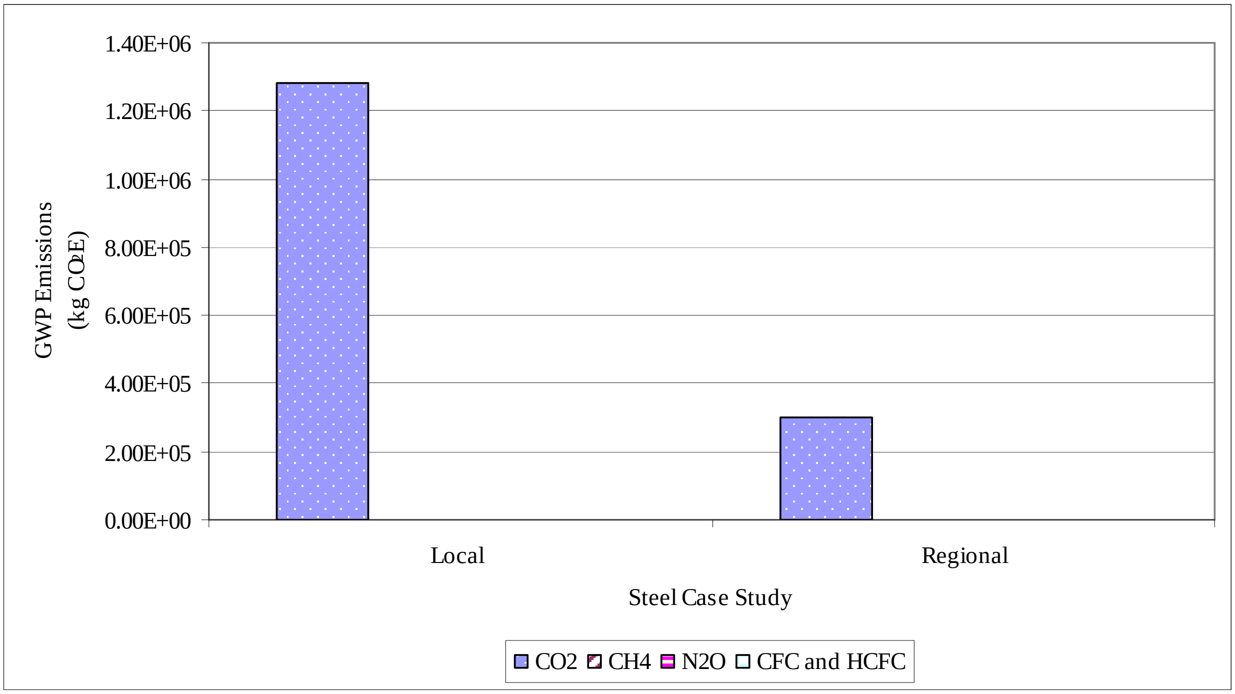


Figure 86. GWP Emissions – Local and Regional Impacts – Steel Case Study

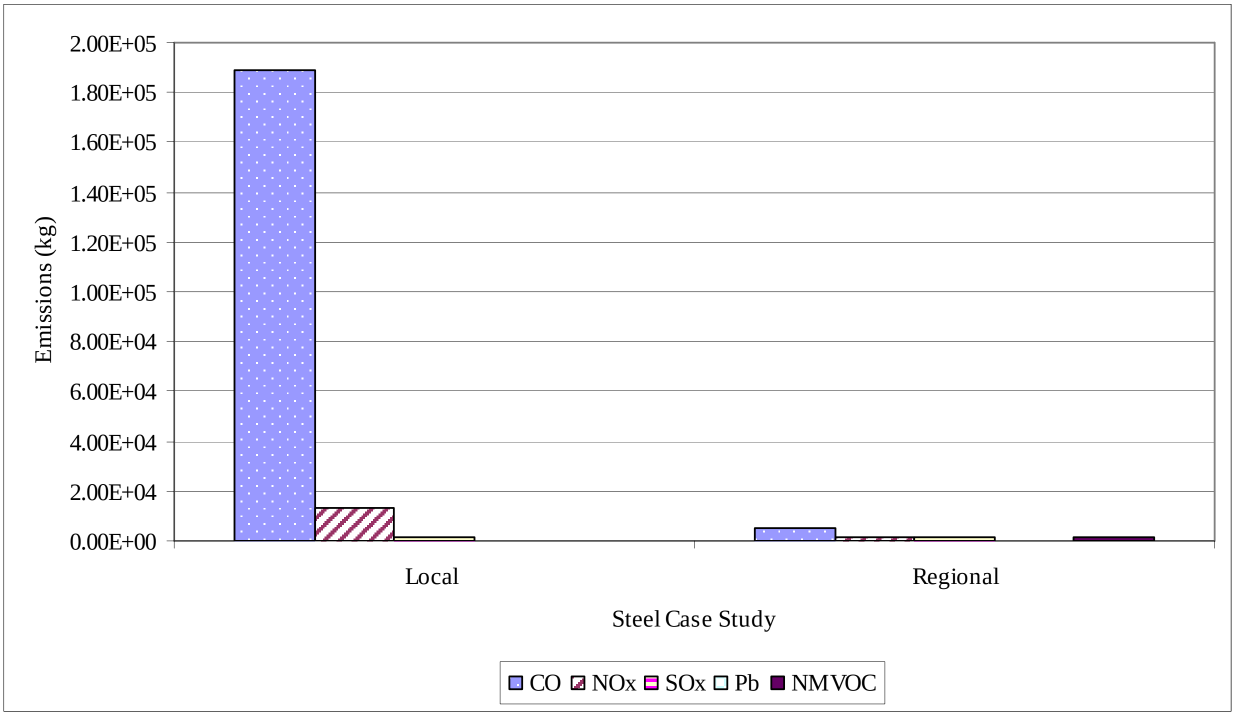


Figure 87. Emissions – Local and Regional Impacts – Steel Case Study

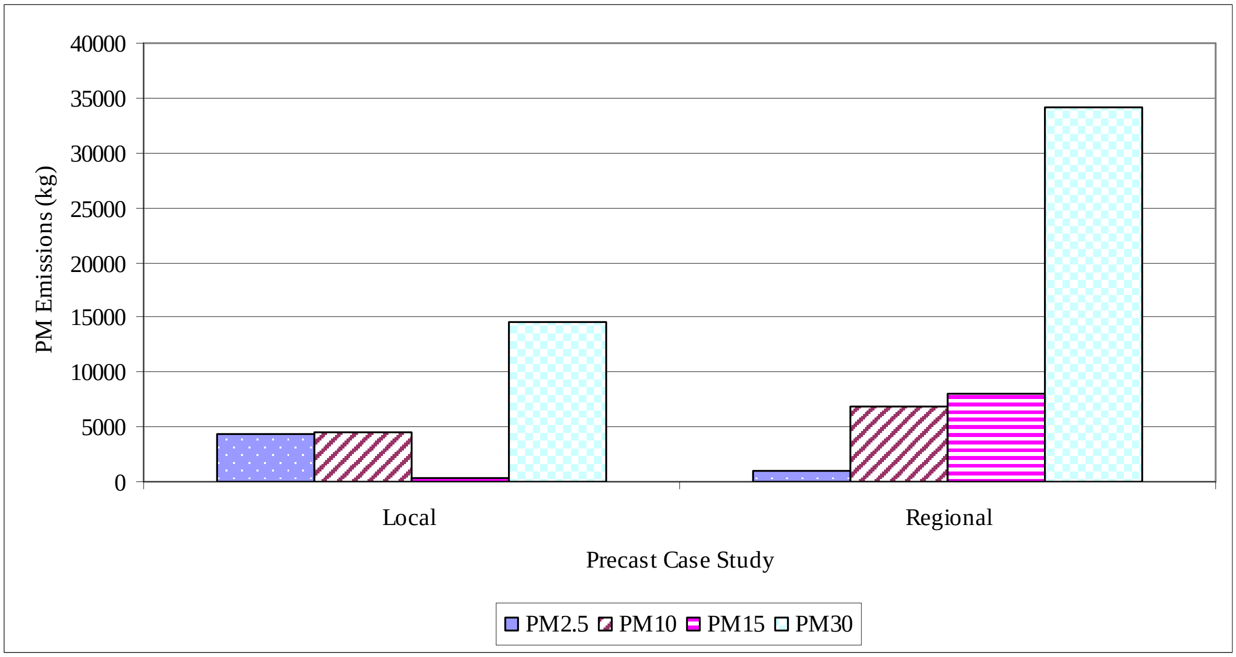


Figure 88. PM Emissions – Local and Regional Impacts – Precast Case Study

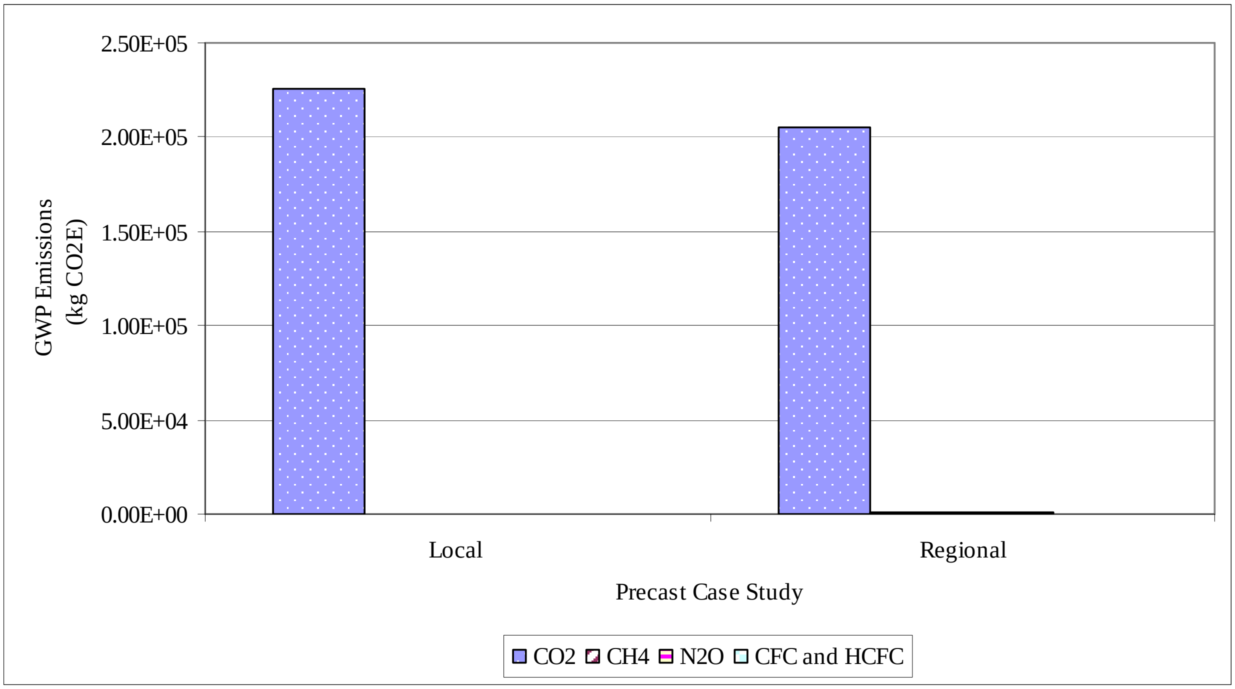


Figure 89. GWP Emissions – Local and Regional Impacts – Precast Case Study

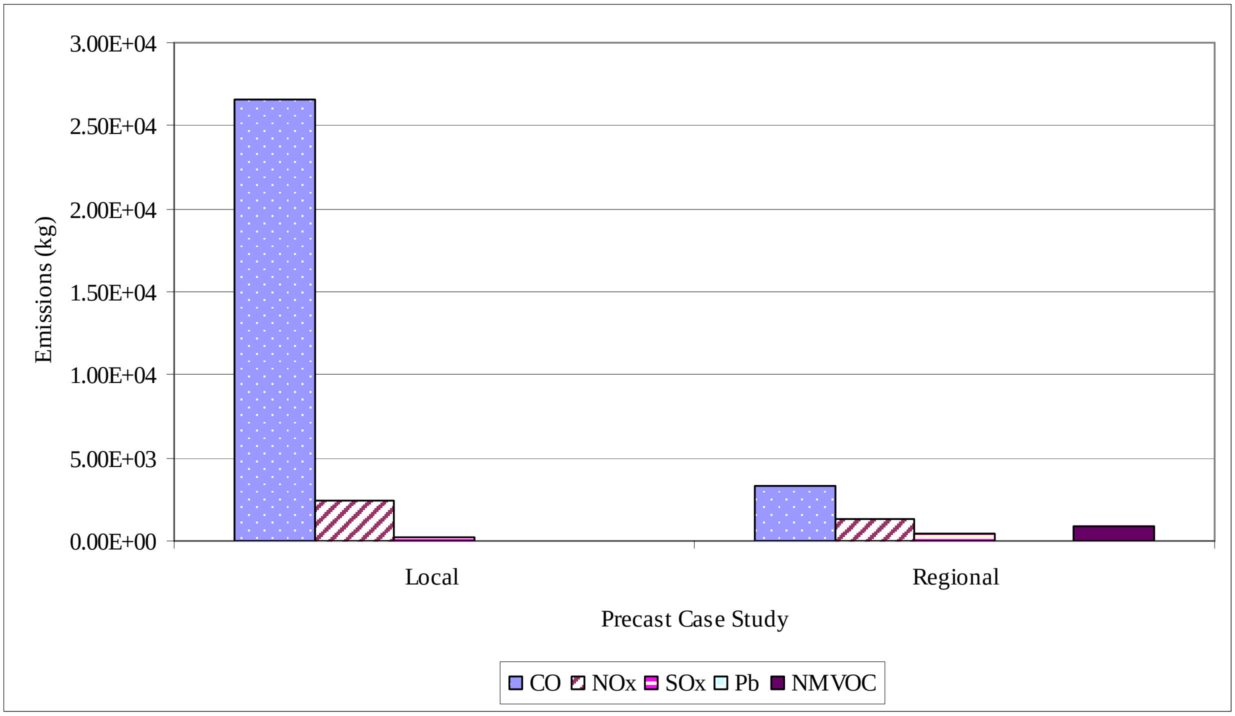


Figure 90. Emissions – Local and Regional Impacts –Precast Case Study

6.4 SENSITIVITY ANALYSIS

Sensitivity analyses were performed on key components of the model to better understand elements of uncertainty and key variables that can greatly impact the results. Varying levels of analyses were performed ranging from broader factors to specific variable in equations. In total thirteen scenarios were investigated and are listed in Table 21. The sensitivity analyses focused on the *total* LCI results from the *steel case study*. The scenarios are grouped into four main scenario categories of ratio, distance, paved and unpaved road vehicle weights, and services and are graphically represented in Figure 91 through Figure 102. The following discussion is organized according to categories within the respective emissions of PM, GWP, and then grouped emissions of CO, NOx, SOx, PB, and NMVOC.

Table 21. Scenarios for Sensitivity Analyses

	Scenario
1	Equipment - Ratio from 0.9 to 0.5
2	Equipment - Ratio from 0.9 to 0.1
3	Transportation Ratio from 0.5 to 0.9
4	Transportation Ratio from 0.5 to 0.1
5	Concrete Distance from 2.4 km to 10 km
6	Additional transportation distance 500 km to Class 7
7	Additional transportation distance 1000 km to Class 7
8	Worker Transportation from 30-40 to 60- 80 workers/day
9	Worker Transportation from 10-20 to 20-40 miles
10	Vehicle Weight Paved Road from uniform distribution 2-40 tons to 2 tons
11	Vehicle Weight Paved Road from uniform distribution of 2-40 tons to 40 tons
12	Vehicle Weight Unpaved Road from uniform distribution of 2-40 tons to 40 tons
13	Reduced EIO-LCA Services

6.4.1 Sensitivity Analysis – Ratio Scenarios

Sensitivity analyses were performed on input ratios for both equipment and transportation and are shown in Figure 91 through Figure 93. The user inputs a ratio for both aspects from 0 to 1, which estimates the overall relationship with diesel and gasoline usage. In the original steel case study, the ratio of diesel to gasoline for equipment was 0.9, and the ratio for transportation was 0.5. For equipment, the ratio was reduced to both 0.5 and 0.1 in two different result runs. For transportation, the ratio was first increased to 0.9 and then decreased to 0.1. In terms of PM emissions (see Figure 91), the ratio has minimal impacts for all PM emissions. For GWP emissions (see Figure 92), the ratio has minimal impact, except for a slightly lower levels in CO2 emission when the equipment ratio decreases. Conversely, when the equipment ratio decreases, the CO emissions are higher. These results are reasonable when emissions for individual pieces are evaluated.

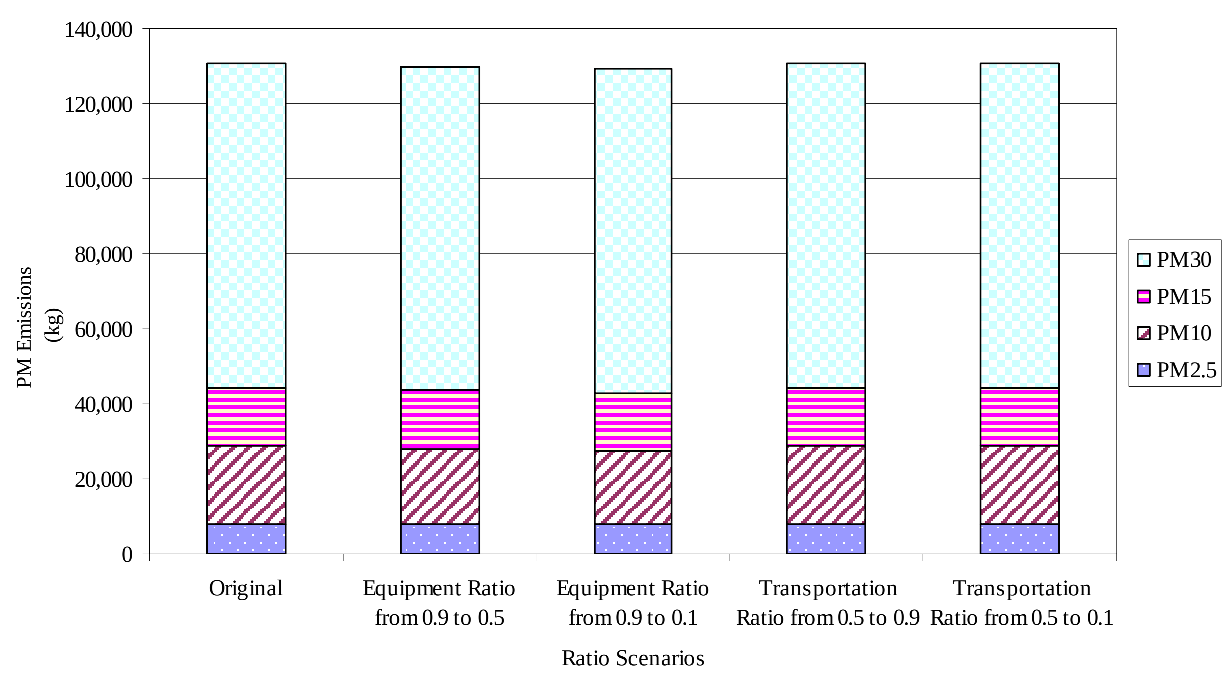


Figure 91. PM Emissions – Ratio Scenarios – Steel Case Study

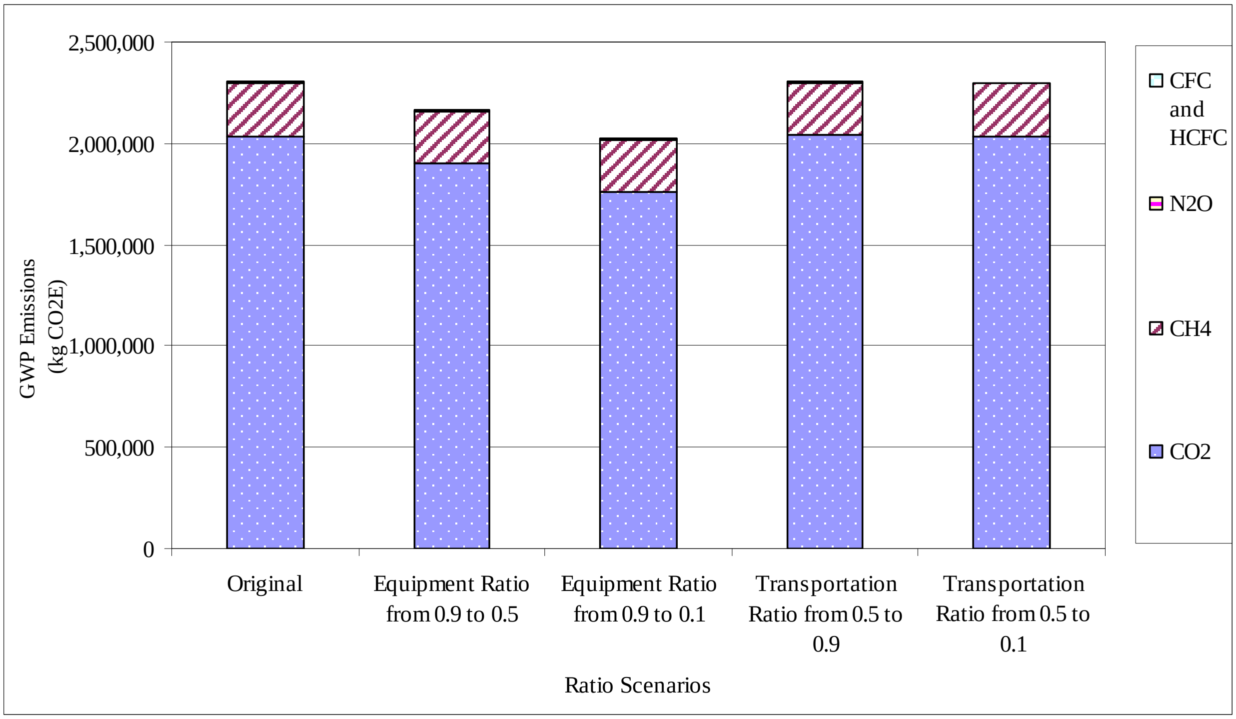


Figure 92. GWP Emissions – Ratio Scenarios – Steel Case Study

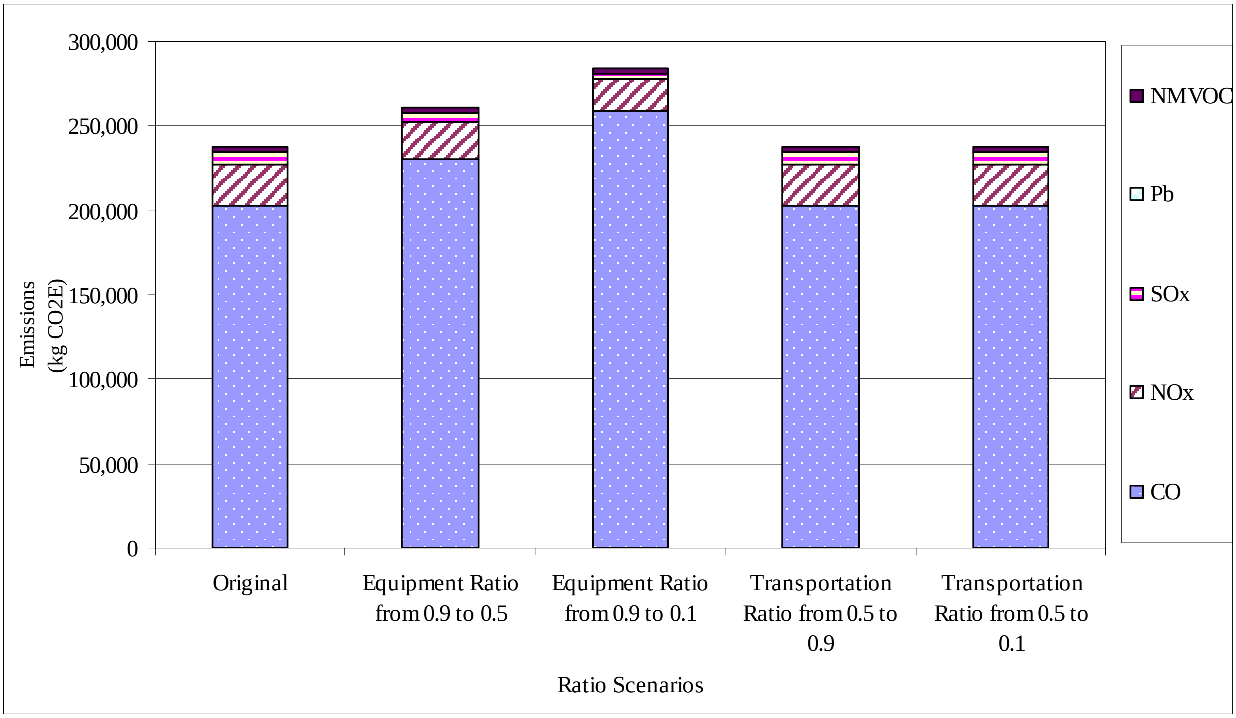


Figure 93. Emissions – Ratio Scenarios – Steel Case Study

6.4.2 Sensitivity Analysis – Distance Scenarios

Analyses were performed on different distance scenarios with more information on scenarios shown in Table 21, numbers 5 through 9. For all emissions, except PM, the analyses had minimal impact on the total LCI results, as shown in Figure 94 through Figure 96. PM emissions are considerably greater when the number of construction workers per day and the distance the construction workers travel are increased. These results indicate that user should focus on the most accurate information as possible for these input items.

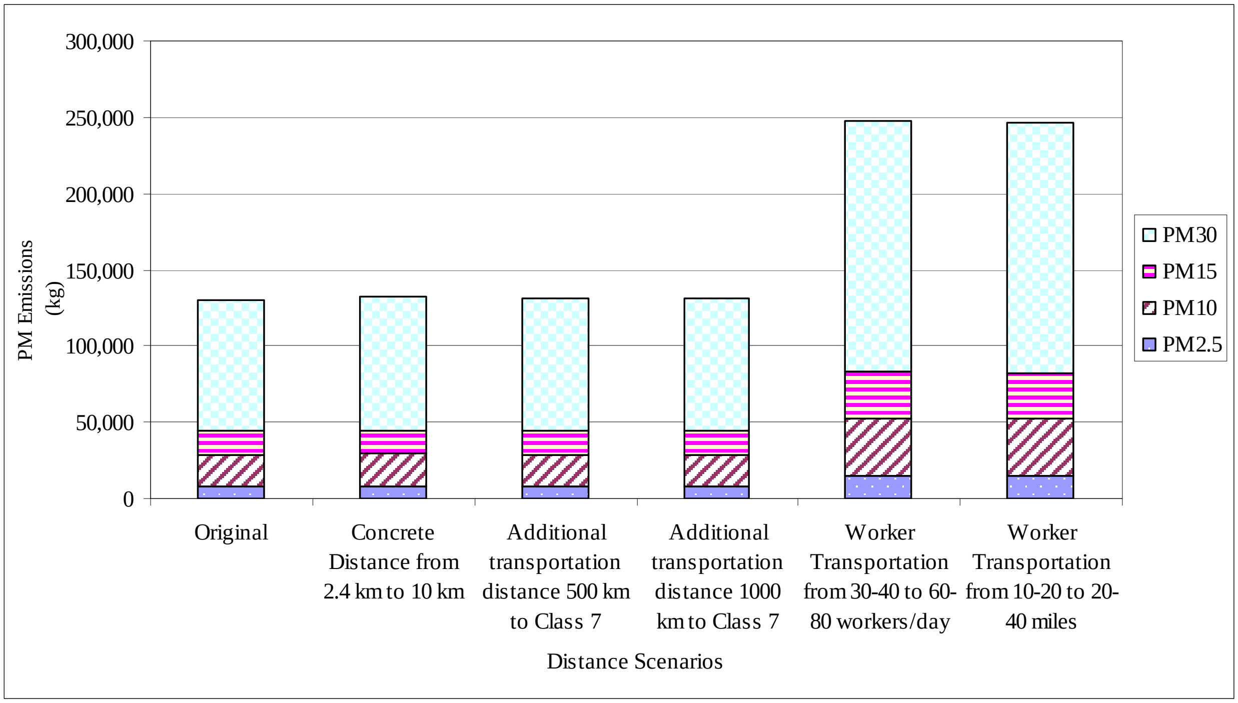


Figure 94. PM Emissions – Distance Scenarios – Steel Case Study

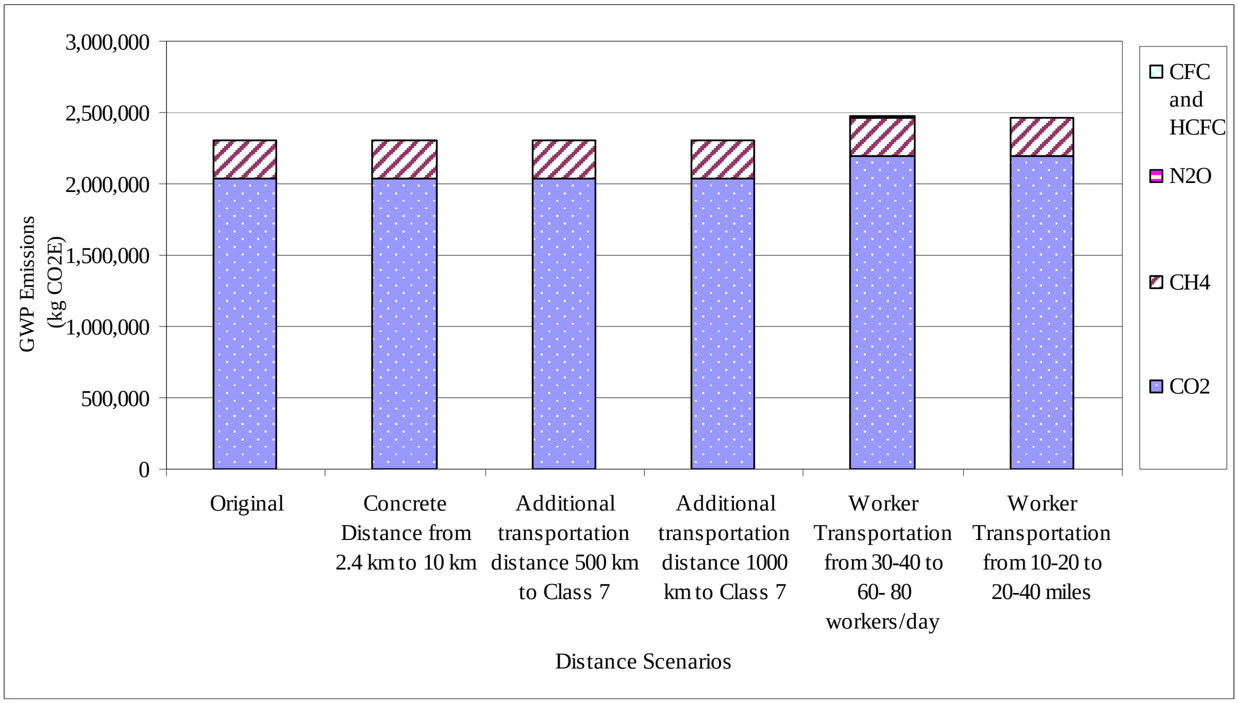


Figure 95. GWP Emissions – Distance Scenarios – Steel Case Study

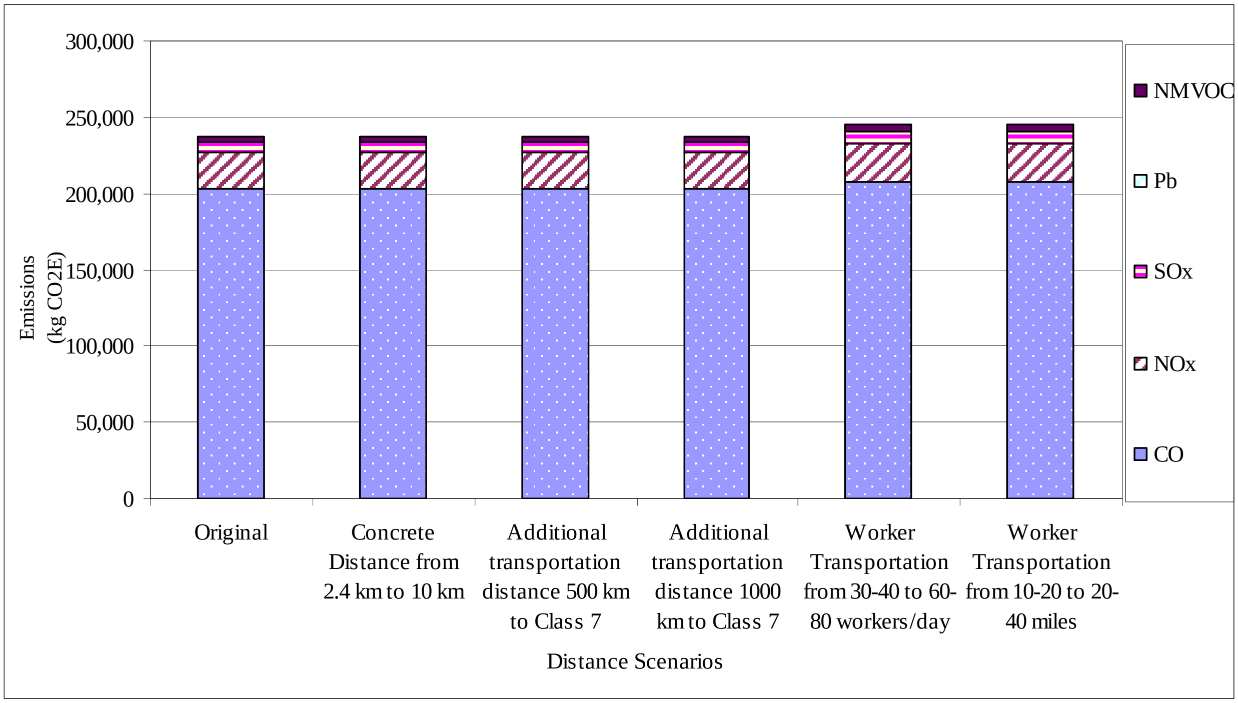


Figure 96. Emissions – Distance Scenarios – Steel Case Study

6.4.3 Sensitivity Analysis – Vehicle Weight Scenarios

Since a significant component of PM emission results are due to traveling on paved and unpaved roads, sensitivity analyses were performed on the key variable in the emission factor equations, the vehicle weight (Figure 97 through Figure 99). The original results for both paved and unpaved roads included uniform distributions in the range of 2 to 40 tons. The scenarios for paved roads reduced the weight to 2 tons only, and then 40 tons only. The results indicated that the vehicle mass has an impact on the PM results, see Figure 97. For unpaved roads, the 40 ton weight was modeled, since the majority of the vehicles on the unpaved roads will be more massive. Results for unpaved road indicated the vehicle weight for unpaved roads was less significant. These unpaved roads results, however, may be more indicative of the fact that minimal lengths of unpaved roads were modeled in the steel case study.

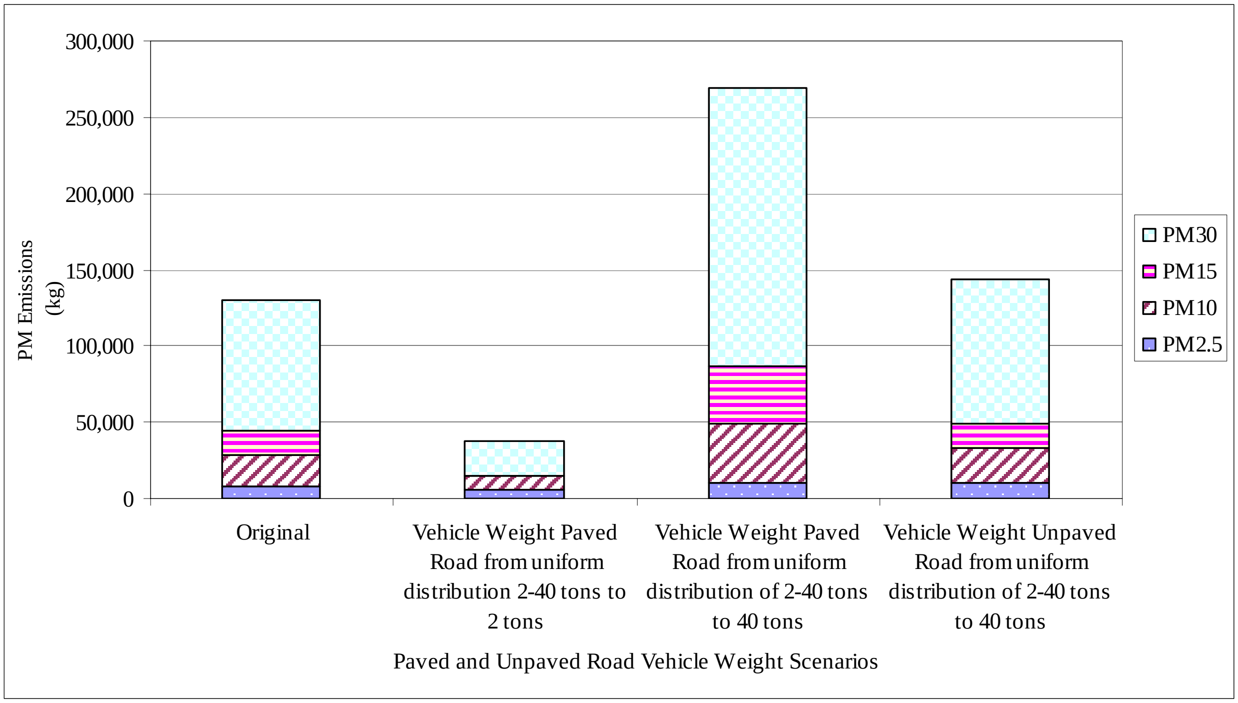


Figure 97. PM Emissions – Vehicle Weight Scenarios – Steel Case Study

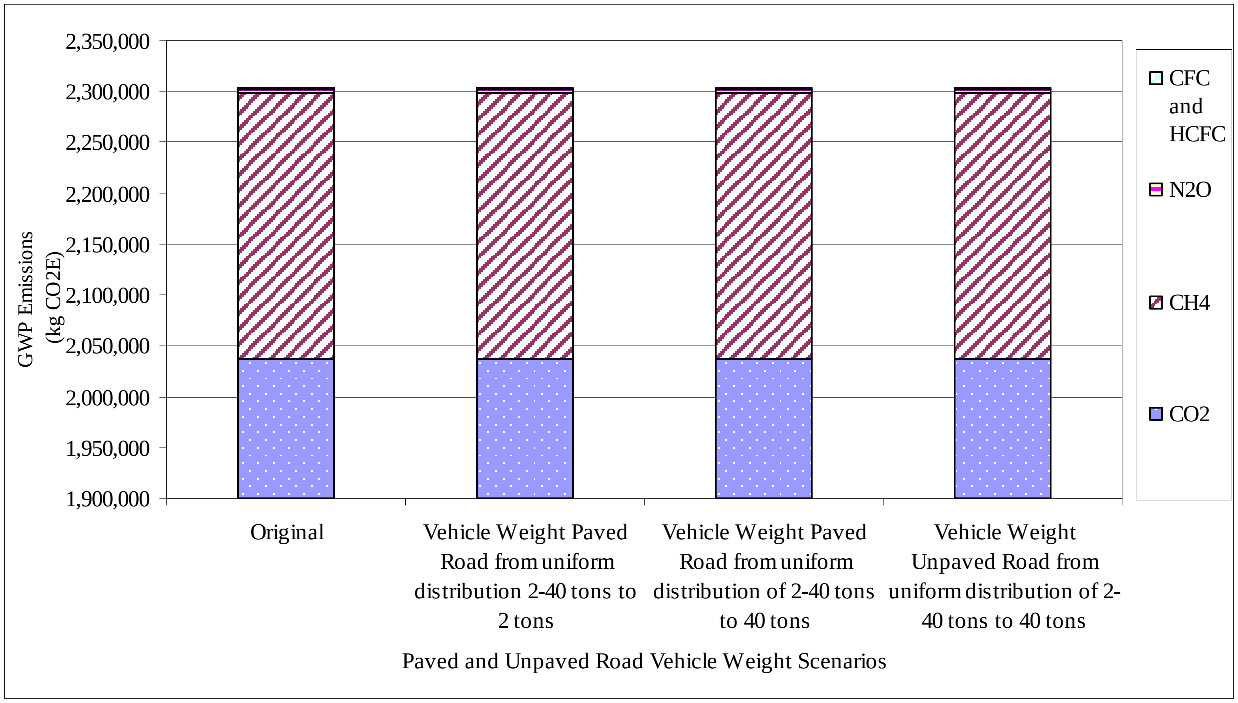


Figure 98. GWP Emissions – Vehicle Weight Scenarios – Steel Case Study

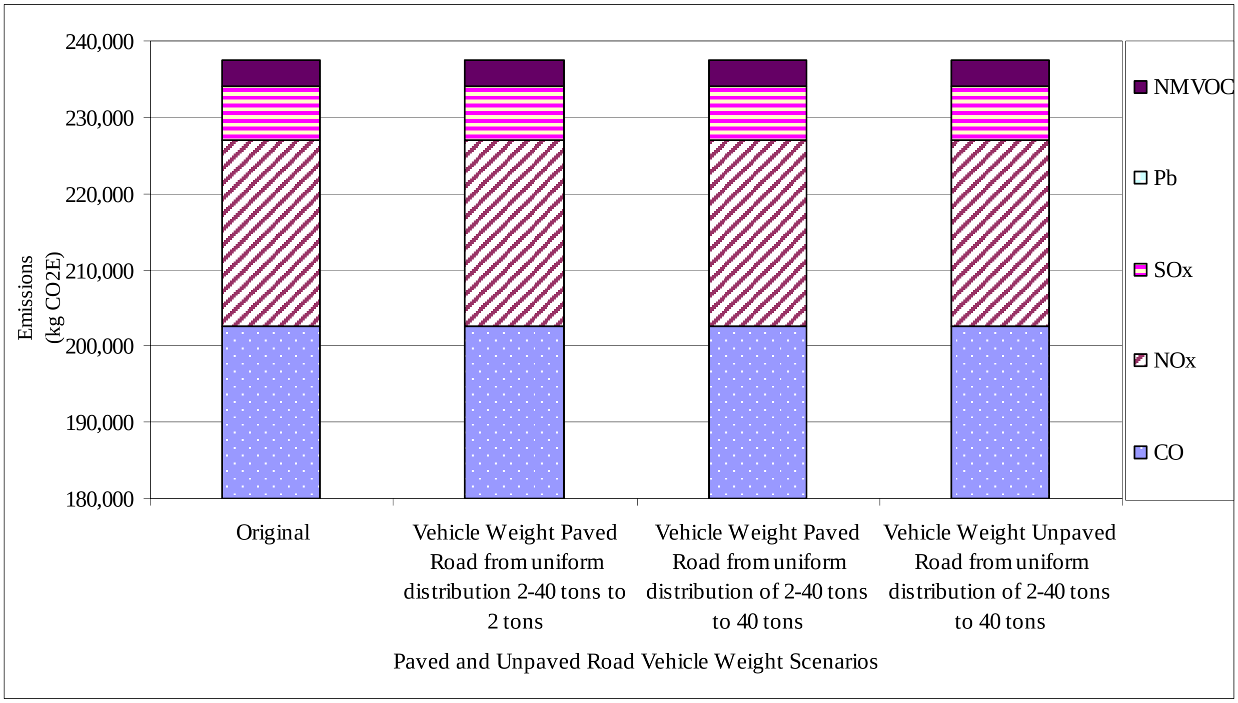


Figure 99. Emissions – Vehicle Weight Scenarios – Steel Case Study

6.4.4 Sensitivity Analysis – Service Scenario

The final sensitivity analysis was performed on examining the selected service sectors. Selecting the services sectors can be somewhat subjective, for example, should one include motion picture and video industries? The model and presented steel case study results took a fairly broad view of service sectors, on a percentage of construction dollars, the services sectors were about 33% ($433,000 divided by $13,000,000). A sensitivity analysis was performed with a more narrow view looking specifically at more traditionally construction service sectors only (architects, engineers etc.) with a reduction in the percentage at about 22%. The services sectors selected for the sensitivity analysis are shown in Table 22. The results indicate that the reduction in service sectors is relatively minimal. This is due to primarily to the fact that the sectors which were eliminated had minimal overall economic or environmental impacts.

Table 22. Service Sectors – Sensitivity Analysis

Securities, commodity contracts, investments
Insurance carriers
Insurance agencies, brokerages, and related
Monetary authorities and depository credit intermediation
Real estate
Legal services
Accounting and bookkeeping services
Architectural and engineering services
Specialized design services
Custom computer programming services
Computer systems design services
Other computer related services, including facilities management
Management consulting services
Waste management and remediation services
Environmental and other technical consulting services
Scientific research and development services
Management of companies and enterprises
Office administrative services
Facilities support services
Employment services
Business support services

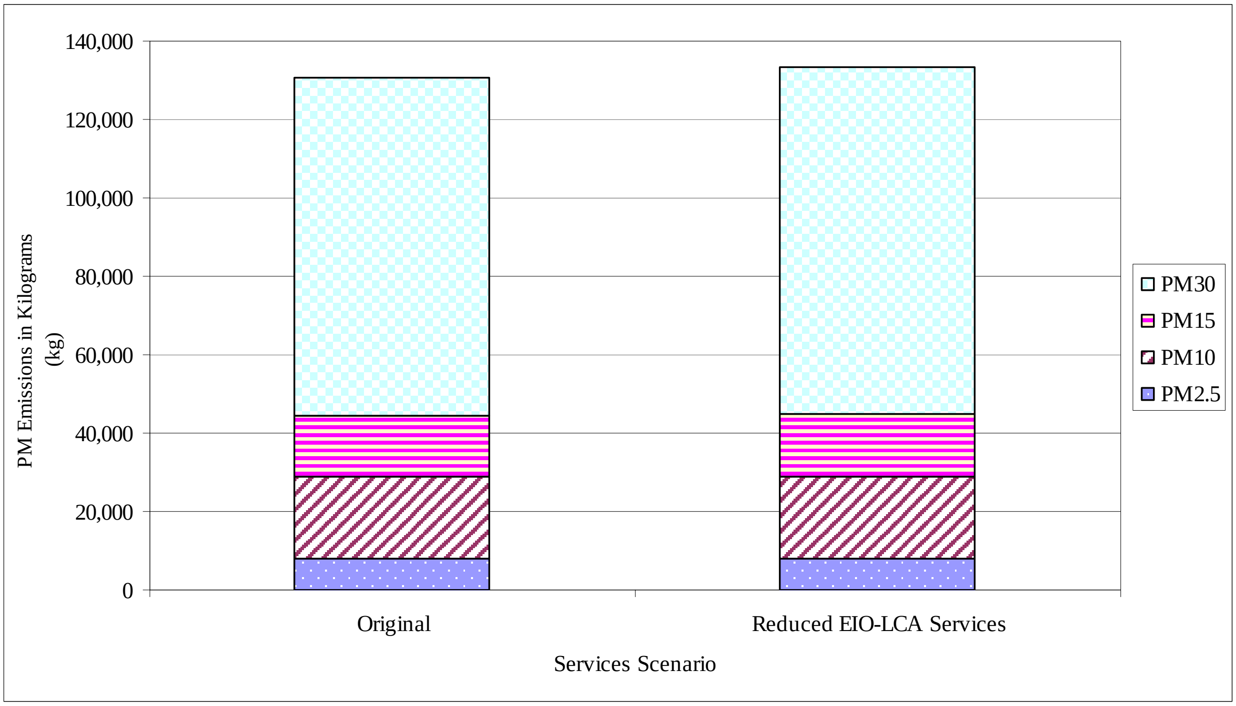


Figure 100. PM Emissions – Services Scenario – Steel Case Study

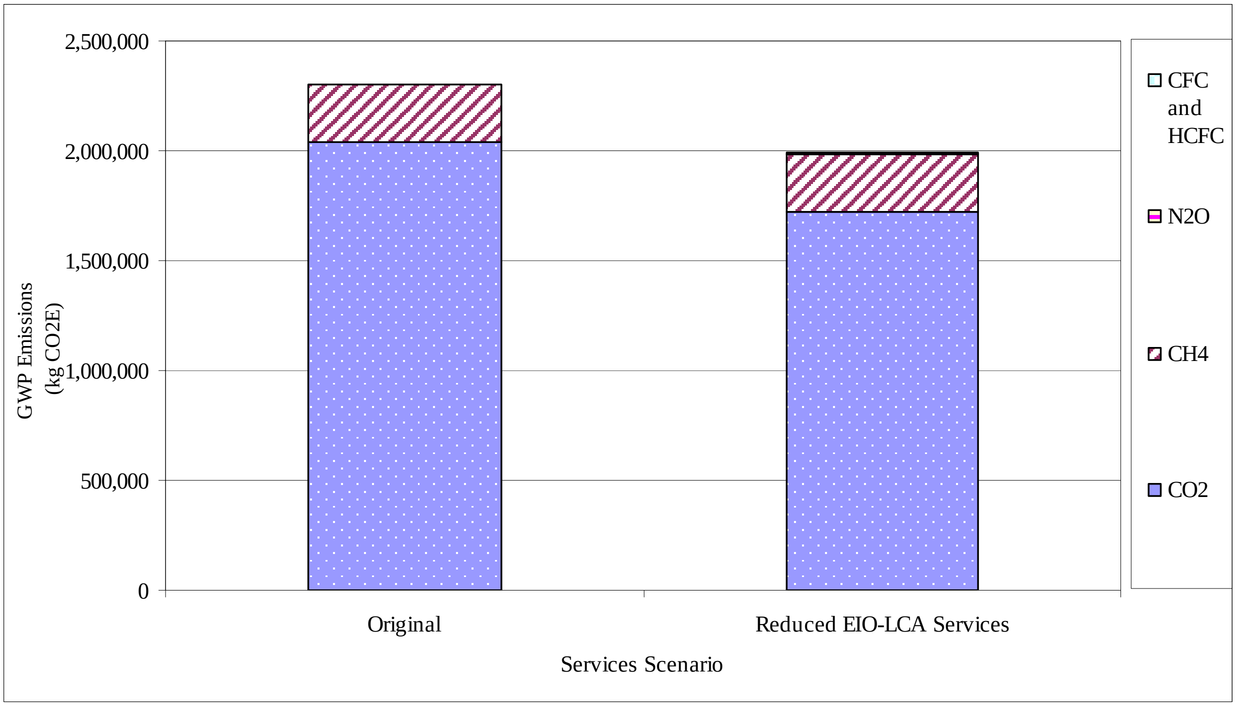


Figure 101. GWP Emissions – Service Scenario – Steel Case Study

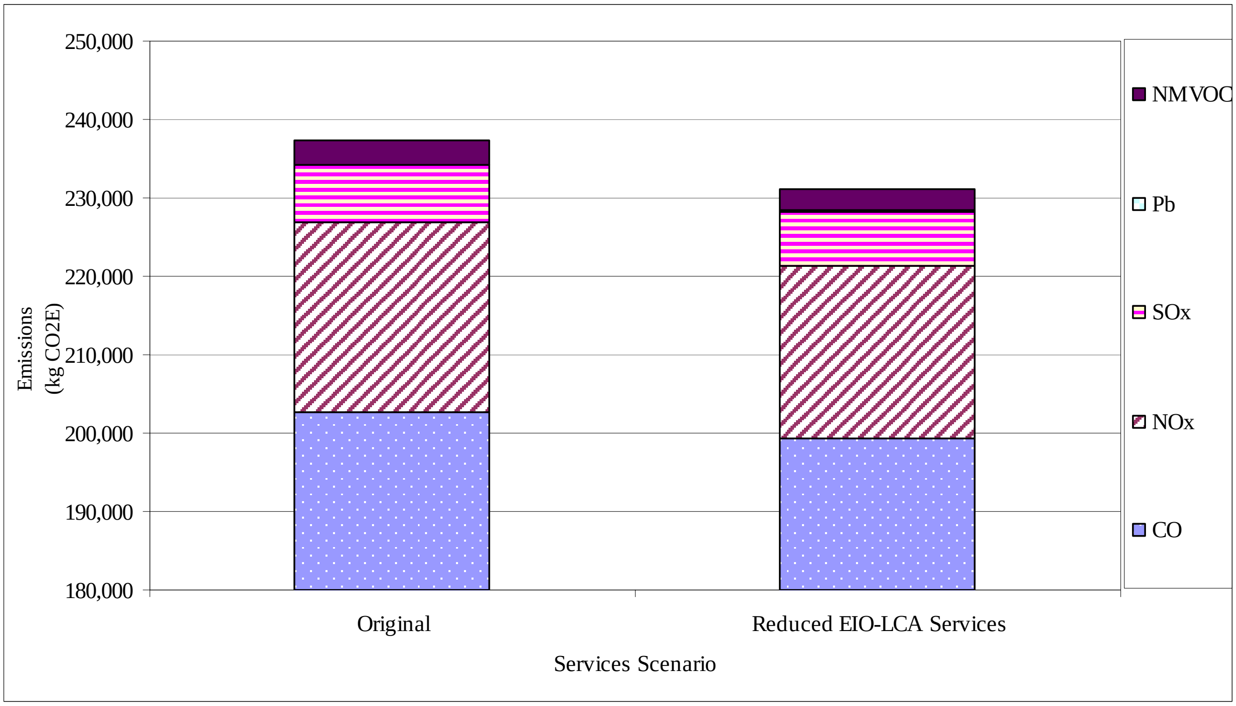


Figure 102. Emissions – Service Scenarios – Steel Case Study

7.0 HYBRID MODELING DISCUSSION

7.1 HYBRID MODELING AND DECISION ANALYSIS

The use of decision analysis techniques in the life cycle inventory stage is not recommended. Preliminary conceptual development of this research involved exploring the use of decision making techniques, such as multi-criteria decision analysis (MCDA), to assist in the development of the life cycle inventory stage. The use of decision making methods in LCA has precedence (Kiker et al. 2005; Madu et al. 2002; Rahimi and Weidner 2004a; Rahimi and Weidner 2004b; Seppala et al. 2002), but only in the life cycle impact assessment stage. After reviewing the literature and developing a better understanding of LCA and its relationship with decision making methods, the conclusion, at this time, is that decision analysis in the life cycle inventory stage is not recommended.

Initially the use of multi-criteria decision making techniques appeared to be reasonable because as one develops the life cycle inventory, many decisions are made. Often the decision can be somewhat arbitrary in nature. In the life cycle inventory stage, the LCA developer has several options for data collection including but not limited to the following:

1. Develop unique inputs and outputs relevant to specific LCAs under investigation; for example, partner with a manufacturing plant to collect information or develop surveys.
2. Rely on publicly available information, including published LCAs.
3. Use pre-existing process data.
4. Use I-O inventory data.
5. Use multiple combinations of all available or collected data.

Higher level decisions exist as well as sub-level decisions, and within each of the above options, additional questions arise. For example, an LCA practitioner who uses LCA software to develop an inventory is often required to make decision of what pre-determined process to use, “Should I use the Franklin’s unit process for a passenger car or ETH-ESU’s passenger car?”

While the LCA practitioner is required to develop a thorough understanding of pre-existing process, I-O, or any set of data, the final decision can still be somewhat random and further contribute to the overall uncertainty of the entire LCA. Often the decision is based on ease of data availability, history with data sets, and general education on available inventories. An LCA practitioner may be unknowledgeable of I-O data availability and use, and may only use available process data, excluding significant processes. The embedded and multi-layer aspects of decisions in the life cycle inventory stage are important elements in the recommendation to not use decision making in life cycle inventory, as will be discussed below.

Before developing the final recommendation, research on decision making methods was considered with specific emphasis in methods already employed in LCA and focusing on using a tool to gather expert opinion to assist other people conducting hybrid LCAs. The criteria in the scope included basically the advantages and disadvantages of process versus input-output. One example is the issue of the boundary - is it more important to have a fully inclusive boundary or is it more important to have product specific LCA?

Many decision making methods were considered with a focus on multi-attribute utility theory (MAUT) and Analytical Hierarchy Process/Analytical Network Process (AHP/ANP). The use of MAUT is practical when the multiattribute value or utility function has mutual preferential independence of the attributes under consideration (Keeney and Raiffa 1976; Seppala et al. 2002). A necessary condition for an additive decomposition of the multiattribute value (or utility) function is mutual preferential independence of the attributes, see Keeney and Raiffa (1976) for more detail. After consideration, the proposed attributes under consideration did not exhibit mutual preferential independence; therefore, using the additive decomposition of the multiattribute value or utility function was not possible making MAUT impractical.

Regarding AHP/ANP, meetings were held with Dr. Saaty, the developer of AHP/ANP, to discuss application of AHP/ANP. Specifically, exploring the relationship between hybrid LCI and AHP/ANP. AHP/ANP is a relatively popular decision making method due to its ease of use. AHP/ANP uses a hierarchical structure and is an additive preference model based on evaluation and weights. The weights are determined through pair-wise comparisons on a one- to nine-point scale. Questions to experts are usually in the nature of, “How much more important is Option A versus Option B with respect to this criteria?” In meeting with Dr. Saaty and reading his work, a key component to AHP/ANP is his belief that humans have an innate ability to make accurate judgments and when structured according to AHP/ANP principles the final results are decisions that are reasonable or ‘correct.’ Dr. Saaty has numerous examples demonstrating the accurateness of AHP/ANP in real world situation such as market shares, foreign policy decisions, and life decisions.

Understanding the innate human component to AHP/ANP was critical in the final outcome of using any or all decision making tools in this research. The researchers discussed the original higher level list of criteria for hybrid LCI models, and ultimately the higher level lists transcend to the smallest unit process. In the end, the questions that we would have been posing to LCI practitioners would have been similar to: “Process X has say 100 kg of CO_2, Process Y has 200 kg of CO_2. What emission value is more accurate?” A decision of this nature cannot be made in life cycle inventories by experts because rational judgments on emission amounts are not generally innate or intuitive. Therefore, the researchers concluded that for hybrid life cycle inventories the use of decision modeling was not applicable.

7.2 RECOMMENDATIONS ON CREATING A HYBRID LCA

While section 2.4.4 recommends using augmented process-based LCA for creating a hybrid model, this section lays out more specific procedural advice and information on hybrid LCA modeling.

7.2.1 Recommended Procedural Framework

The first step in hybrid LCA modeling is creating a high-level process flow diagram describing the process or product. For example, in construction, the high-level process flow diagram included broad categories such as transportation, equipment, and waste. I-O can then be used to validate the perceived high-level process flow diagram. The LCA practitioner is checking to determine if the major impacts are either included or not included, and the original process diagram can be informed by the I-O results and modified as needed. In the case of construction, for example, architectural firms were typically one of the top ten sectors in terms of economic activity in I-O output for commercial construction, indicating that construction services could have significant impact. Services are typically not included in the construction phase of life cycle assessments (Guggemos and Horvath 2005; Junnila et al. 2006), and therefore the environmental impacts due to construction services, such as architectural firms, would not have been included in the analysis. In addition, if the LCA practitioner is unfamiliar with the product or process being modeled, then I-O can be used to generate the high-level process diagram in the first instance.

With the refined process diagram established, Step Two is developing the LCI data for each unit process, or the "quest for the best LCI." This research has found that the core of hybrid modeling is exploring and investigating the best possible available data for the processes under consideration. The goal in hybrid LCA modeling is finding the most accurate and appropriate information to compile a thorough life cycle inventory. In many ways, this is the true research component behind LCAs because the current state of life cycle inventories is sparse and inconsistent.

Selecting the most appropriate LCI for a given process or product is based on many different factors. One practical consideration is related to the data availability. To exemplify, modeling service sectors would be difficult, albeit not impossible, using a purely process framework. Existing process data on service sectors is readily available through I-O LCA information. Therefore, using I-O LCA for modeling service sectors is not only quick and practical, but also accounts for the entire supply chain.

The decision to use process or I-O data is often based on the modeling framework, especially in terms of units. Process inventory demand is typically in physical units, such as pounds, ton-miles, and BTU; whereas, I-O LCA inventory demand is in monetary units. The decision to model with process of I-O data can be based on how the material quantities are estimated. For example, in the hybrid construction LCA model, temporary materials were modeled using I-O LCA information. This decision was made because it was more practical to estimate the dollar values of temporary materials, as opposed to the physical units of temporary materials. For example, mass quantities of a temporary material such as 'wood' used in concrete formwork, would have to be estimated with multiple wood densities if process modeling was used. Formwork consists of many elements such as plywood, walers, and vertical posts, all with different wood densities. Instead, I-O LCA data for several sectors was used in conjunction with

R.S. Means dollar values of material to obtain the temporary formwork material inventories. Deciding to use process or I-O data can be made at several levels of the model. As described previously, I-O can be used initially to identify the significant sectors or processes. I-O/process hybrid decisions can also be made deeper in the LCA model, as the temporary materials example above demonstrates. I-O LCA data can also be disaggregated within sectors to obtain the required information as shown in equipment manufacturing example in Section 4.3.2.1. This disaggregation is similar to Joshi's Model III (2000).

In terms of a strategy for deciding whether to use process and I-O data, the decision can also center on life cycle stages. Using an example of a passenger car, an LCA could conceivably be completed using purely process or I-O data, but combing the two into a hybrid model creates an LCA with a defined and non-exclusionary boundary, includes all life cycle stages, and is easier to conduct. One practical way to conduct a hybrid LCA for a car, or other LCAs, is to model the raw materials and manufacturing phases in I-O LCA, and then model the use and end-of-life with process data. The advantage of using this approach is the first two phases can be done quickly and holistically. It is realistic to assume from a broad perspective that the raw materials and manufacturing phases of a Ford Focus is not that much different than a Chevrolet Impala. The use and end-of-life phases could be relatively more complex with more scenarios, so modeling these phases with process LCA data would allow for greater flexibility and sensitivity analyses. Therefore, one recommendation is to model raw materials and manufacturing with I-O LCA data, and other phases with process LCA data.

Another strategy to combine I-O and process data is to first obtain the economic and environmental data from I-O, basically a list of the highest 'sorted' sectors. With that information, the sectors can be modeled with either the associated I-O data or 'removed' and modeled with process data. The sectors that are not considered by either process or I-O can then be evaluated and reported, so selecting a boundary will be less arbitrary and fully disclosed.

Combining I-O and process data does take practical experience and familiarity with several different inventory sets; however, the final hybrid LCA can produce results with a well-defined, yet broad boundary.

7.2.2 LCI Data Issues

In response to the LCI information gap, both public and private industries have supported a U.S. Life-Cycle Inventory Database. The U.S. LCI Database project will create publicly available life cycle inventories with the goal consistency and transparency.

Consistency and transparency in existing LCI processes is important in hybrid modeling because a lack of both can lead to double-counting and unreliable results. One example is a life-cycle assessment of a passenger car. If a researcher decides to use input-output life cycle inventory information for a passenger car, then the researcher must also include use phase information. For discussion, assume that the I-O LCI information is more accurate; thus, the reason for the selection. To obtain use phase information, the researcher then decides to use a pre-existing passenger car unit process available in a LCA software program, but the information within the selected unit process includes phases already accounted for as a part of the I-O inventory. Adding the selected I-O and process information resulted in double-counting phases. If documentation is not available or inconsistencies exist in the documentation, then the possibility of double-counting and inaccuracies occur.

7.2.3 Uncertainty and Distributions

Another option in the developing the most appropriate hybrid LCI is modeling with distributions, if the researcher has several life cycle inventories for the same unit process. Using distributions advances LCAs from deterministic models, towards models that incorporate ranges of values with associated uncertainties. The hybrid model created as a part of this research modeled the inventories and construction processes with distributions when and where appropriate and available. For example, since several unit processes for diesel were available, the inventory list for diesel was modeled as a distribution. Additionally distributions were established when exact values were not known, such as the commute distance for construction workers.

7.2.4 Target the End

The last recommendation of "target the end" deals with the impact assessment stage. Life cycle inventory assessment methods, such as Eco-Indicator or Impact 2002+, contain lists of damage and/or characterization factors with associated emissions, and some of these factors may not match exactly with the life cycle inventory lists leading to under- or over-estimation in the impact assessment phases. For example, in Eco-Indicator 99's impact category, Carcinogens, a damage factor for "Diesel soot particles" is 9.78E-06 DALYs/kg. "Diesel soot particles" is fairly broad and can include many different types of emissions; therefore, the LCA modeler is required to make assumptions as to the type of emissions and allocation of the amounts. In software programs, such as SimaPro, the programs probably do not recognize "possible" pairings and totally disregard the associated life impact assessment results.

Additionally, pairing of the list is time intensive and requires a fairly extensive knowledge of chemistry terminology. One example is acetic acid, which has many different names, Ethanoic acid, Methanecarboxylic acid, Acetyl hydroxide (AcOH), Hydrogen acetate (HAc). The LCA modeler is required to know or research all the possible names of the inventory and impact assessment emissions to ensure proper pairing and accurate impact assessment results.

One suggestion to minimizing errors in the impact assessment phase due to pairing issues is to use a consistent inventory and impact assessment list in terms of chemical names.

7.2.5 Time Intensive

One of the goals of hybrid LCA modeling was to improve time and cost associated with conducting LCAs. While creating the augmented process-based hybrid construction LCA was initially very time intensive, future construction LCAs will be much less time intensive. In general, however, the augmented process-based hybrid LCA is not less time-intensive than traditional LCAs.

8.0 CONTEXT

8.1 GREEN BUILDING RATING SYSTEMS

The United States Green Building Council (USGBC) is a vital component in the continued development of green design and construction, a movement that has continued to progress and is "the most vibrant and powerful force to impact building design and construction in more than a decade" (Cassidy 2003). A key component in the development and momentum behind the USGBC is Leadership in Energy and Environmental Design (LEED), a green building rating and assessment tool. Currently in Version 2.2, LEED was initially introduced in 1998 with improvements, revisions, and refinements made to LEED. Several LEED products exist, which are either fully released, in the pilot phase, or under development:

- LEED-NC: New commercial construction and major renovations projects
- LEED-EB: Existing building operations
- LEED-CI: Commercial interiors projects
- LEED-CS: Core and shell projects
- LEED-H: Homes
- LEED-ND: Neighborhood development
- LEED Application guide; Retail, multiple buildings/campuses, schools, healthcare, laboratories, lodging.

LEED-NC, most commonly used, has four-level classification system of Certified (26 to 32 points), Silver (33 to 38 points), Gold (39 to 51 points), and Platinum (52 to 69 points) related to different point totals. Points are achieved by fulfilling a variety of mandatory and credit opportunities. The points are unequally distributed between six categories: Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, and Innovation and Design.

Table 23. Available or Required Points Related to Construction in LEED Version 2.2

Category	**Points Available/Required for Construction Processes**
Sustainable Sites (14 Points Available)	
Construction Activity Pollution Prevention	Required
Site Development	1
Water Efficiency (5 Points Available)	
Energy and Atmosphere (17 Points Available)	
Fundamental Commissioning of the Building Energy Systems	Required
Enhanced Commissioning	1
Materials & Resources (13 Points Available)	
Building Reuse, Maintain 75% of Existing Walls, Floors & Roof	1
Building Reuse, Maintain 95% of Existing Walls, Floors & Roof	1
Building Reuse, Maintain 50% of Interior Non-Structural Elements	1
Construction Waste Management, Divert 50% from Disposal	1
Construction Waste Management, Divert 75% from Disposal	1
Material Reuse, 5%	1
Material Reuse, 10%	1
Recycled Content, 10%	1
Recycled Content, 20%	1
Regional Materials, 10% Extracted, Processed & Manufactured	1
Regional Materials, 20% Extracted, Processed & Manufactured	1
Rapidly Renewable Materials	1
Certified Wood	1
Indoor Environmental Quality (15 Points Available)	
Construction IAQ Management Plan, During Construction	1
Construction IAQ Management Plan, Before Occupancy	1
Low-Emitting Materials, Adhesives & Sealants	1
Low-Emitting Materials, Paints	1
Low-Emitting Materials, Carpet Systems	1
Low-Emitting Materials, Composite Wood & Agrifiber	1
Indoor Chemical & Pollutant Source Control	1
Innovation & Design Process (5 Points Available)	
LEED™ Accredited Professional	1
Total Prerequisites	**2**
Total Credits	**22**
Percentage of Total Credits Related to Construction Phase	**32%**

LEED is impacting the construction industry in terms of operations, procurement, and training. A review of LEED and its relationship with construction can reveal some of the key opportunities the construction industry has in terms of reducing environmental impacts and potentially market opportunities. The applicable credits related to construction processes were subjectively determined and listed in Table 23. Determination of commonality between LEED and construction phase was on the basis of direct contractor involvement, e.g. procurement of regional materials, or direct impact to the construction worker, e.g. limiting exposure to volatile organic compounds in paints. Of the 69 total points, 22 points are directly related to construction processes and construction workers, representing almost 32% of the total points not including two categories that are required.

In the Sustainable Sites category, the intent of the Construction Activity Pollution Prevention requirement is to reduce pollution from construction activities by controlling erosion, water sedimentation, and dust generation. The reduction in pollution from construction activities is implemented through an Erosion and Sedimentation Control (ESC) Plan for all construction projects. The ESC plan must conform to the more stringent erosion and sedimentation requirements of the 2003 U.S. EPA Construction General Permit (CGP) or local standards and codes. The CGP describes the requirements of the National Pollutant Discharge Elimination System (NPDES) program. Typically, NPDES requirements are only for projects greater than one acre; however, all projects attempting LEED certification are required to implement NPDES requirements regardless of the project size. A plan typically addresses concerns such as soil loss during construction due to stormwater runoff and wind erosion, prevention of sedimentation into storm sewers or streams, and prevention of air pollution from dust and particulate matter. Potential solutions are seeding during and after construction, installing silt fencing, and installing sediment traps and basins.

Another construction related credit within the Sustainable Sites category is Site Development: Protect and Restore Natural Habitat. The intent of this credit is the conservation of existing natural areas, restoration of damaged areas, and promotion of biodiversity. This credit relates to construction activity by establishing limits for construction operations to minimize site disturbance to the existing site. For example, construction activities such as haul roads should be contained and planned so construction equipment and routing is not damaging existing habitats.

The Energy and Atmosphere category for construction processes is mainly represented by building commissioning and enhanced commissioning. The intent of commissioning is verifying the building's energy systems are functioning properly and in accordance with design documents. General commissioning is a LEED requirement, while enhanced commissioning can be a LEED point that occurs earlier in the project and includes more rigorous verification and documentation. Although the construction team directly involved in the project cannot perform the commissioning, an independent employee of the company can perform the commissioning. These credits occur during the construction phase and will be managed by the construction team.

The Materials and Resources category has 13 possible points and one requirement of Storage and Collection of Recyclables. All 13 points are related to the construction phase because the construction company is ultimately responsible for procurement and transportation of the materials. The designer and possibly the owner are also actively involved in aspects of the Materials and Resources category through project drawings and specifications. Three points are related to Building Reuse in differing percentages and material types: (1) maintain 75% of existing walls, floors, and roofs; (2) maintain 95% of existing walls, floors, and roofs; (3) maintain 50% of interior non-structural elements. The construction company is directly involved in all of these activities during the removal and reuse of the existing structure.

The Construction Waste Management credits include one point for diverting 50% construction, demolition, and land-clearing debris from disposal, and another point for diverting an additional 25%. The intent of Construction Waste Management credits is to divert construction, demolition, and land clearing debris from landfill disposal and promote recycling of materials both in the manufacturing process and reusability. These two points directly impact construction activities from planning construction waste bin areas, to sorting materials, documenting percentages either by weight or volume, and locating haulers and recycle centers. The impact of these two points on a construction site is relatively substantial because construction waste management plans change standard operation procedures during construction and can require the construction company to need additional personnel due to the documentation. Some potential materials to recycle include cardboard from delivery of new purchases, metals, brick, concrete, carpet, and glass.

The next credits within the Materials and Resource Category require the contractor to potentially alter procurement strategies and find and develop new suppliers who meet LEED goals for the project. The following credits relate to materials reuse, recycled content, regional materials, rapidly renewable materials, and certified wood.

The intent of the two materials reuse credits, at 5% and 10%, is to reduce raw material use and reduce waste. Salvaged materials can include components such as furniture, flooring, bricks, and cabinetry, but not mechanical, electrical, and plumbing components. Projects that involve companies leaving an old facility and building a new facility have an opportunity to greatly exceed the 5 to 10% goals. The construction company would be involved with deconstruction elements of the old facility along with procurement of salvaged materials.

The use of recycled materials on the project can achieve two points depending on the percentage of total value, either 10% or 20%. Further, within these credits, LEED has established requirements for post-consumer and pre-consumer content. The contractor will need to identify suppliers that achieve the goal.

Attainment of the procurement of Local/Regional material credit will require the contractor to develop a network of locally businesses and rethink logistics and scheduling efforts. It should be noted that ‘locally’ is defined broadly by LEED with a maximum radius of 500 miles. This definition can mean that a project in Pittsburgh, Pennsylvania can procure material in Toronto, Canada and still attain the local/regional credit. Finally, two LEED points are available for use of rapidly renewable materials, such as bamboo, wool, and cotton, and use of certified wood products

With a total of 15 points available in the Indoor Environmental Quality (IEQ), six points relate to construction processes and exposure of construction workers. Two credits for the indoor air quality during construction and before occupancy have the intent to improve not only the air quality for the construction workers but also the occupants. Attainment of the credit, Construction Indoor Air Quality (IAQ) Management Plan: During Construction, requires developing an IAQ management plan that addresses protection of the heating, ventilation, and air conditioning equipment to limit contamination pathways from construction dust and other air pollutants by means of installing devices like filtration media. The IAQ plan requires protection of on-site absorptive material from moisture damage. During the pre-occupancy phase the credit, Construction IAQ Management Plan: Before Occupancy, intends to limit exposure to occupants from contamination emitted during the construction phase from construction activities and installation of new material off-gassing. To obtain a point for this credit, the contractor may either flush-out the space before occupancy with outdoor air at a minimum of 14,000 cubic feet per square feet of floor area, or conduct baseline IAQ testing after construction ends and prior to occupancy to demonstrate that contaminant concentrations are below specified levels.

Four credits in the IEQ relate to low-emitting materials for adhesives and sealants, paintings and coatings, carpet systems, and composite wood and agrifiber products. The intent of these credits is to reduce indoor air contaminants to improve health and safety of construction workers and building occupants. The contaminant associated with adhesives and sealants is volatile organic compounds (VOCs) and attainment of this credit requires all adhesives and sealants comply with VOC limits established by the South Coast Air Quality Management District (SCAQMD) and Green Seal Standards for commercial adhesives. Typical paints and coatings also contain VOCs; therefore, achievement of that credit also deals with reducing that amount of VOCs to comply with the LEED criteria of not exceeding VOC limits established in Green Seal Standards and SCAQMD depending on the paint or coating application. For carpet installations, the carpets must meet testing and product requirements established by the Carpet and Rug Institute’s Green Label Plus program, and the carpet cushion must meet the Institute’s Green Label program. The use of Composite Wood and Agrifiber products on a LEED project and achievement of the associated credit requires the use of no added urea-formaldehyde resin.

The last category, Innovation and Design Process, has five possible points available, one of which is the use of LEED accredited professional. With the increasing implementation of LEED, more contractors are becoming LEED professionals. The other four credits available are open for interpretation by the USGBC, so additional credits are available for construction processes.

While the contractor has direct involvement and ultimate success with LEED projects, work still needs to occur in term of improving pure on-site construction activities. For example, on-site construction issues are dealt with in a relatively generic manner in the Construction Activity Pollution Prevention credit. As the hybrid model results show, equipment combustion is a significant contributor to overall emissions, but LEED fails to deal with this significant issue. Additionally, local materials is currently defined at using products that have been extracted, harvested or recovered, as well as manufactured, within 500 miles of the project site with a minimum of 50% of the total materials value. Recommendation is made to reduce the radius to less than 500 miles, and base the new distances on more strategic values based on locally available materials.

8.2 NATIONAL CONSTRUCTION POLICIES

8.2.1 United States – Construction Environmental Regulations

The U.S. government has several mechanisms that have the ability to enact laws and regulations related to the environment and construction. The U.S. Congress has enacted several environmental acts through laws, and the U.S. EPA and the U.S. Department of Labor have the jurisdiction to enforce the acts through publicly commented regulations. The process is generally – bill is introduced by Congress, if Congress and the President pass the bill, then the bill becomes a law and an act. Congress authorizes certain government agencies such as the U.S. EPA to create and enforce regulations. Before a regulation is implemented, it is open for public comment; the final step is codification and publication in the Code of Federal Regulations (CFR). The major environmental acts directly or indirectly impacting the construction industry are as follows:

- National Environmental Policy Act (NEPA) of 1969. NEPA is the basic national charter for protecting the environment.
- Clean Air Act (CAA). CAA is the comprehensive Federal law that regulates air emissions from area, stationary, and mobile sources. The CAA authorizes the U.S. EPA to develop National Ambient Air Quality Standards (NAAQS).
- Clean Water Act (CWA). CWA establishes the basic structure for regulating discharges of pollutants into the waters, gives the U.S. EPA the authority to implement pollution control programs, sets water quality standards for all contaminants in surface waters, establishes discharging permit requirements for point sources into navigable channels, and funds construction of sewage treatment plants.

- Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or Superfund) and Superfund Amendments and Reauthorization Act (SARA). Superfund created a tax on chemical and petroleum industries along with giving Federal authority to respond directly to hazardous substances releases. The collected taxes established a fund to clean up abandoned or uncontrolled hazardous waste sites. SARA addressed the U.S. EPA's concerns in administering the Superfund program and made several changes and additions to the program. Some of the issues addressed in SARA were establishment of permanent remedies and innovative treatment technologies in cleaning up hazardous sites, integration of existing Federal and State environmental standards, establishment of new enforcement tools, increased focus on human health and public involvement, and establishment of an increased size in the trust fund.

- Resource Conservation and Recovery Act (RCRA). RCRA grants U.S. EPA the authority to control hazardous wastes from the 'cradle-to-grave' (generation, transportation, treatment, storage, and disposal) along with establishing the framework for managing non-hazardous wastes. Amendments to RCRA allow EPA to address environmental problems from underground storage tanks.

- Endangered Species Act (ESA). ESA provides conservation of threatened and endangered plants and animals in their natural habitat.

- Occupational and Safety Health Act (OSHA). OSHA ensures worker and workplace safety by requiring employers to provide work conditions free from hazards such as exposures to toxic chemicals, excessive noise levels, hot or cold temperatures, and unsanitary conditions. This act also established the National Institute for Occupational Safety and Health (NIOSH) as the research institute for OSHA, which is a division of the U.S. Department of Labor (U.S. Environmental Protection Agency 2005b).

Along with establishing major national Acts, the U.S. government has also attempted to regulate on-site construction activities by implementing two major regulations related to stormwater management and new nonroad diesel emission standards. As authorized under the CWA, the National Pollutant Discharge Elimination System (NPDES) permit program attempts to control water pollution from point sources that discharge pollutants into U.S. waters. In most instances, the NPDES permit program is administered by authorized state agencies, for example, the Allegheny County Conservation District approves NPDES permits in Allegheny County, Pennsylvania. Construction activities that disturb one acre or more are required to obtain a NPDES permit by developing and implementing stormwater pollution prevention plans. The U.S. EPA has developed Best Management Practices (BMPs) to offer guidance to contractors and designers some of which include minimizing disturbance, preserving natural vegetation, covering stockpiles, installing silt fences and inlet protection, stabilizing construction entrances, and installing sediment traps (U.S. Environmental Protection Agency 2005c).

In the past, the U.S. EPA focused on mobile sources with minimal regulation on nonroad sources. In recent years, however, the U.S. EPA increased their policy initiatives and focused on nonroad diesel engines, which includes construction equipment. According to the U.S. EPA, about 2 million pieces of construction equipment are used in the U.S.; further, an average bulldozer emits as much PM as 500 cars (U.S. Environmental Protection Agency 2006d).

The major pollutants from mobile sources include carbon monoxide, hydrocarbons, nitrogen oxides, particulate matter, toxics, and greenhouse gases. Of the first four pollutants mentioned and with respect to contribution of on-road and non-mobile sources, the U.S. EPA reports with following data as shown in Table 24 (U.S. Environmental Protection Agency 2006c).

Table 24. 1999 Emission by Sources

	Carbon Monoxide	Hydrocarbons	Nitrogen Dioxides	Fine Particulate Matter ($PM_{2.5}$)
On-Road Mobile Sources	51%	29%	34%	10%
Nonroad Mobile Sources	26%	15%	22%	18%
Other (Not Mobile Sources)	23%	53%	44%	72%

Nonroad engines in the past were required to meet modest emission requirements and emitted relatively large amounts of nitrogen oxides (NO_x) and particulate matter (PM). In addition to emission requirements to nonroad diesel engines, the EPA implemented new fuel requirements that reduced the allowable level of sulfur in fuel supplied to these engines by more than 99%. Starting in 1993, the EPA implemented the following policies related to nonroad engines and construction activities (U.S. Environmental Protection Agency 2005e). Table 25 displays the progression of the nonroad diesel legislation, culminating in the 2004 Clean Air Nonroad Diesel Rule which is the comprehensive rule, reducing PM and NOx emissions by 90% along with reducing the sulfur content in fuel by more than 99%. The EPA estimates that by 2030, reduction of these emissions will prevent 12,000 premature deaths, 8,900 hospitalizations, and one million work days lost, equating to a dollar figure of $80 billion on an annual basis. The 2004 Clean Air Nonroad Diesel Rule is one component of the Clean Air Rules of 2004.

Table 25. Nonroad Diesel Milestone Summary

Year	Description
1993	Highway Low Sulfur Diesel Rule: Limited the sulfur content of highway diesel fuel.
1997	2004 Highway Diesel Rule: Established emissions regulations to reduce NO_x and hydrocarbons from heavy-duty diesel trucks and buses to be implemented in 2004.
1998	Tier 2 and 3 Nonroad Diesel Rule: Established emission standards for new nonroad diesel engines, which included construction, agriculture, airport, marine equipment, and industrial equipment.
2000	2007 Clean Diesel Truck/Bus and Low Sulfur Diesel Rule: Considered a comprehensive program to reduce emissions from heavy-duty diesel trucks and buses along with highway diesel fuel. This rule applies to new 2007 engines and vehicles; the sulfur fuel reduction by 97% begins in mid-2006.
2000	Voluntary Diesel Retrofit Program: A program that was established to encourage and educate owners to install pollution reduction devices on existing fleet equipment and use cleaner diesel fuel.
2003	Clean Air Nonroad Diesel Proposal: This was an EPA proposal to further reduce emissions from nonroad diesel engines
2004	Clean Air Nonroad Diesel Rule: Standards that established significant emission reductions from nonroad diesel.

The U.S. EPA established a Clean Construction USA program, which is one program of many within the National Clean Diesel Campaign. Clean Construction USA is a voluntary program to reduce diesel exhaust emissions from existing construction equipment. Since current regulations only effect new equipment, Clean Construction USA is an attempt by the U.S. EPA to capture the emissions from the existing, older fleet. The existing nonroad fleet of about 1.8 million pieces of equipment can remain in operation for about 25 to 30 years. The U.S. EPA partnered with the Association of General Contractors of America (AGC) to encourage retrofitting of public and private fleets, properly maintaining equipment, and using cleaner fuel (U.S. Environmental Protection Agency 2006a). To exemplify the impacts of clean diesel techniques on construction projects, the U.S. EPA represented three case studies: the Central Artery/Tunnel Project, I-95 New Haven Harbor Crossing Improvement Program, and the Dan Ryan Expressway.

The Central Artery/Tunnel Project, also known as the Big Dig, is located in Boston, Massachusetts. The project, administered by the Massachusetts Turnpike Authority, includes 161 lane miles of new highway in a 7.5 mile long corridor. Reducing environmental impact was achieved by retrofitting equipment, using lower emission diesel fuel, and reducing idling time. Retrofitting equipment was considered due to the proximity of residential homes, hospitals, and sensitive receptors. Although, the initial program recommended updating 50 pieces of equipment, over 100 pieces were retrofitted. The pieces of equipment that were retrofitted were chosen mainly due to the equipment use and its relationship to the proximity of residential and hospitals and for health and safety of workers during tunnel work. The technology, Diesel Oxidation Catalysts (DOCs), was selected because the DOCs reduce HC, CO, and PM; the cost was inexpensive; the downtime was about 2 hours; and DOCs are on the U.S.EPA's verified technology list. The contractors reported no operational difficulties with the retrofitted equipment, such as loss of power or additional fuel consumption. In addition to using the DOCs, the MTA required the use of lower emission diesel fuel to reduce NO_x emission and reduce smoke. The fuel used was Lubrizol's $PuriNO_x$. The operators reported that slightly more fuel was consumed and more power was needed in deep mud situation. In terms of idling, operators were required to turn off inactive equipment and dump trucks were not allowed to idle for more than 5 minutes (U.S. Environmental Protection Agency 2006b).

The Big Dig project was used as a model for other construction projects across the United States, such as the I-95 New Haven Harbor Crossing Improvement Program. Located in southern Connecticut, this project is administered by Connecticut Department of Transportation (CONNDOT) and includes constructing a 7.2 mile stretch of interstate. Retrofitting of equipment was required due to the long construction period, 2002 to 2013, and the proximity of New Haven, East Haven, and Branford. New Haven, East Haven, and Branford are non-attainment areas for ozone; New Haven is a non-attainment area for PM_{10} and $PM_{2.5}$. CONNDOT formed an air quality working group to understand the advantages and disadvantages of implementing the construction emission controls, and the group decided to implement DOCs and use $PuriNO_x$ given the low cost and proven experience with the Big Dig project. Installation of DOCs are required for all nonroad vehicles with an engine horsepower rating of greater than 60 hp and will be on site for more than 30 days. Idling time is limited to 3 minutes and truck staging zones are located away from fresh air intakes, air conditioners, and windows. Compliance was enforced though monthly reporting (U.S. Environmental Protection Agency 2006b).

The Dan Ryan Expressway, located in Chicago, Illinois, is expected to be completed in August 2007. This project's scope of work is adding an express lane in both directions from 31st Street to the I-57 interchange. While the Big Dig and I-95 projects required the use of NO_x, this project required the use of ultra low diesel fuel (ULSD) *or* the installation of DOCs. The Dan Ryan Expressway also implemented idling restrictions and dust control measures. It is anticipated that about 290 pieces of equipment will either be retrofitted or use ULSD fuel. In addition prevention pollution air monitors were set up along the construction zone to monitor levels before, during, and after construction (U.S. Environmental Protection Agency 2006b).

At the state level, California is attempting to supplement the U.S. EPA's nonroad by regulating in-use nonroad equipment for existing fleet. Capturing in-use fleet provides a more expansive policy impact, than only new engines that are or will be regulated by federal standards. Further, some of California's emission requirements are more stringent than the federal requirements (California Air Resources Board 2006).

At the local level, in 2003 New York City (NYC) amended their administrative code to use ultra low sulfur diesel fuel and the best available technology by nonroad vehicles in city construction. NYC's legislative findings and intent state that NYC is a severe-17 non-attainment area for ozone. Ozone is formed in the presence of nitrogen oxides (NO_x), VOCs, and sunlight. NO_x is one of the major pollutants from diesel exhaust, along with particulate matter which has been associated with an increased rate of cancer, decreased lung functions, and asthma (New York City 2003; U.S. Environmental Protection Agency 1997). A non-attainment area means that the area does not meet air quality standards for certain pollutants. The law was enacted after September 11, 2002 in an attempt to mitigate air pollution from construction activities associated with rebuilding Ground Zero to protect the people in Lower Manhattan.

With respect to national emissions and the results from the hybrid model, consistent with the model's results on construction equipment emissions, the Federal government, after many years, has started to implement strategies to reduce non-road emissions. Since construction vehicles are in service for many years, more aggressive strategies for existing fleet, as exemplified in the state of California, is recommended.

8.3 PROJECT DELIVERY METHODS AND GREEN DESIGN

Since this section of the document, while directly related to construction, acts independently, the information is located in Appendix J.

9.0 CONCLUSION

This section summarizes the findings with respect to the initial research questions and suggestions for future work.

9.1 REVIEW OF INITIAL RESEARCH QUESTIONS

The focus of this research was three broad areas of construction, hybrid LCA modeling, and context. First, in terms of commercial core and shell construction in the United States, the research determined the life cycle inventory and life cycle impact assessment of the construction processes of a typical commercial building as represented in the case study for the steel construction building and further validated in the precast case study. Life cycle inventory results – while all are available – focused on PM emissions, GWP, SO_x, NO_x, CO, Pb, and non-methane VOCs, energy usage, and solid and liquid wastes. Additionally, the modeled results were compared with the entire building life cycle with results that indicated that construction, while not as significant as the use phase, is as important as the other life cycle stages. This hybrid construction LCA is unique because it is one of the first that incorporates impact assessment methods.

Second, with regards to hybrid LCA modeling, the augmented process based LCA proved to be effective in modeling the construction phase and allowed for efficient combining of process and input-output results. Including input-output results, especially the construction sectors, is critical in construction LCA modeling. In the steel case study for the broad construction results, services had the highest level of methane emissions, and they were a significant contributor to CO_2 emissions.

Table 26 compares the construction phase boundary between this research and other research, and this research has found is important to include construction services, equipment manufacturing, and fugitive dust (driving on paved and unpaved roads, and dust from operating construction equipment). Additionally, these categories, along with transportation, had significant environmental impacts.

Table 26. Construction Boundary Comparisons

	Junnila, Horvath, Guggemos 2006	Guggemos and Horvath 2005	Model Results
On-site energy	x	x	x
Equipment utilization	x	x	x
Transportation	x	x	x
Temporary Materials	x	x	x
Construction Workers Transportation			x
Construction Services			x
Equipment Manufacturing			x
Fugitive Dust			x

Thirdly, the construction industry as a whole was looked at in terms of LEED and construction legislation. A review of construction within the LEED framework was discussed, and while the contractor has direct involvement and ultimate success with LEED projects, work still needs to occur in terms of improving pure on-site construction activities. Construction legislation is somewhat lacking; although, positive steps are occurring at the national level in terms of nonroad vehicles. Additional national legislation is recommended to deal with existing fleet retrofits with California and New York serving as models. Preliminary research on project delivery methods and green design was conducted and green project characteristics were identified with future work recommended on green project success factors.

One major finding of the research is that it is critical to include service sectors while modeling LCAs, which this finding not only pertains to construction but can also extend to other LCAs as well. Past LCAs, such as Guggemos and Horvath (2005), did not include service sectors, so this research has improved upon and helped to advance how construction is modeled within the LCA framework. Additionally, other research did not focus on a large pool of construction equipment, rather more generic horsepower ranges. Providing a diverse mixture of construction equipment improves the usability and applicability of the LCA construction models and improves the accuracy of results. While this research focused on commercial construction in the United States, the framework can be extended to other construction types and countries, including developing countries. The framework allows for considerable flexibility with minimal effort to make changes to data sources. Examples of changes to the model in developing countries may include changes to construction equipment for combustion emissions, fuel usage, and equipment types. Developing countries may also employ different construction practices and levels of equipment use. The model may also be used to compare not only the entire project, but also different construction activities, such as comparing the environmental impacts of augercast piles versus driving steel piles.

9.2 FUTURE WORK AND RECOMMENDATIONS

The overall body of knowledge of construction LCAs needs to be further developed and expanded, and this research contributed to its development. But more research, especially case studies, are needed so deeper and more in-depth comparisons can be made to further refine the ultimate results.

Modeling construction was difficult for several reasons including its dynamic and short-lived nature. While construction sites are short-lived, the impacts on the surrounding communities can be significant, and an analysis was performed as a part this research exemplifying regional and local issues. Regulating construction sites has been modest, leading to gaps in data and information. Furthermore, data that is available is often difficult to interpret due to complex contractual arrangements; for example, one construction company acts in many different roles - one company can simultaneously act as a general contractor, construction manager, and subcontractor. These different roles can create confusion and inaccurate data in construction surveys that the government collects on a regular basis. More and better data needs to be collected at the national, state, and local levels to further advance and understand the impact of on-site construction. Construction companies should also contribute to data collection efforts to begin to benchmark their own environmental performance.

It is recommended that the USGBC refines its next LEED version to more deeply incorporate on-site construction activities because the current version glosses over this significant building life cycle phase. Another recommendation is to more narrowly and strategically define the transportation radius for local materials.

In terms of the life cycle impact assessment stage, this research selected and implemented Eco-Indicator 99 and Impact 2002+ into the model. Future research can look at other methods, such as the Tool for the Reduction of Chemicals and Other Environmental Impacts (TRACI). In addition, uncertainty within Eco-Indicator 99 can be examined through including all three perspectives of Hierarchist, Individualist, and Egalitarian.

While this research ultimately selected the augmented process LCA approach, research is currently being conducted on construction LCAs using the input-output approach. Modifications to the current EIO-LCA version for construction are available on-line in the beta version. The input-output approach has benefits such as including the entire supply chain, along with its ease of use. Upon completion of this research and the research at Carnegie Mellon, it is anticipated that both models will be combined to create a “hybrid-hybrid” construction LCA, leading to further refinement of construction LCAs.

In conclusion, this research is a reminder to include construction in building LCAs because glossing over this phase can lead to under-reporting in building LCAs.

APPENDIX A. EIO-LCA INFORMATION

EIO-LCA INFORMATION

The majority of this discussion is based on information from Hendrickson et al. (2006). The four basic components of EIO-LCA are shown in Figure 103. The general concept behind EIO-LCA is that a change in economic demand represented by a purchase from a specific sector is applied to the EIO-LCA model. The purchase then resonates throughout the EIO-LCA model to estimate all of the supply chain connection, and then the model computes the associated environmental discharges from the original purchase.

The I-O model, developed by Wassily Leontief, divides the economy into sectors, such as New Passenger Car, and can be visualized as a large matrix of 500 rows and 500 columns where each sector is represented by one row and one column. "The tables can represent total sales from one sector to others, purchases from one sector, or the amount of purchases from one sector to produce a dollar of output for the sector (Hendrickson et al. 2006)." In other words, the columns can be thought of as the recipe for the purchase.

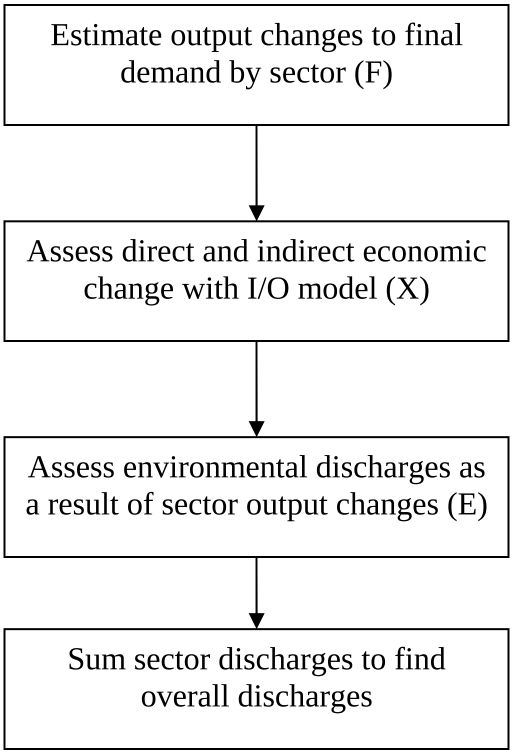


Figure 103. Description of EIO-LCA Process from (Hendrickson et al. 2006)

Information in Figure 104 shows more detailed information on the matrix structure, also known as transaction matrix, behind EIO-LCA. An entry of X_{ij} is the input to sector j from sector i. The total output X_i is the sum across the rows, also represented by O_i, and the final demand of consumers, Y_i. GDP is calculated as the sum of all final demands, Y. In addition, value added is the difference between total input X_j and intermediate input I_j.

	Input to sectors (j)				*Intermediate output O*	*Final demand Y*	*Total output X*
Output from sectors (i)	1	2	3	n			
1	X_{11}	X_{12}	X_{13}	X_{1n}	O_1	Y_1	X_1
2	X_{21}	X_{22}	X_{23}	X_{2n}	O_2	Y_2	X_2
3	X_{31}	X_{32}	X_{33}	X_{3n}	O_3	Y_3	X_3
n	X_{n1}	X_{n2}	X_{n3}	X_{nn}	O_n	Y_n	X_n
Intermediate input ***I***	I_1	I_2	I_3	I_n			
Value added ***V***	V_1	V_2	V_3	V_n		GDP	
Total input ***X***	X_1	X_2	X_3	X_n			

Figure 104. Economic Input-Output Example

Equation 6

$$x = (I + A + A \times A + A \times A \times A + \ldots)y = (I - A)^{-1} y$$

where: $x =$ *Vector of inputs*

$I =$ *Identity matrix*

$A =$ *Direct requirements matrix*

$y =$ *Vector of desired output*

The production of the desired output is (I x y); direct contributions are represented in (A x y); and indirect contributions are (A x A x y). The supply chain infinite series is equal to $(I–A)^{-1}$.

This economic information is then used to determine the environmental impacts by using Equation 7. This mathematical model is realized in the publicly free EIO-LCA model at www.eiolca.net.

Equation 7

$$b_i = R_i x = R_i (I - A)^{-1} y$$

where: $b_i =$ *Vector of environmental burdens*

$R_i =$ *Matrix of diagonal elements of impact per dollar of output*

$x =$ *Vector of inputs*

$y =$ *Vector of desired output*

APPENDIX B. NONROAD DESCRIPTION

NONROAD DESCRIPTION

The section describes the U.S. EPA's software program, Nonroad. Along with the User's manual, several technical reports were reviewed to obtain a thorough understanding of the model in terms of methodology and calculations. This section is a summary of Nonroad as a software tool and the technical reports. In general, Nonroad 2005 is the most comprehensive tool available to estimate construction equipment emissions due to its depth and breadth. While there are some negative aspects of the Nonroad model, the depth of the model outweighs any negative aspects.

Emissions related to nonroad equipment evolved through a series of tiered regulations and culminated in a final ruling, and the Nonroad program has developed in parallel with the regulations. The software was created as a tool for the U.S. EPA, State agencies, and other air pollution agencies to estimate pollution from nonroad equipment in order to comply with State Implementation Plans (SIPs), which are required by the 1990 Clean Air Act Amendment and other regulations (Harvey 2003). Nonroad 2005 calculates past, present, and future emission inventories for the majority of nonroad equipment. Nonroad equipment includes equipment used for recreational vehicles, logging, agriculture, construction, industrial, residential and commercial lawn and garden, recreational and commercial marine vessels, locomotive, and aircraft. The U.S. EPA regulation of nonroad vehicles and equipment, except aircraft, did not occur until the mid-1990s. The list of equipment in Nonroad is more than 340 types that can be disaggregated by horsepower rating; further, Nonroad includes four types of fuel: gasoline, diesel, compressed natural gas (CNG), and liquefied petroleum gas (LPG). The program reports six exhaust emissions: hydrocarbons (HC), NO_x, carbon monoxide (CO), carbon dioxide (CO_2), sulfur oxides (SO_x), and particulate matter (PM). The hydrocarbons can be further broken down to total hydrocarbons (THC), total organic gases (TOG), non-methane organic gases (NMOG), non-methane hydrocarbons (NMHC), and volatile organic compounds (VOC). Particulate matter is reported as PM_{10} and $PM_{2.5}$. Finally, the model reports emissions for non-exhaust HC for diurnal, refueling, spillage, vapor displacement, hot soak, running loss, tank permeation, hose permeation, and crankcase emissions.

A user can select geographic areas of interest included in each run from the highest level, national, to the lowest level, county. Additional detailed modeling can be done as an advanced feature. In terms of temporal results, Nonroad estimates the current year, projects future year emissions, and backcasts past years. The program accounts for fleet growth, scrapping (or end-of-service life), and control programs. The time periods of a run range from one year, to seasonal periods or monthly. The main components for the emissions are calculated by Equation 8.

Equation 8.

$$I = EF \times Act \times LF \times RP \times Pop$$

where*:* $I =$ *Exhaust emission inventory (tons/year)*

$EF =$ *Emission factor (g/hp-hr)*

$Act =$ *Activity (hours/year)*

$LF =$ *Load factor*

$RP =$ *Average rated power*

$Pop =$ *Equipment population (units)*

Activity *(*hours/year) represents annual equipment usage. Equipment activity estimates were mainly developed by Power Systems Research, Inc. (PSR). PSR data has a comprehensive database of application-specific activity; PSR conducts yearly surveys of equipment users to determine a usage rate disaggregated by engine application and fuel type. PSR data was reviewed by Pechan (1997) to understand methodology and accuracy.

Rated power is defined as “the maximum power level that an engine is designed to produce at its rated speed” (U.S. Environmental Protection Agency 2004b). Since nonroad engines operate at varying speeds and load, the rated power needs to be adjusted by a load factor to take into account those factors along with idling. The load factors used in NONROAD were calculated from PSR which based the load factor calculation on annual usage hours, fuel consumption, and fuel consumption rate. PSR's methodology was also evaluated by Pechan (1997).

The model calculates estimated equipment population, age distribution of those populations, annual equipment sales, and equipment scrappage. Equipment scrappage is when the piece of equipment retires from the service fleet and is no longer emitting or consuming fuel. This aspect accounts for emissions over time due to fleet turn-over, emission deterioration, emission standards, technology changes, and equipment population changes due to sales growth trends (U.S. Environmental Protection Agency 2005a).

Equation 8**.** was used in this research primarily to calculate fuel usage in gallons/hour for a given piece of construction equipment.

APPENDIX C. HYBRID LCA CONSTRUCTION FIGURES

HYBRID LCA CONSTRUCTION FIGURES

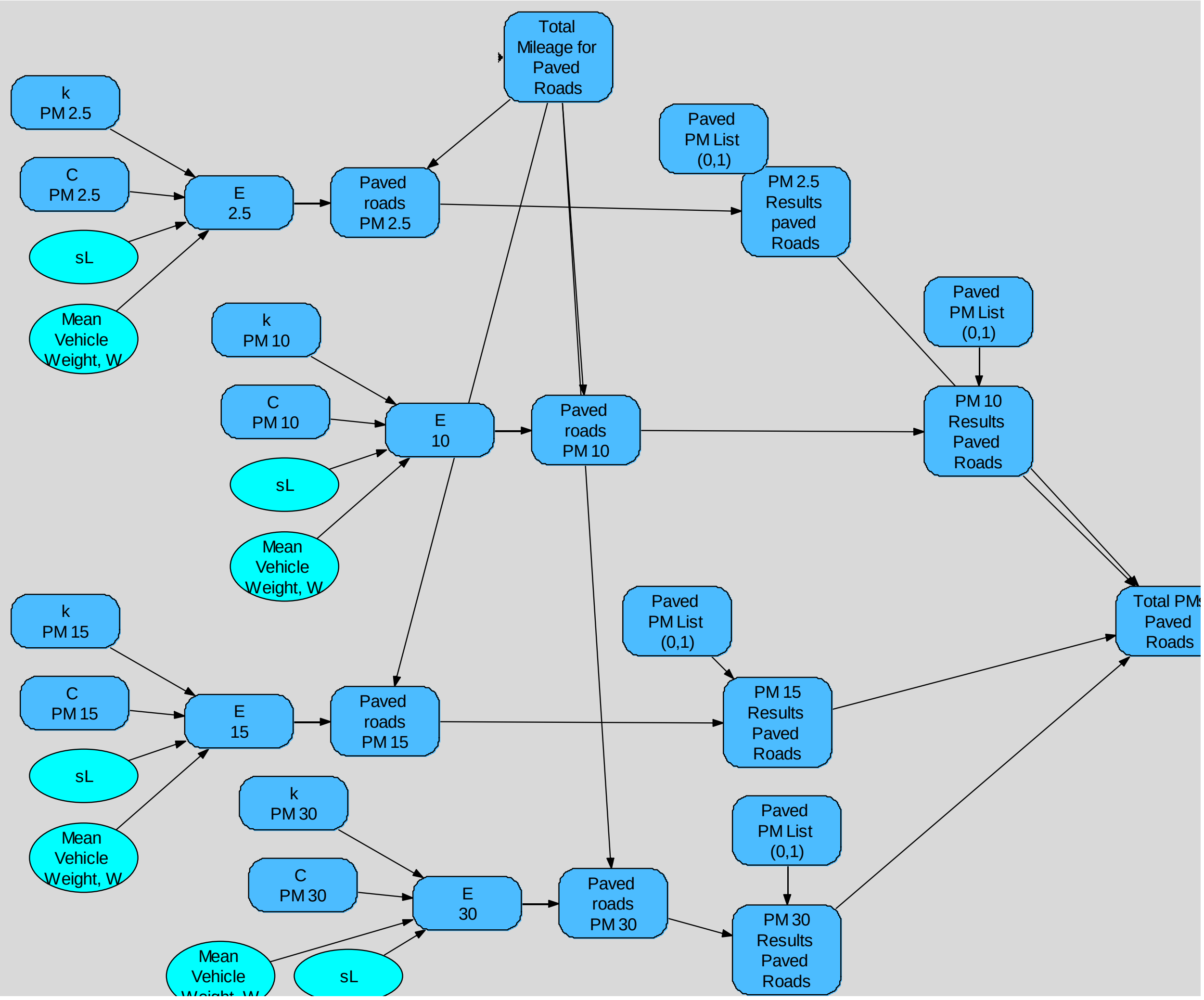


Figure 105. Dust Generation from Unpaved Roads - Detailed Model

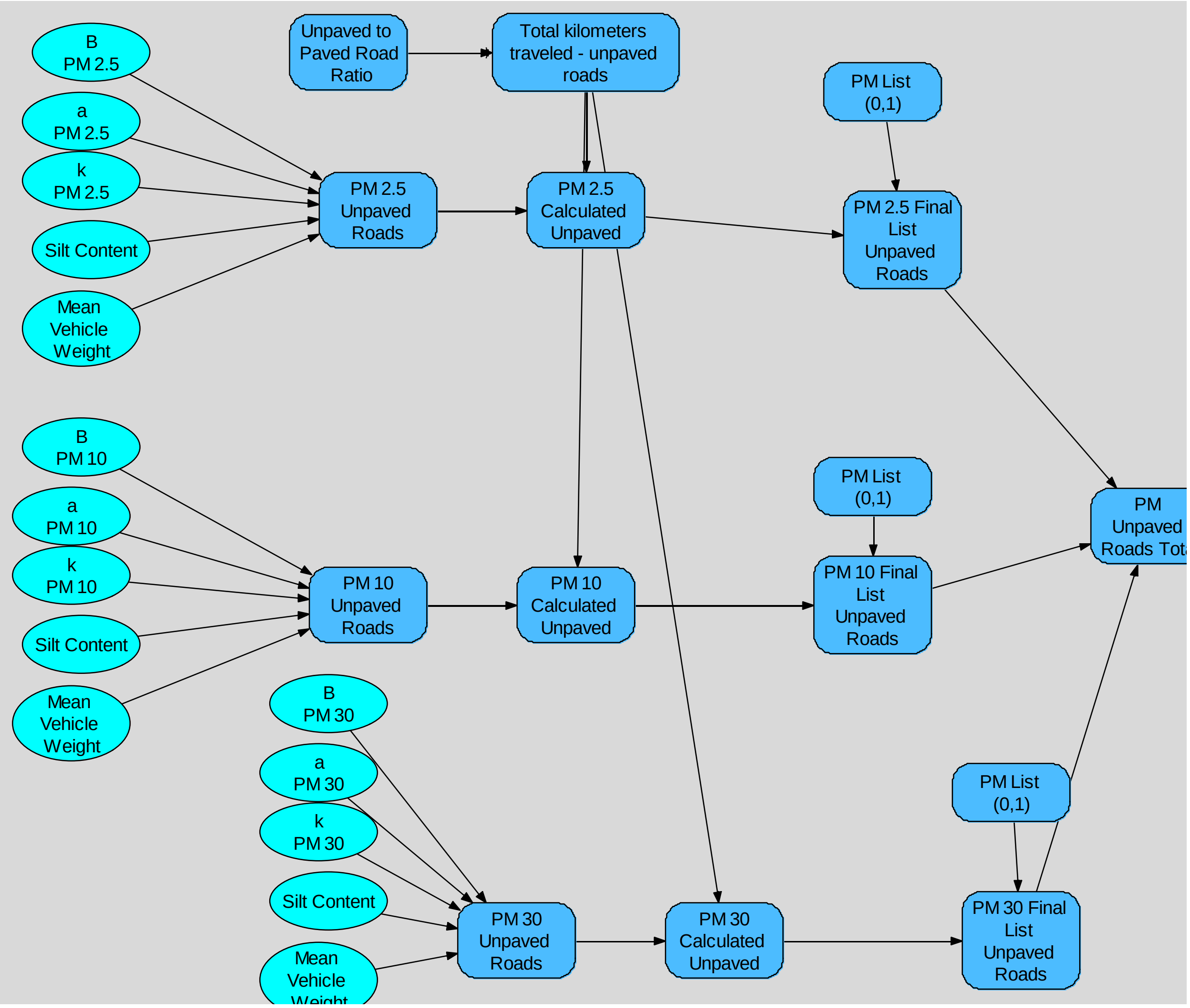


Figure 106. Dust Generation from Unpaved Roads - Detailed Model

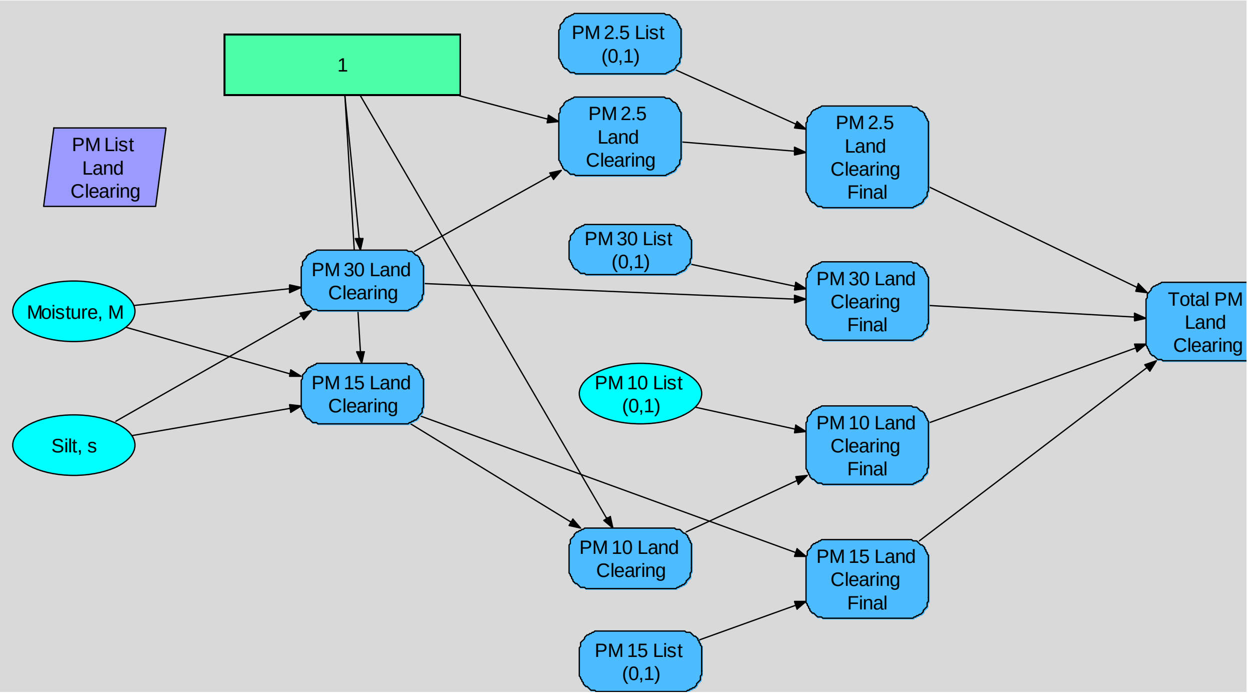


Figure 107. Heavy Construction Operations - Detailed Model

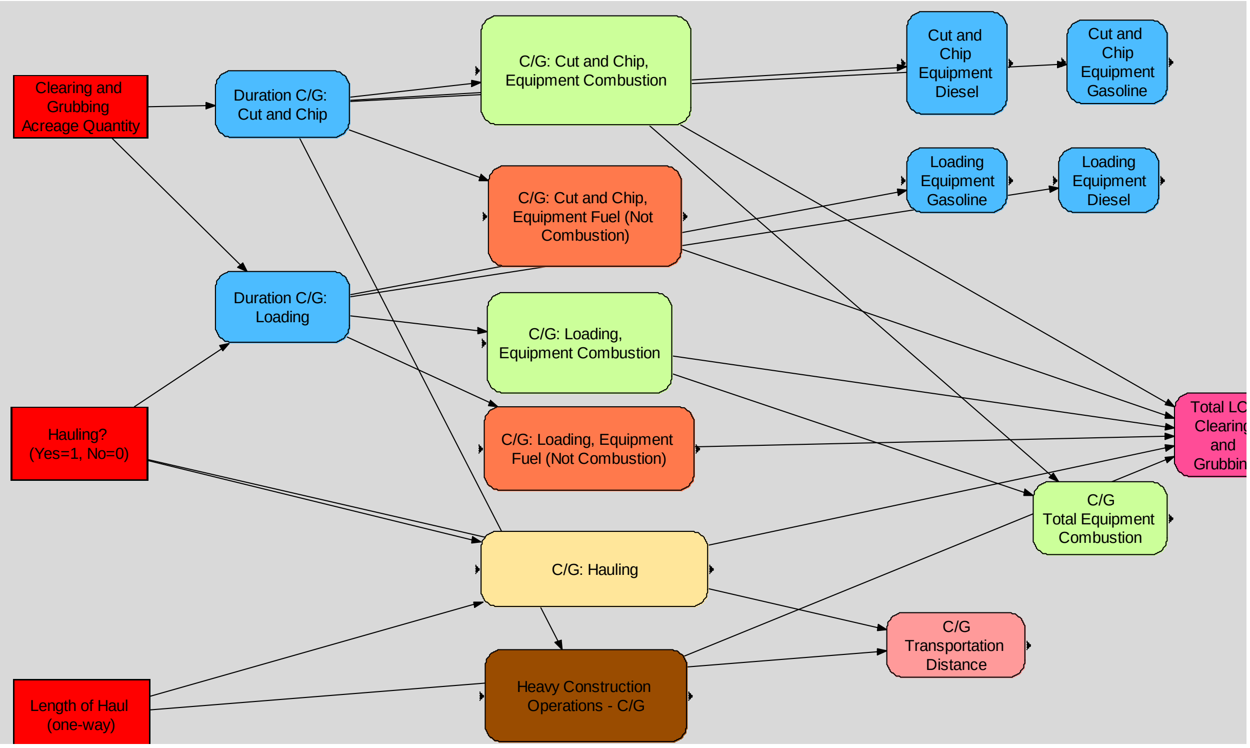


Figure 108. Clearing and Grubbing - Detailed Model

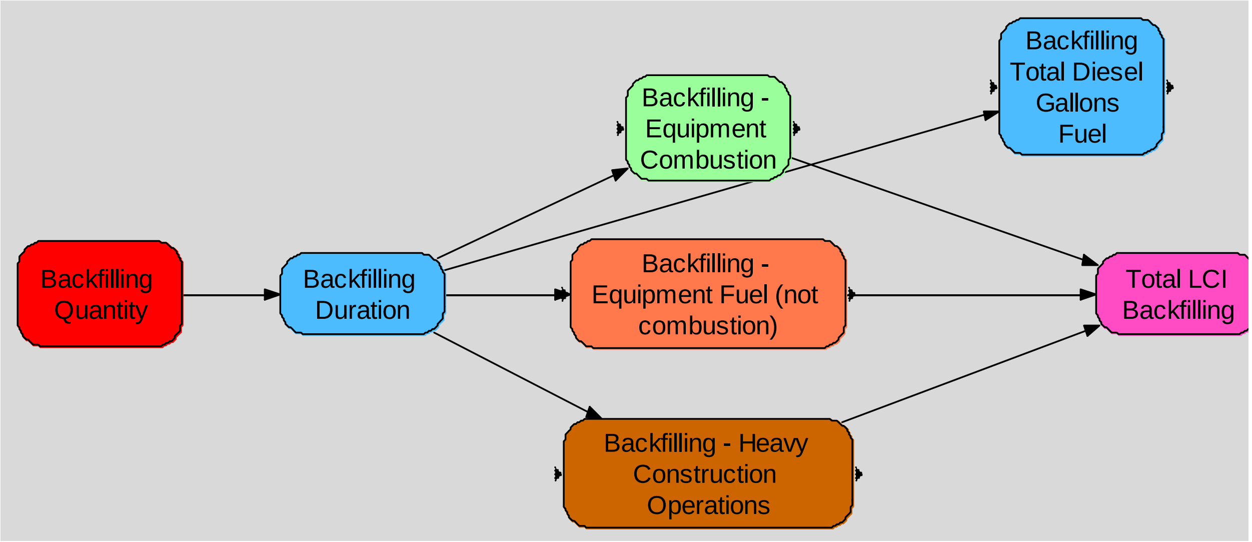


Figure 109. Backfilling - Detailed Model

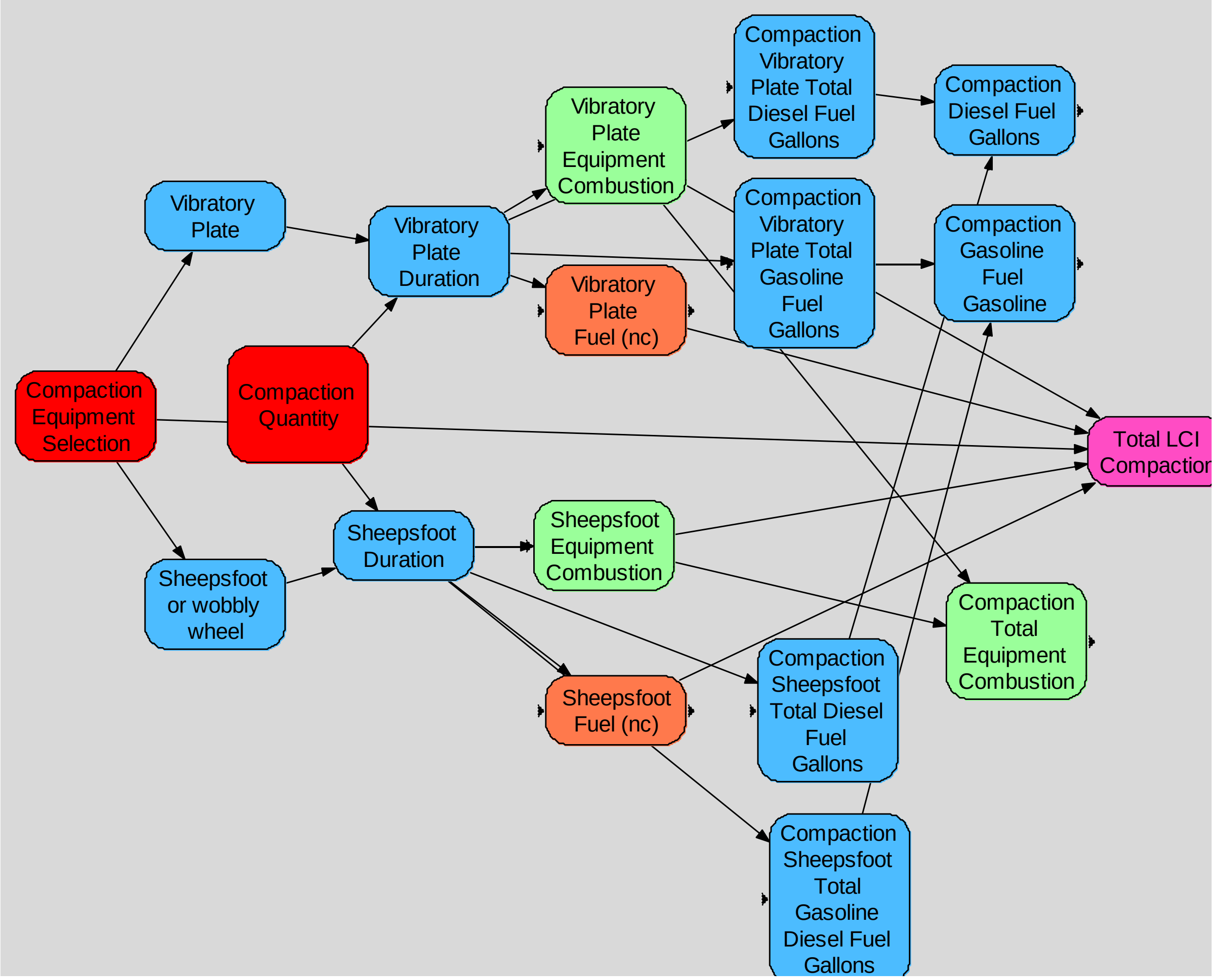


Figure 110. Compaction - Detailed Model

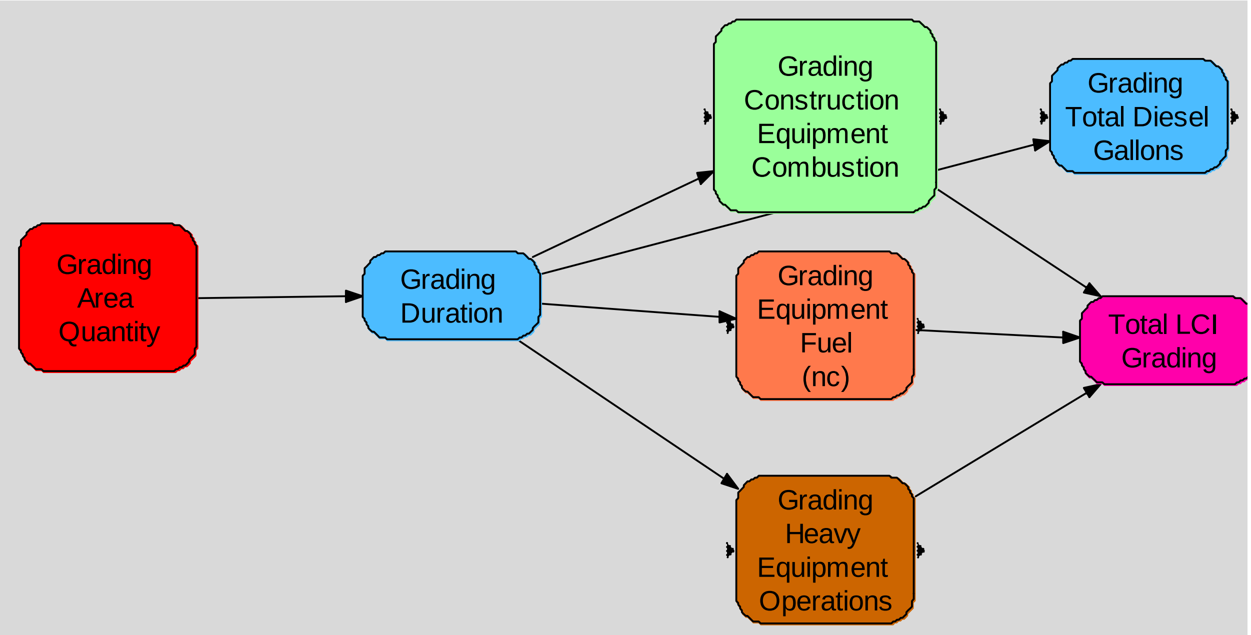


Figure 111. Grading - Detailed Model

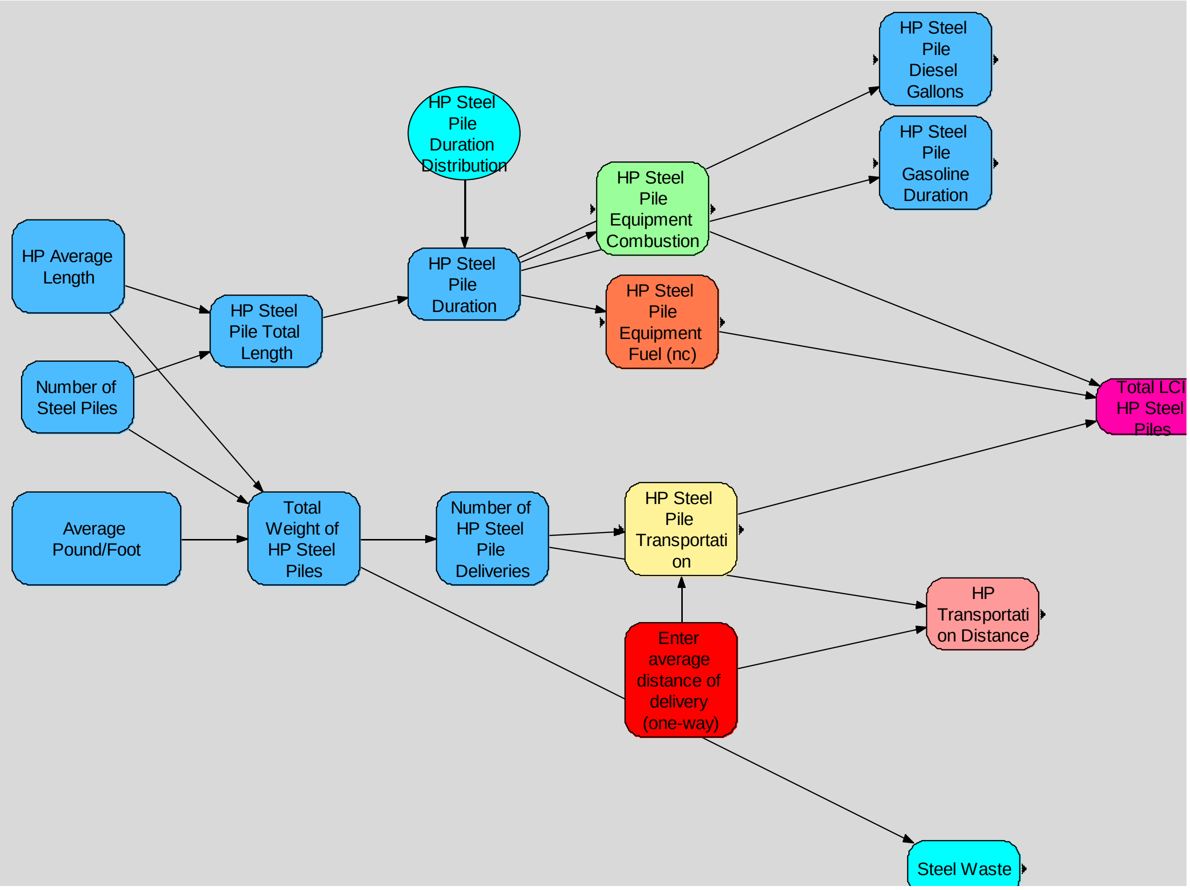


Figure 112. Driven Steel Piles – Detailed Model

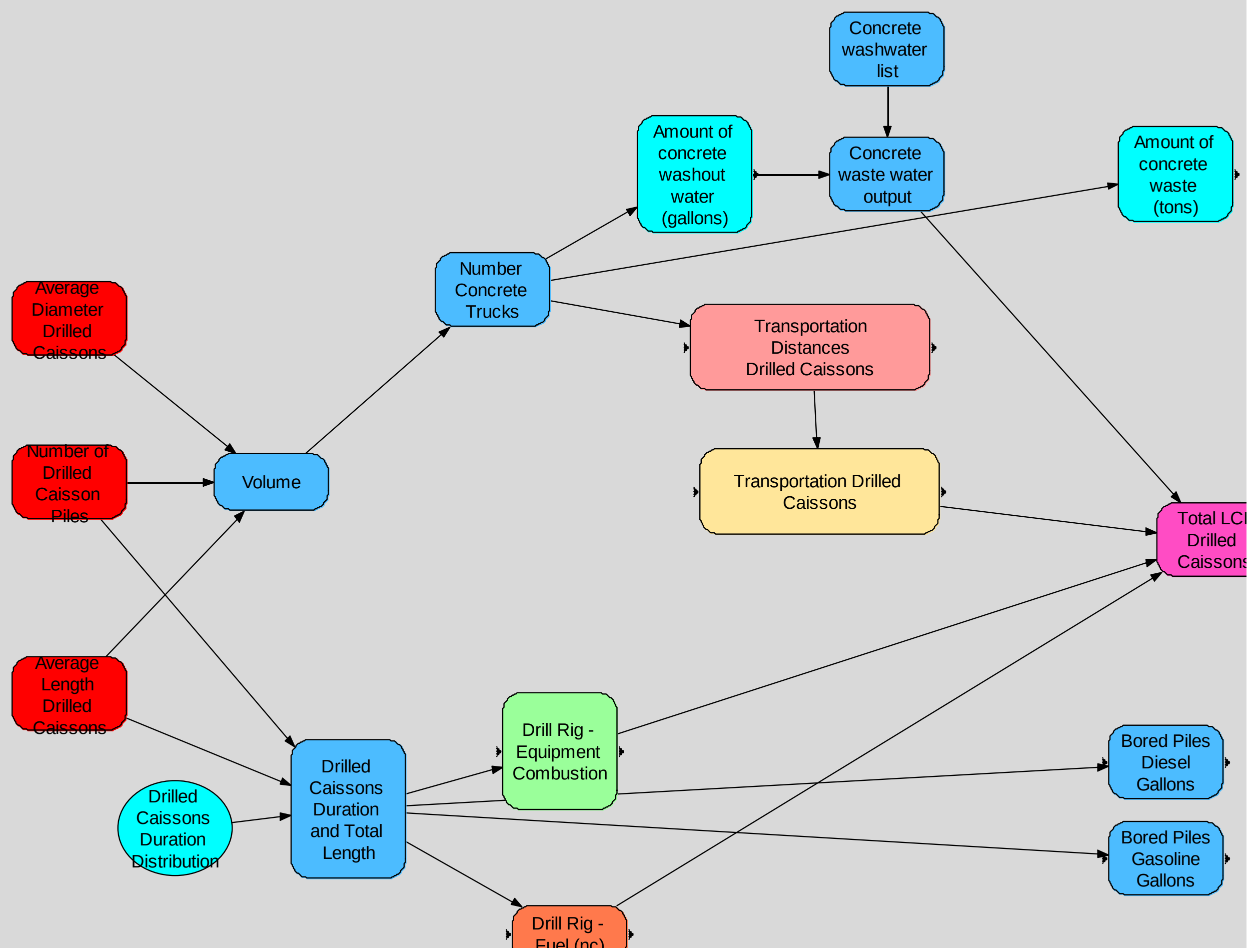


Figure 113. Bored Piles, Drilled Caissons – Detailed Model

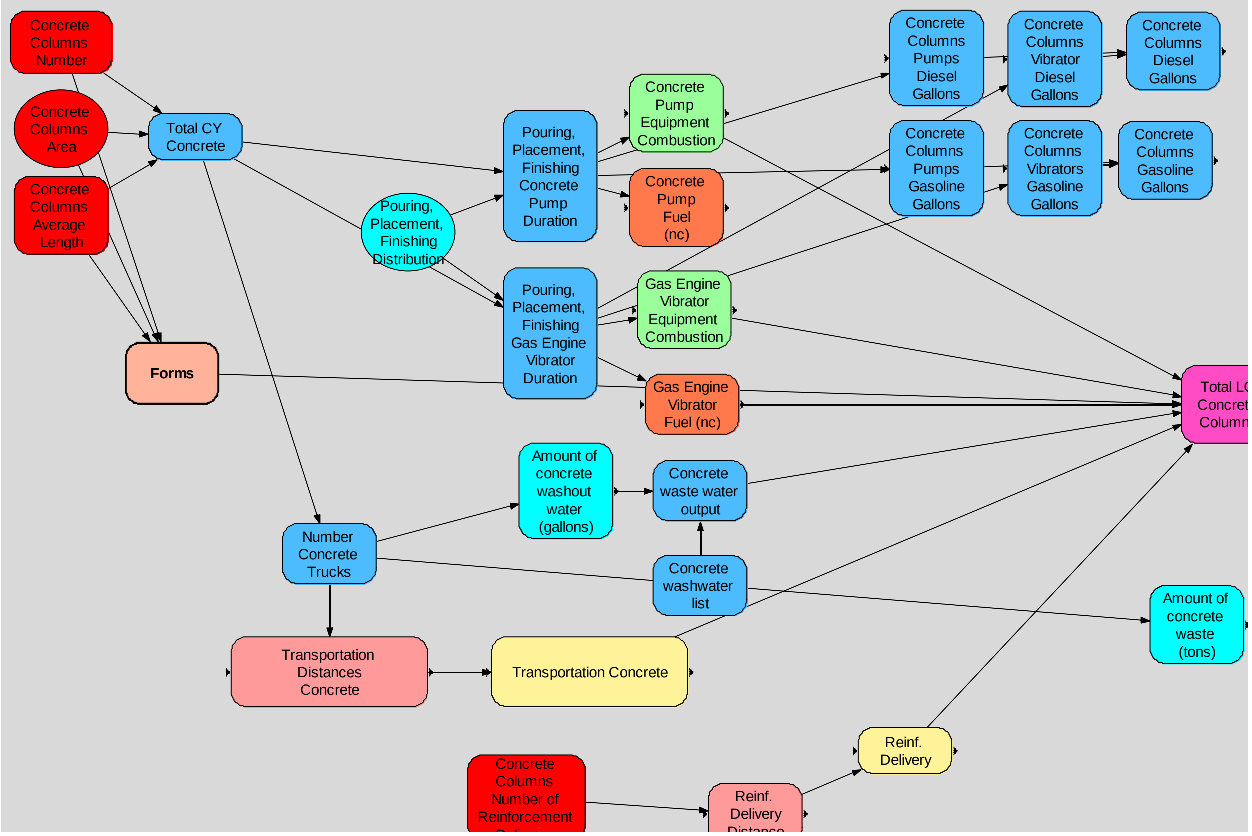


Figure 114. Concrete Columns – Detailed Model

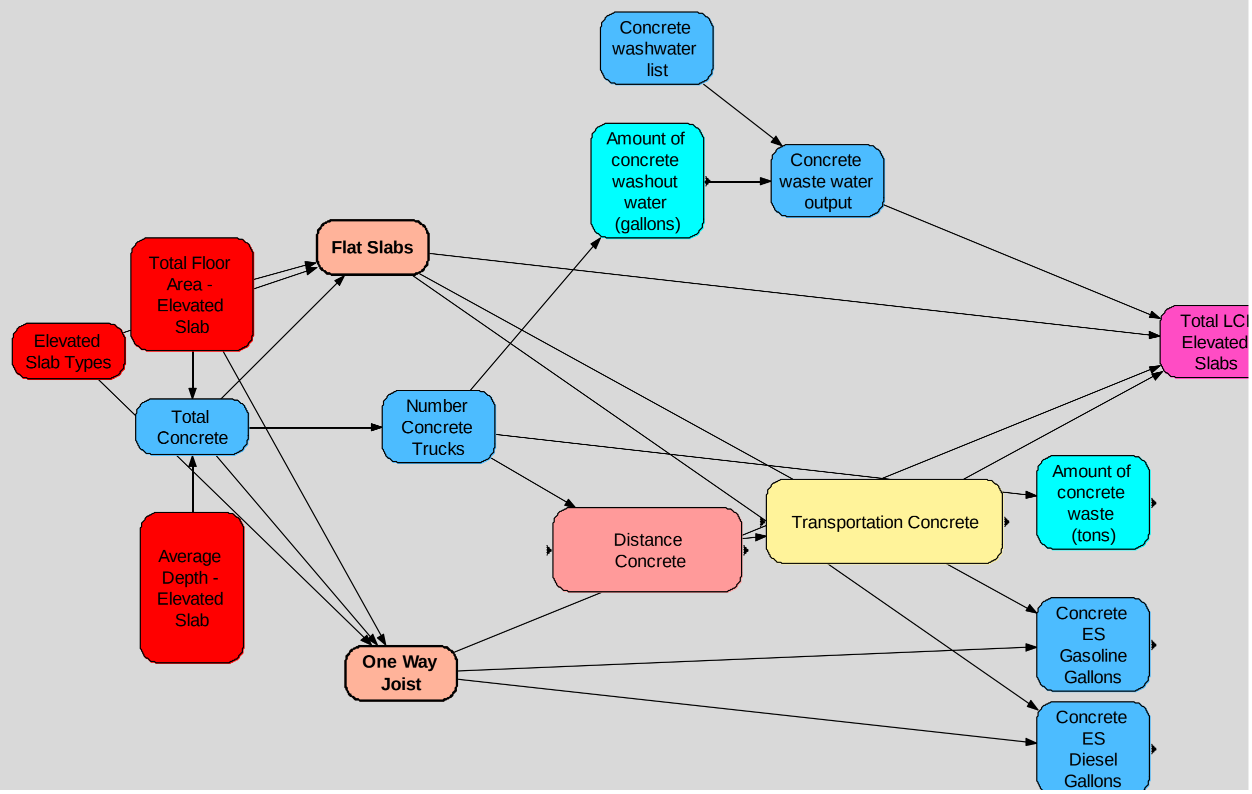


Figure 115. Elevated Slabs - Detailed Model

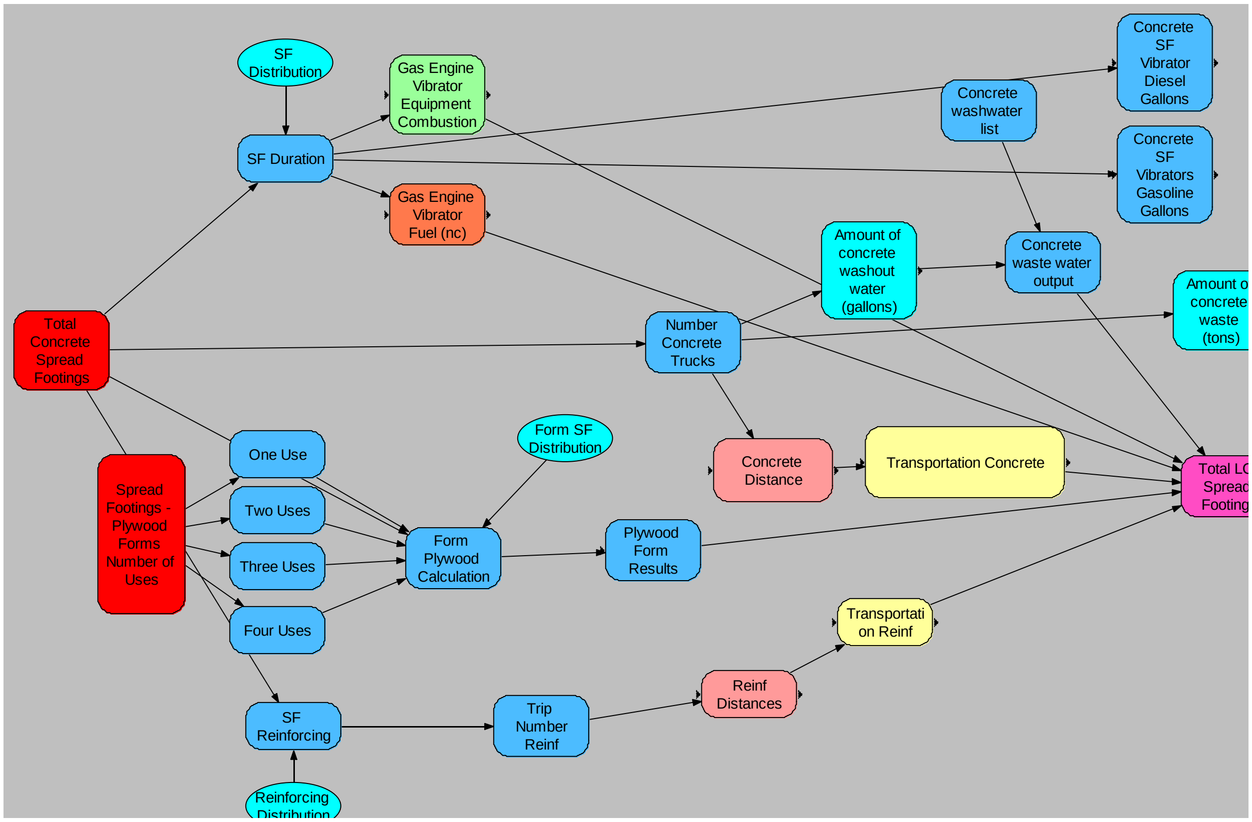


Figure 116. Spread Footings - Detailed Model

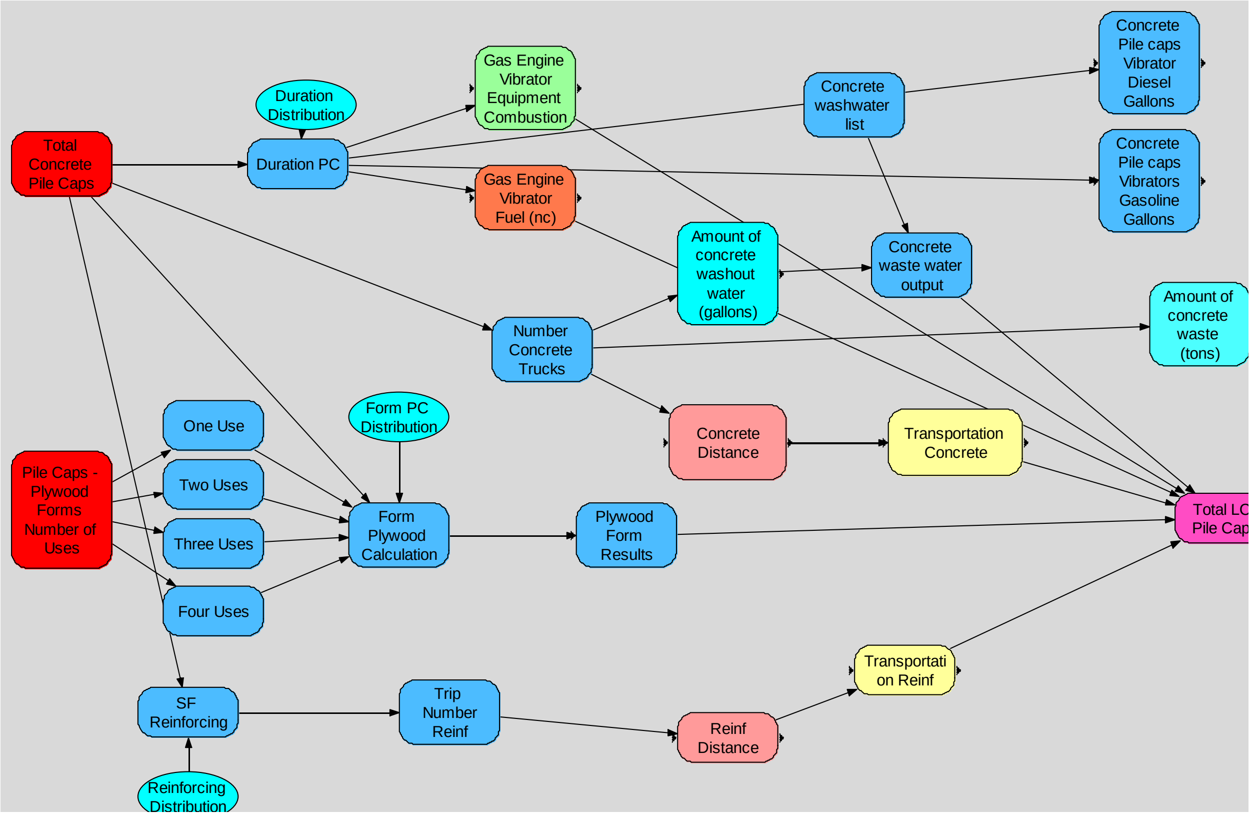


Figure 117. Pile Caps - Detailed Model

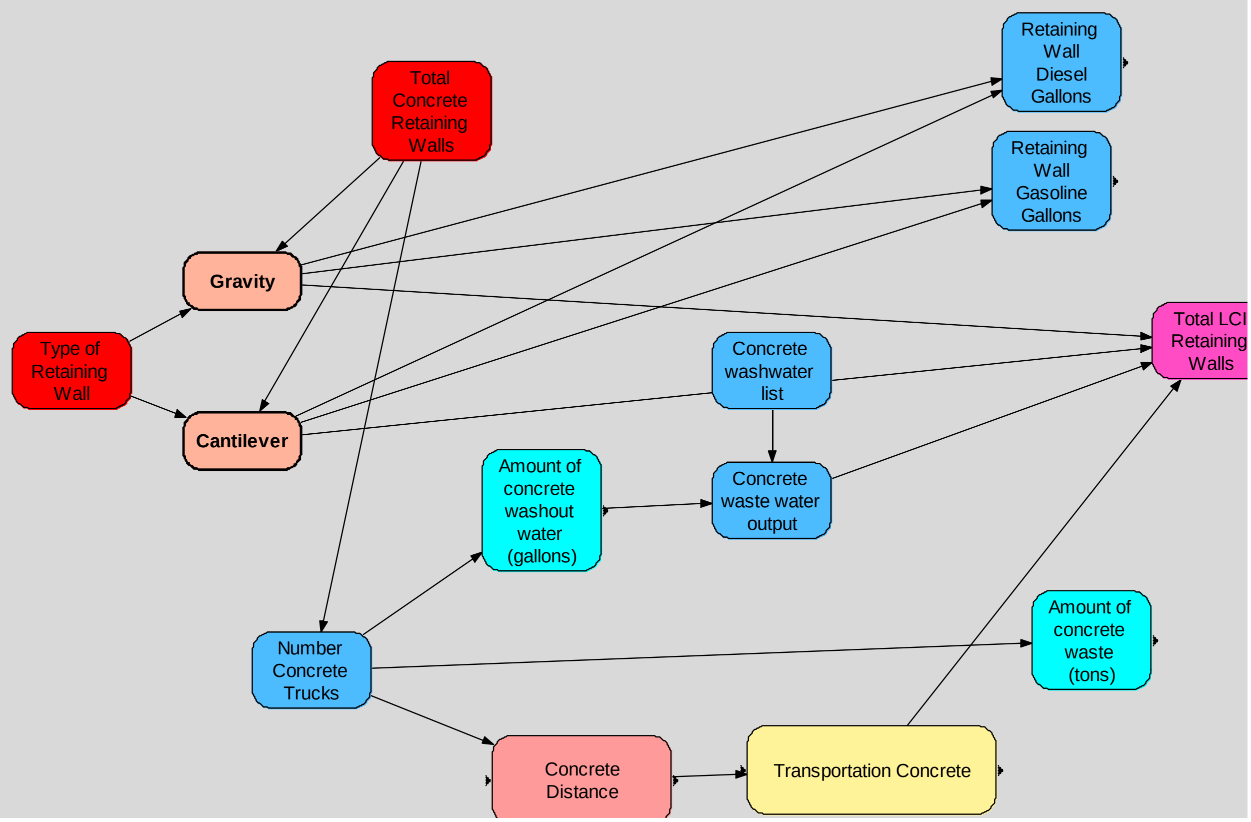


Figure 118. Retaining Wall - Detailed Model

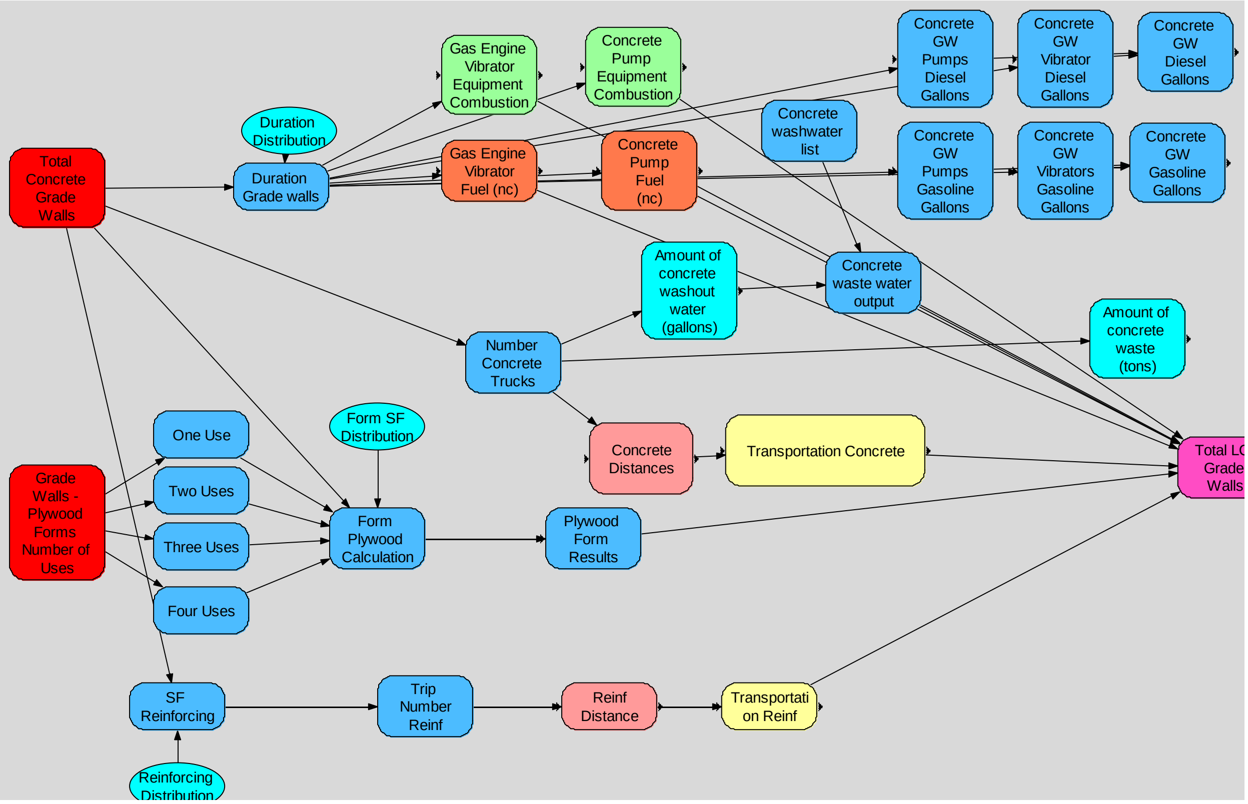


Figure 119. Grade Walls - Detailed Model

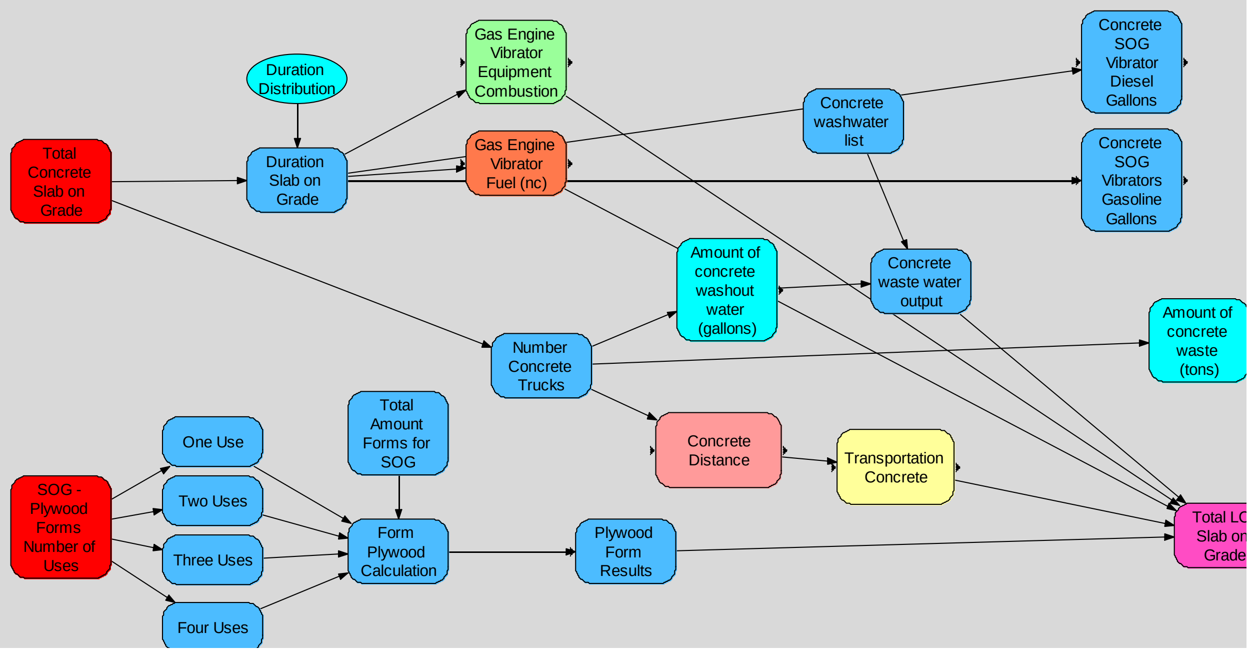


Figure 120. Slab on Grade - Detailed Model

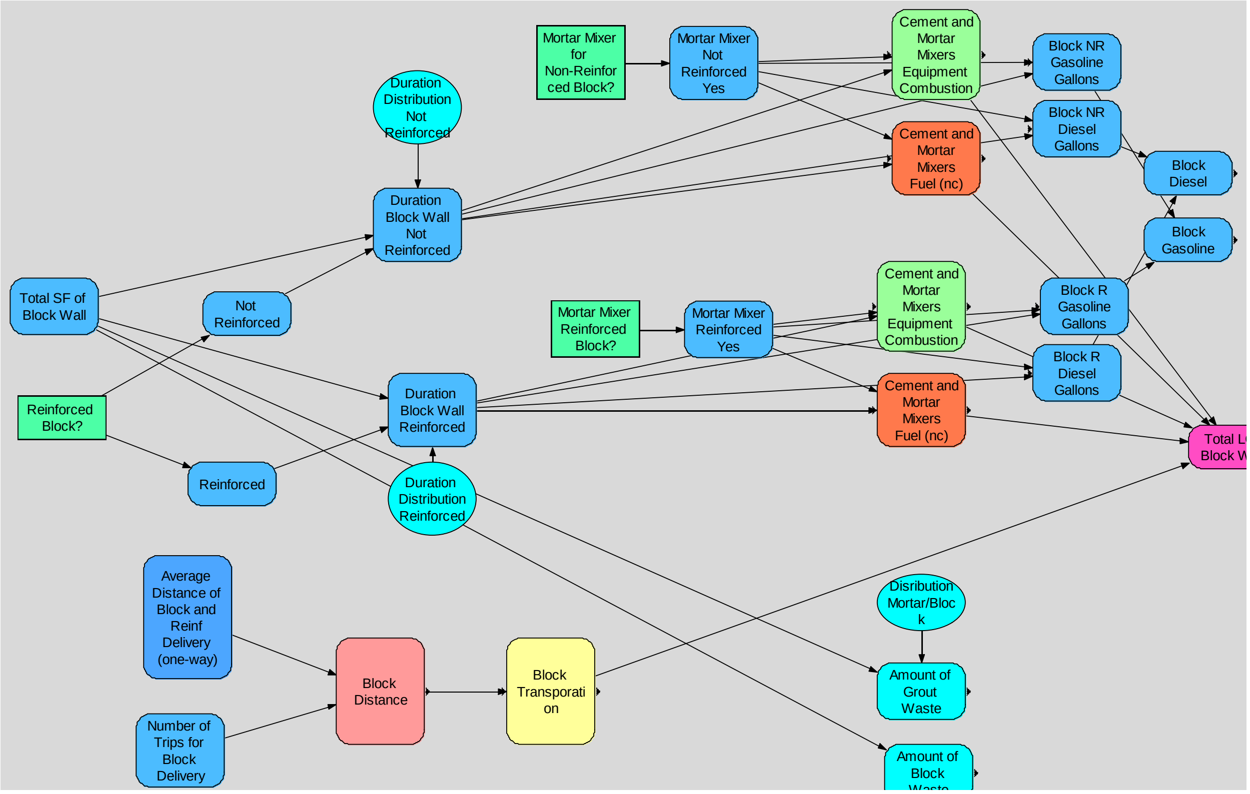


Figure 121. Block - Detailed Model

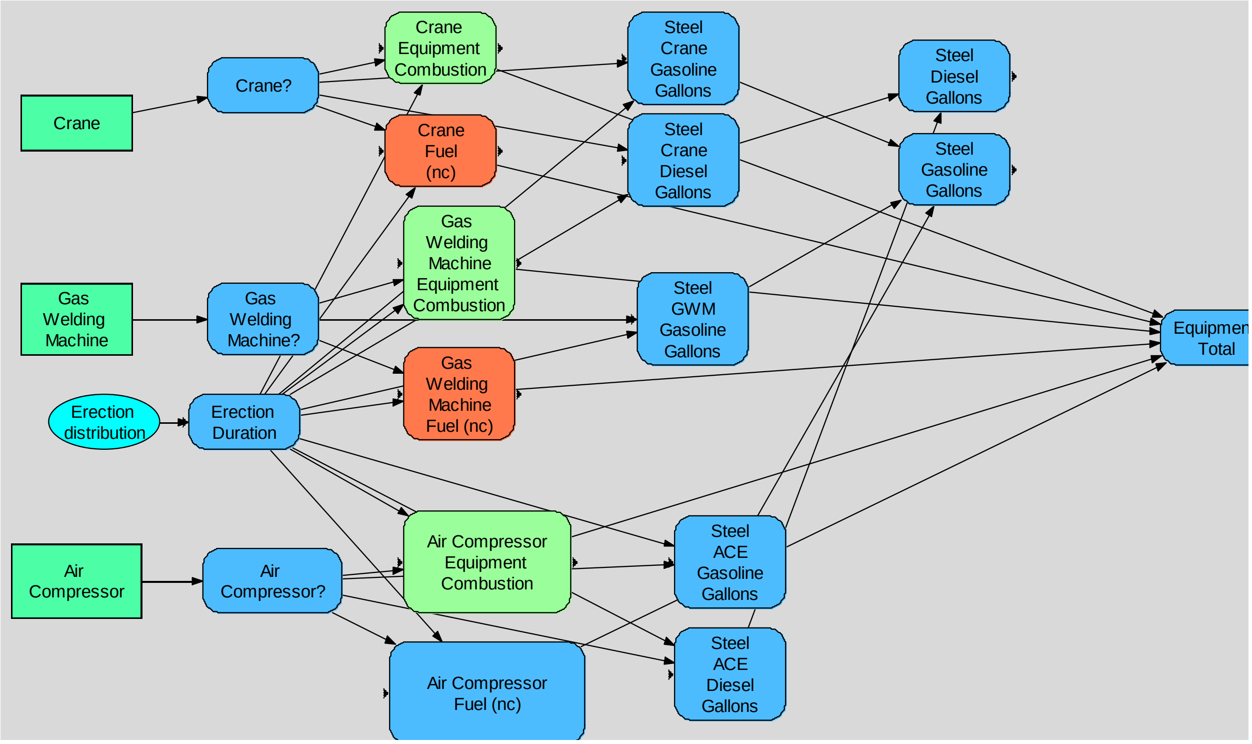


Figure 122. Steel Equipment - Detailed Model

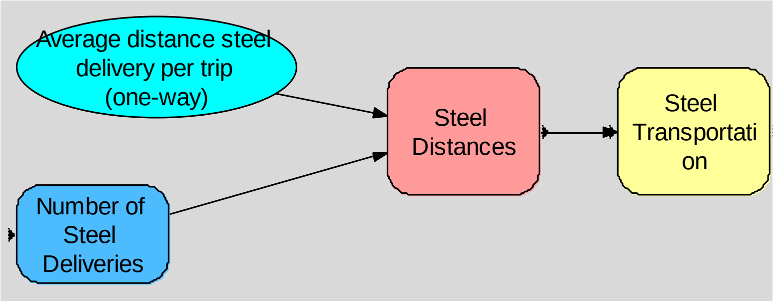


Figure 123. Steel Transportation - Detailed Model

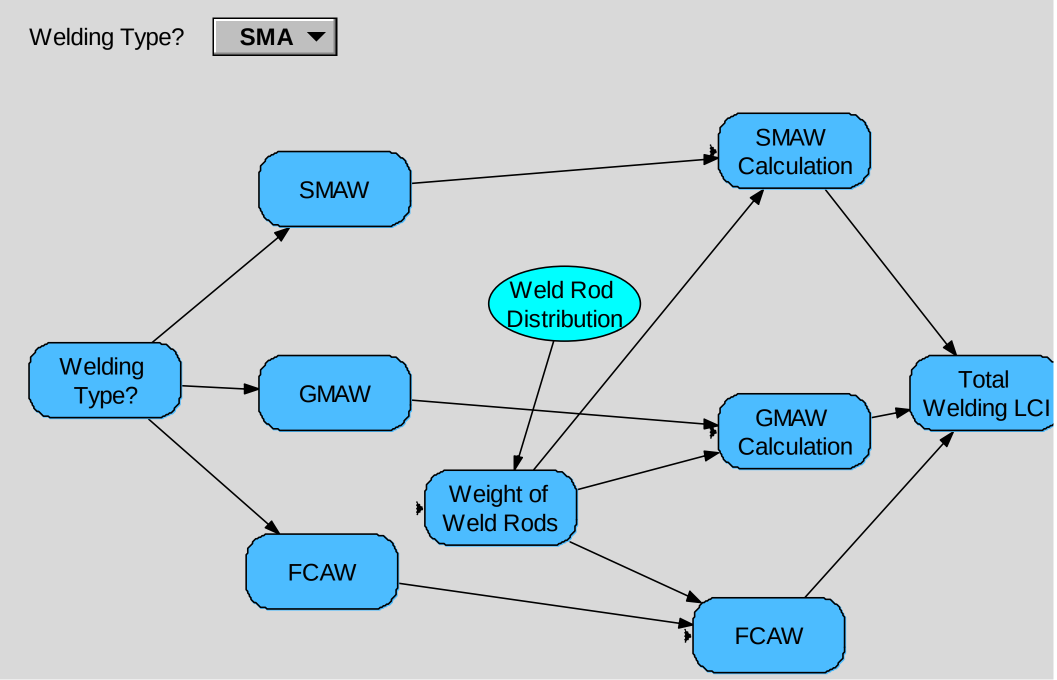


Figure 124. Steel Welding – Detailed Model

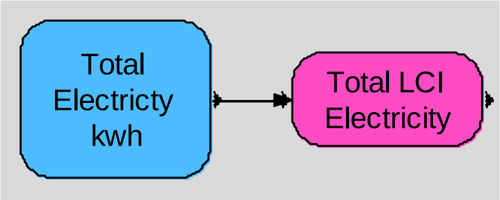


Figure 125. On-Site Electricity - Detailed Model

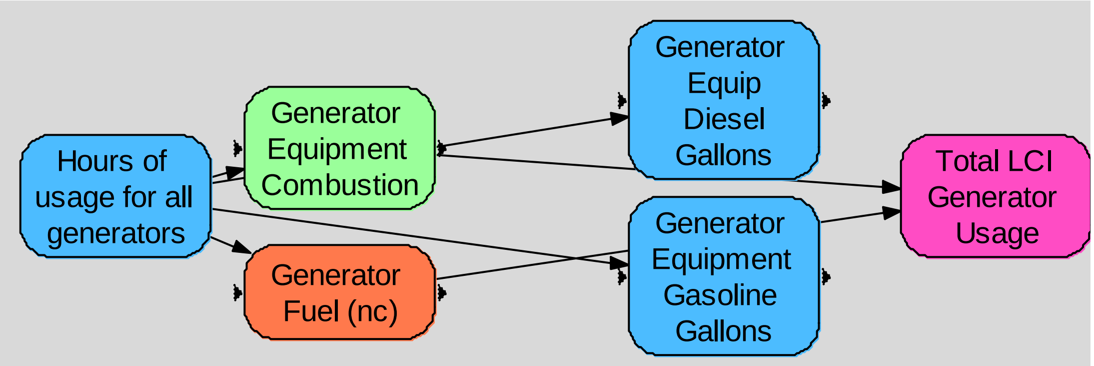
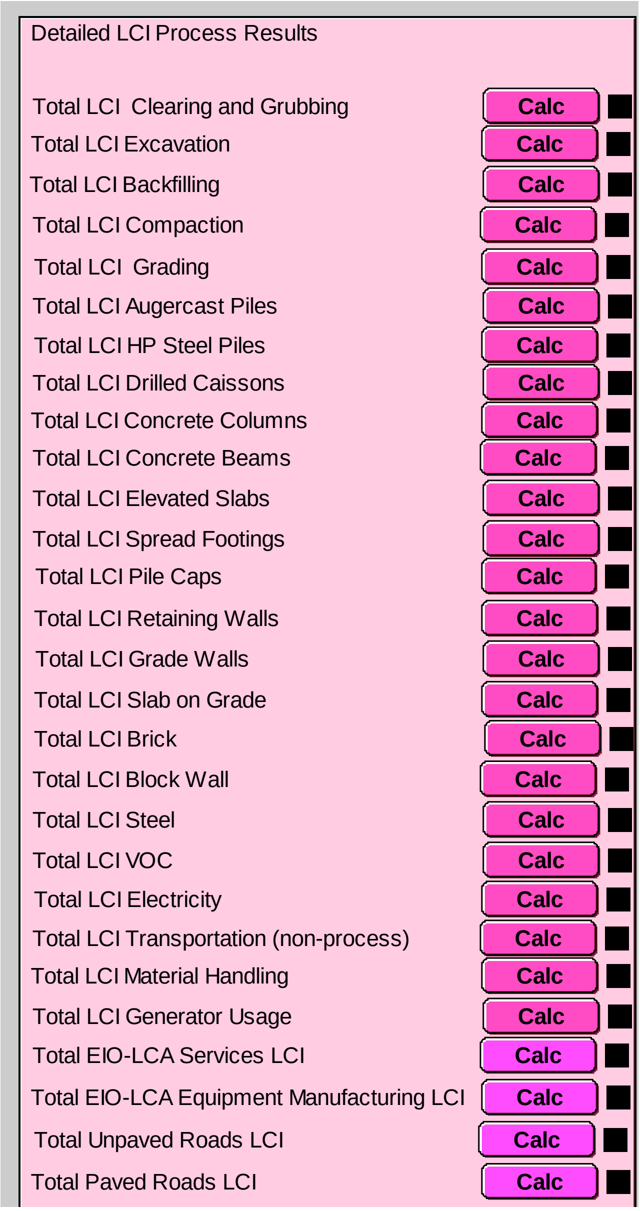


Figure 126. Generator - Detailed Model

Figure 127. Total LCI – Results



Detailed LCI Process Results

Total LCI Clearing and Grubbing	Calc	■
Total LCI Excavation	Calc	■
Total LCI Backfilling	Calc	■
Total LCI Compaction	Calc	■
Total LCI Grading	Calc	■
Total LCI Augercast Piles	Calc	■
Total LCI HP Steel Piles	Calc	■
Total LCI Drilled Caissons	Calc	■
Total LCI Concrete Columns	Calc	■
Total LCI Concrete Beams	Calc	■
Total LCI Elevated Slabs	Calc	■
Total LCI Spread Footings	Calc	■
Total LCI Pile Caps	Calc	■
Total LCI Retaining Walls	Calc	■
Total LCI Grade Walls	Calc	■
Total LCI Slab on Grade	Calc	■
Total LCI Brick	Calc	■
Total LCI Block Wall	Calc	■
Total LCI Steel	Calc	■
Total LCI VOC	Calc	■
Total LCI Electricity	Calc	■
Total LCI Transportation (non-process)	Calc	■
Total LCI Material Handling	Calc	■
Total LCI Generator Usage	Calc	■
Total EIO-LCA Services LCI	Calc	■
Total EIO-LCA Equipment Manufacturing LCI	Calc	■
Total Unpaved Roads LCI	Calc	■
Total Paved Roads LCI	Calc	■

Figure 128. Detailed LCI Construction Process - Results

APPENDIX D. R.S. MEANS DETAILED MODEL INFORMATION

R.S. MEANS DETAILED MODEL INFORMATION

Table 27. Excavation, Hydraulic Excavator, Duration Distribution Information

Excavation	Labor Hours/cy	Min	Median	Max
RS Means 02315-424-1800 through 1850 Page 37 Excavating, Bulk Bank Measure Hydraulic Excavator	0.067	0.044	0.0555	0.067
	0.044			

Table 28. Driven Steel Piles, Duration Distribution Information

Steel Piles - H Sections	Depth (in)	Pounds/ft	Labor Hours/VLF	Min	Median	Max
RS Means 02455-600-0250 through 1400 Page 45 Steel Piles, H Sections 50' Long	10	42	0.105	0.105	0.1135	0.125
	10	57	0.105			
	12	53	0.108			
	12	74	0.108			
	14	73	0.119			
	14	89	0.119			
	14	102	0.125			
	14	117	0.125			

Table 29. Bored Piles – Drilled Caissons, Duration Distribution Information

Bored Piles - Drilled Caissons	Diameter (in)	Labor Hours/VLF	Min	Median	Max
RS Means 02465-800-0010 Bored Piles Open style, machine drilled, to 50' deep, in stable ground, no casing or ground water 18" to 84" diameter	18	0.24	0.24	0.432	0.64
	24	0.253			
	30	0.32			
	36	0.384			
	48	0.48			
	60	0.5333			
	72	0.6			
	84	0.64			

Table 30. Concrete Column – Plywood with Wood Frame Form Information

Concrete Column - Forms - Plywood with Wood Frame					
RS Means 03310-410-5000 through 7150 Page 85 Forms in Place, Columns					
Size	Area	Use	LH	Material Cost ($/SFCA)	Percentage for reuse
8	64	1	0.194	2.18	
8	64	2	0.164	1.25	57%
8	64	3	0.152	0.87	40%
8	64	4	0.149	0.72	33%
12	144	1	0.178	2.19	
12	144	2	0.152	1.2	55%
12	144	3	0.145	0.87	40%
12	144	4	0.142	0.71	32%
16	256	1	0.173	2.23	
16	256	2	0.149	1.17	52%
16	256	3	0.139	0.89	40%
16	256	4	0.136	0.73	33%
24	576	1	0.168	2.54	
24	576	2	0.148	1.4	55%
24	576	3	0.139	1.02	40%
24	576	4	0.134	0.83	33%
36	1296	1	0.16	2.26	
36	1296	2	0.139	1.27	56%
36	1296	3	0.131	0.9	40%
36	1296	4	0.128	0.74	33%
			SFCA Average	2.28	
				Two Use Average	0.55
				Three Use Average	0.40
				Four Use Average	0.33

Table 31. Concrete Column – Plywood with Steel Frame Form Information

Concrete Column - Forms - Plywood with Steel Frame				
RS Means 03310-410-7500 through 7755 Pages 85 to 86 Forms in Place, Columns				
Size (Square Inch)	Material Cost ($/SFCA)	Min	Median	Max
8	3.26	$1.38	$2.45	$3.41
10	2.45			
12	3.11			
16	3.41			
20	1.64			
24	1.54			
30	1.38			
Average ($/SFCA)	2.40			

Table 32. Concrete Columns – Round Steel Form Information

Concrete Column - Forms - Round Steel				
RS Means 03310-410-3000 through 3350 Page 85 Forms in Place, Columns				
Size (Square Inch)	Material Cost ($/lf)	Min	Median	Max
12	10.45	10.45	15.2	32
16	11.75			
20	12.9			
24	14.15			
30	16.25			
36	17.4			
48	24			
60	32			
Average ($/lf)	17.3625			

Table 33. Concrete Columns - Round Fiberglass Form Information

Concrete Column - Forms - Round Fiberglass				
RS Means 03310-410-0500 through 0850 Page 85 Forms in Place, Columns				
Size (Square Inch)	Material Cost ($/lf)	Min	Median	Max
12	6.4	6.4	10.6	16.45
16	7.65			
18	8.5			
24	10.6			
28	11.8			
30	12.35			
36	16.45			
Average ($/lf)	10.54			

Table 34. Concrete Columns - Round Fibertube Form Information

Concrete Column - Forms - Round Fibertube				
RS Means 03310-410-1500 through 2000 Page 85 Forms in Place, Columns				
Size (Square Inch)	Material Cost ($/lf)	Min	Median	Max
8	1.51	1.51	5.65	40
10	1.94			
12	2.32			
14	3.03			
16	3.54			
20	5.65			
24	7.3			
30	10.4			
36	13.15			
42	31.5			
48	40			
Average ($/lf)	10.94			

Table 35. Concrete Beams – Form and Reinforcing Information

Concrete Beams - Forms and Reinforcing				
RS Means 033105-10 Structural Concrete, Proportionate Quantities Page 625 Beams				
		Forms (sf/ft)	Reinforcing (lb)	Reinforcing (lb/ft)
Spans (ft)	Forms (sf)	(sf/ft)	(lb)	(lb/ft)
16	130	8.13	165	10.31
20	110	5.50	170	8.50
16	90	5.63	170	10.63
30	85	2.83	175	5.83
10	90	9.00	170	17.00
16	85	5.31	180	11.25
20	75	3.75	185	9.25
16	65	4.06	215	13.44
30	60	2.00	200	6.67
10	85	8.50	175	17.50
16	75	4.69	180	11.25
20	62	3.10	200	10.00
16	62	3.88	215	13.44
10	75	7.50	185	18.50
16	65	4.06	225	14.06
20	51	2.55	200	10.00
	Average	5.03	188.13	11.73
	Min	2	165	5.83
	Median	4.38	182.50	10.94
	Max	9	225	18.5

Table 36. Concrete Beams - Material Cost and Form Use Information

Concrete Beams - Forms

RS Means 01310-405-0500 through 2500
Page 84
Form in Place, Beams and Girders

	Size, Width (in)	Area (in2)	Use	Labor Hours	Material Cost ($/SFCA)	Percentage for reuse
Exterior Spandrels	12	144	1	0.213	3.76	
	12	144	2	0.175	1.99	53%
	12	144	3	0.163	1.5	40%
	12	144	4	0.155	1.22	32%
	18	324	1	0.192	3.22	
	18	324	2	0.175	1.77	55%
	18	324	3	0.157	1.29	40%
	18	324	4	0.152	1.05	33%
	24	576	1	0.181	2.95	
	24	576	2	0.166	1.66	56%
	24	576	3	0.152	1.18	40%
	24	576	4	0.148	0.96	33%
Interior Beam	12	144	1	0.16	4.1	
	12	144	2	0.141	2.03	50%
	12	144	3	0.132	1.64	40%
	12	144	4	0.127	1.33	32%
	24	576	1	0.15	3.01	
	24	576	2	0.132	1.69	56%
	24	576	3	0.125	1.2	40%
	24	576	4	0.122	0.97	32%
				Min	0.96	
				Median	1.65	
				Max	4.10	
					Two Use Average	0.54
					Three Use Average	0.40
					Four Use Average	0.32
					Total Average	0.42

Table 37. Concrete Beams – Installation Information

Concrete Beams	
RS Means 03310-240-0300 through 0350 Page 102 Concrete in Place Beams	
Loading/Span Length	Labor Hours
5 kip/lf, 10' Span	12.804
5 kip/lf, 25' Span	10.782
Average	11.793

Table 38. Concrete Elevated Slabs - Form and Reinforcing Information

Concrete Elevated Slabs - Forms and Reinforcing						
RS Means 033105-10 Structural Concrete, Proportionate Quantities Page 623 Flat Slab						
Live load (psf)	Span (lf)	SF Forms/SF Floor Area	LB Rebar/SF Floor Area	Min	Median	Max
50	20	1.03	2.34	2.34	3.88	5.3
	25	1.03	2.99			
	30	1.03	4.09			
100	20	1.03	2.83			
	25	1.03	3.88			
	30	1.03	4.66			
200	20	1.03	3.03			
	25	1.03	4.23			
	30	1.03	5.3			
		Average LB Rebar/SF Floor Area	3.71			

Table 39. One-Way Joists – Form and Reinforcing Information

Concrete One Way Joists - Form and Reinforcing				
RS Means 033105-10 Structural Concrete, Proportionate Quantities Page 623 One way Joist				
LL (psf)	Span (lf)	SF Forms/SF Floor Area	LB Rebar/SF Floor Area	SF Pans/SF Floor Area
50	20	1.04	1.4	0.93
	25	1.05	1.8	0.94
	30	1.05	2.6	0.94
100	20	1.07	1.9	0.93
	25	1.08	2.4	0.94
	30	1.07	3.5	0.94
	Average	1.06	2.3	0.94
	Percentages	0.53	-	0.47
	Min	-	1.4	-
	Median	-	2.15	-
	Max	-	3.5	-

Table 40. Spread Footing – Form and Reinforcing Information

Spread Footings			
RS Means 033105-10 Structural Concrete, Proportionate Quantities Spread Footings Page 625			
Size (CY)	Type (psf soil)	SF Forms/CY	Reinforcing/CY
<1	1000	24	44
	5000	24	42
	10000	24	52
1 to 5	1000	14	49
	5000	14	50
	10000	14	50
>5	1000	9	54
	5000	9	52
	10000	9	56
	Min	9	42
	Median	14	50
	Max	24	56

Table 41. Spread Footing – Form Information

Spread Footings - Forms		
RS Means 03110-430-5000 through 5150 Page 87 Forms in place, Footings		
Uses	$/SFCA	Percentage (%)
1	1.83	
2	1.01	55%
3	0.73	40%
4	0.59	32%

Table 42. Pile Caps – Form and Reinforcing Information

Pile Caps			
RS Means 033105-10 Structural Concrete, Proportionate Quantities Pile Caps Page 625 Assume 30 Ton Concrete Piles			
Size (CY)	Cap Type	SF Forms/CY	Reinforcing/CY
<5	Shallow	20	65
	Medium	20	50
	Deep	20	40
5 to 10	Shallow	14	55
	Medium	15	45
	Deep	15	40
10 to 20	Shallow	11	60
	Medium	11	45
	Deep	12	35
>20	Shallow	9	60
	Medium	9	45
	Deep	10	40
	Min	9	35
	Median	13	45
	Max	20	65

Table 43. Pile Caps – Form Information

Pile Caps - Forms in Place		
RS Means 03100-430-3000 Page 87 Forms in Place, Footings Pile Cap, sq. or rect, job-built plywook, 1 use		
Uses	$/SFCA	Percentage (%)
1	2.45	-
2	1.35	55%
3	0.98	40%
4	0.8	33%

Table 44. Cantilever Retaining Walls – Form and Reinforcing Information

Cantilever Retaining Walls				
RS Means 033105-10 Structural Concrete, Proportionate Quantities Retaining Walls Page 625				
Type	Loading	CY/LF	Forms/CY	Reinforcing/CY
Cantilever	Level Backfill	0.2	49	35
		0.5	42	45
		0.8	35	70
		1.1	32	85
		1.6	28	105
	Min	0.2	28	35
	Median	0.8	35	70
	Max	1.6	49	105

Table 45. Gravity Retaining Walls - Form Information

Gravity Retaining Walls			
RS Means 033105-10 Structural Concrete, Proportionate Quantities Retaining Walls Page 625			
Type	Loading	CY/LF	Forms/CY
Gravity, with Vertical Face	Level Backfill	0.4	37
		0.6	27
		1.2	20
Gravity, with Vertical Face	Sloping Backfill	0.3	31
		0.8	21
		1.6	15
	Min	0.3	15
	Median	0.7	24
	Max	1.6	37

Table 46. Retaining Walls - Form Information

Retaining Walls		
RS Means 03110-455-4600 to 4750 Page 89 Retaining Walls, battered, job-built plywood, to 8' high		
Uses	$/SFCA	Percentages (%)
1	1.81	
2	1	55%
3	0.72	40%
4	0.54	30%

Table 47. Grade Walls - Duration Information

Grade Walls	
RS Means 03310-240-4200 to 4500 Page 103 Concrete in Place, Grade Walls	
	LH
8" Thick, 8' High	4.364
8" Thick, 14' High	7.337
12" Thick, 8' High	3.109
12" Thick, 14' High	4.999
15" Thick, 8' High	2.499
15" Thick, 12' High	3.902
15" Thick, 18' High	4.094
Min	2.499
Median	4.094
Max	7.337

Table 48. Grade Wall - Form Information

Grade Wall, below grade, job-built plywood			
RS Means 03110-455-2000 to 2850 Page 89 Wall, below grade and exterior Varying widths and heights			
Interior Wall	Uses	$/SFCA	Percentages (%)
To 8' high	1	2.47	
	2	1.57	64%
	3	1.14	46%
	4	0.93	38%
8' to 16'	1	4.97	
	2	2	40%
	3	1.68	34%
	4	1.51	30%
Exterior Wall			
8' to 16'	1	2.17	
	2	1.19	55%
	3	0.85	39%
	4	0.7	32%
Over 16'	1	2.42	
	2	1.33	55%
	3	0.97	40%
	4	0.79	33%
	First Use Average ($/SFCA)	3.01	-
	Two Use Average (%)	-	53%
	Three Use Average (%)	-	40%
	Four Use Average (%)	-	33%
	Min	0.7	
	Median	1.42	
	Max	4.97	

Table 49. Slab on Grade - Form Information

Forms, Slab on Grade, Bulkhead forms w/keyway, wood, 6" high		
RS Means 03110-445-1000 to 1100 Page 88 Forms in Place, Slab on Grade Bulkhead forms w/keyway, wood, 6" high		
Uses	$/SFCA	Percentages (%)
1	0.97	
2	0.53	55%
3	0.425	44%
4	0.32	33%

Table 50. Brick - Productivity Information

Brick		
RS Means 04810-100-2000 to 2450 Page 120 Unit Masonry Assembly Standard brick, pattern varies		
Unit Masonry Assembly	Number Bricks/SF	LH
Standard, Red, 4" x 2-2/3" x 8", running bond	6.75	0.182
Full Header every 6th course	7.88	0.216
English, full header every second course	10.13	0.286
Flemish, alternate header every course	9	0.267
Flemish, alternate header every sixth course	7.13	0.195
Full headers throughout	13.5	0.381
Rowlock course	13.5	0.4
Rowlock stretcher	4.5	0.129
Soldier course	6.75	0.2
Sailor course	4.5	0.138
Min	4.5	0.129
Median	7.505	0.208
Max	13.5	0.4

Table 51. Block, Not Reinforced- Productivity Information

Concrete Block, Back-Up, Not Reinforced	
RS Means 04810-172- 0050 to 0450 Page 121 Concrete Block, Back up, Not Reinforced	
Thickness (in)	LH
2	0.084
4	0.087
6	0.091
8	0.1
10	0.121
12	0.155
Min	0.084
Median	0.0955
Max	0.155

Table 52. Block, Reinforced – Productivity Information

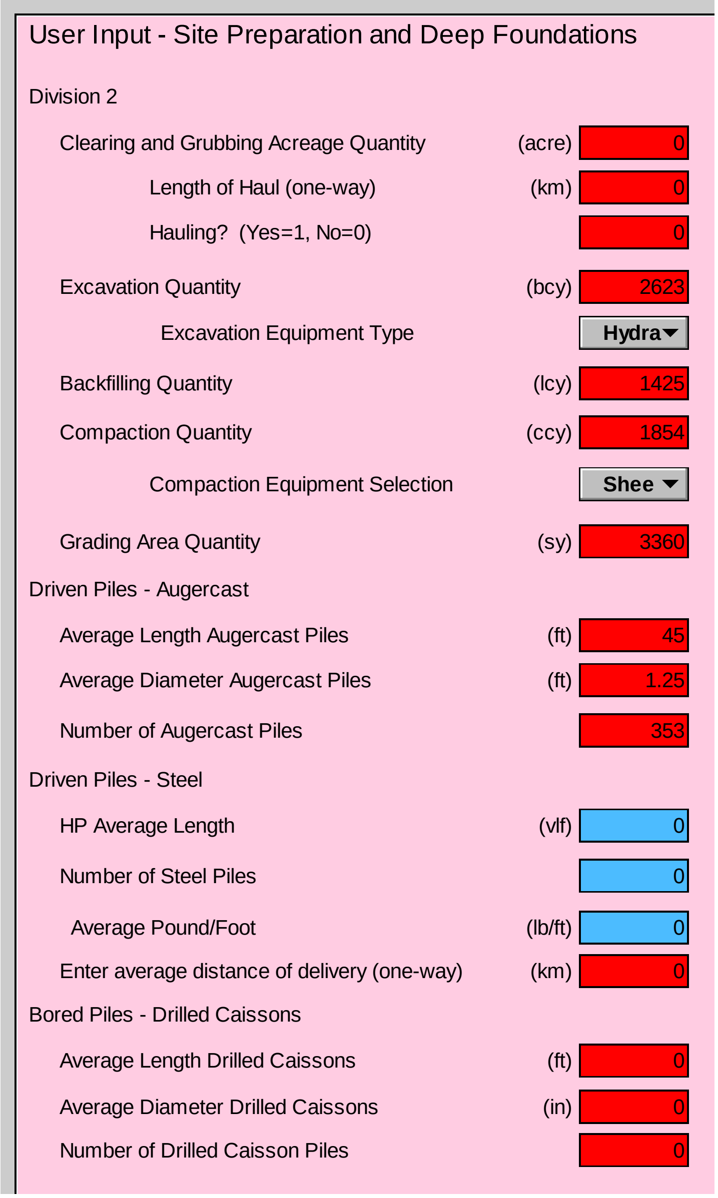
Concrete Block, Back-Up, Reinforced	
RS Means 04810-172-1000 to 1250 Page 121 Concrete Block, Back up, Reinforced	
Thickness (in)	LH
4	0.089
6	0.093
8	0.101
10	0.125
12	0.16
Min	0.089
Median	0.101
Max	0.16

Table 53. Brick and Block – Waste Information

Concrete Bricks and Blocks		
R.S. Means 042110-50 Page 634 Brick, Block, and Mortar Quantities		
Nominal Sizes (in)	Blocks/100 SF	Mortar/M Block, Waste Included Back Up
2	113	36
4	113	51
6	113	66
8	113	82
10	113	97
12	113	112
	Min	36
	Median	66
	Max	112

APPENDIX E. INPUT INFORMATION STEEL STRUCTURE CASE STUDY

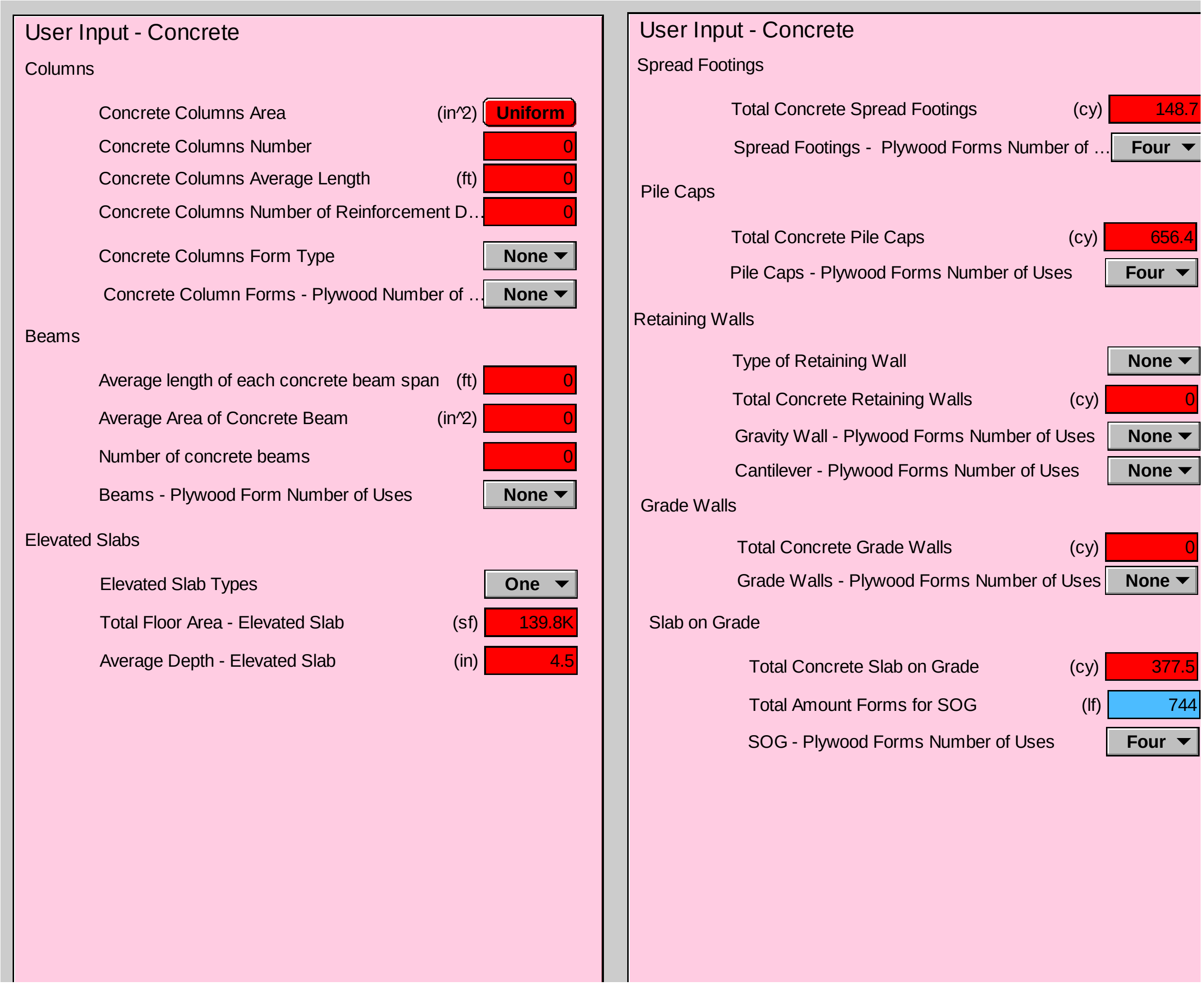
INPUT INFORMATION STEEL STRUCTURE CASE STUDY



User Input - Site Preparation and Deep Foundations

Division 2		
Clearing and Grubbing Acreage Quantity	(acre)	0
Length of Haul (one-way)	(km)	0
Hauling? (Yes=1, No=0)		0
Excavation Quantity	(bcy)	2623
Excavation Equipment Type		Hydra ▼
Backfilling Quantity	(lcy)	1425
Compaction Quantity	(ccy)	1854
Compaction Equipment Selection		Shee ▼
Grading Area Quantity	(sy)	3360
Driven Piles - Augercast		
Average Length Augercast Piles	(ft)	45
Average Diameter Augercast Piles	(ft)	1.25
Number of Augercast Piles		353
Driven Piles - Steel		
HP Average Length	(vlf)	0
Number of Steel Piles		0
Average Pound/Foot	(lb/ft)	0
Enter average distance of delivery (one-way)	(km)	0
Bored Piles - Drilled Caissons		
Average Length Drilled Caissons	(ft)	0
Average Diameter Drilled Caissons	(in)	0
Number of Drilled Caisson Piles		0

Figure 129. User Input –Site Preparation and Deep Foundations– Steel Structure



User Input - Concrete

Columns

Concrete Columns Area (in^2) Uniform
Concrete Columns Number 0
Concrete Columns Average Length (ft) 0
Concrete Columns Number of Reinforcement D… 0
Concrete Columns Form Type None
Concrete Column Forms - Plywood Number of … None

Beams

Average length of each concrete beam span (ft) 0
Average Area of Concrete Beam (in^2) 0
Number of concrete beams 0
Beams - Plywood Form Number of Uses None

Elevated Slabs

Elevated Slab Types One
Total Floor Area - Elevated Slab (sf) 139.8K
Average Depth - Elevated Slab (in) 4.5

User Input - Concrete

Spread Footings

Total Concrete Spread Footings (cy) 148.7
Spread Footings - Plywood Forms Number of … Four

Pile Caps

Total Concrete Pile Caps (cy) 656.4
Pile Caps - Plywood Forms Number of Uses Four

Retaining Walls

Type of Retaining Wall None
Total Concrete Retaining Walls (cy) 0
Gravity Wall - Plywood Forms Number of Uses None
Cantilever - Plywood Forms Number of Uses None

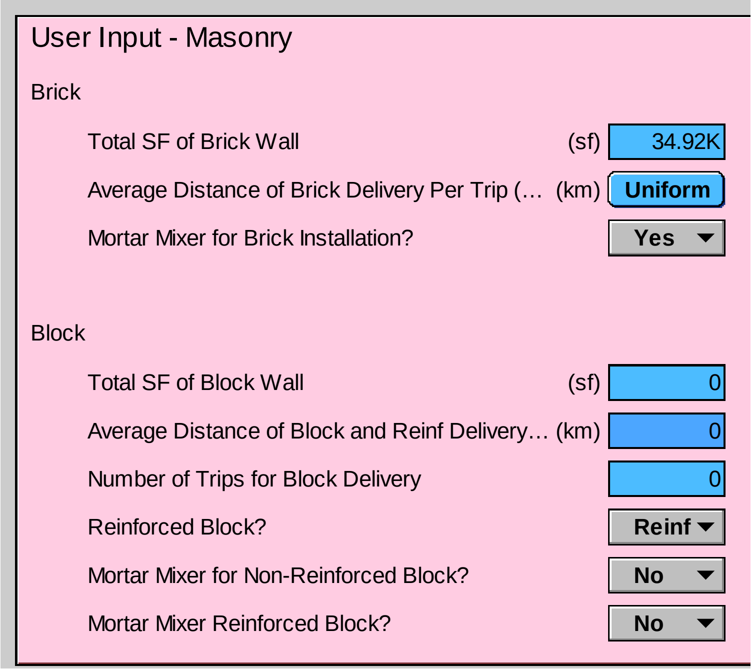
Grade Walls

Total Concrete Grade Walls (cy) 0
Grade Walls - Plywood Forms Number of Uses None

Slab on Grade

Total Concrete Slab on Grade (cy) 377.5
Total Amount Forms for SOG (lf) 744
SOG - Plywood Forms Number of Uses Four

Figure 130. User Input –Concrete– Steel Structure


User Input - Masonry

Brick

Total SF of Brick Wall (sf) 34.92K

Average Distance of Brick Delivery Per Trip (… (km) Uniform

Mortar Mixer for Brick Installation? Yes

Block

Total SF of Block Wall (sf) 0

Average Distance of Block and Reinf Delivery… (km) 0

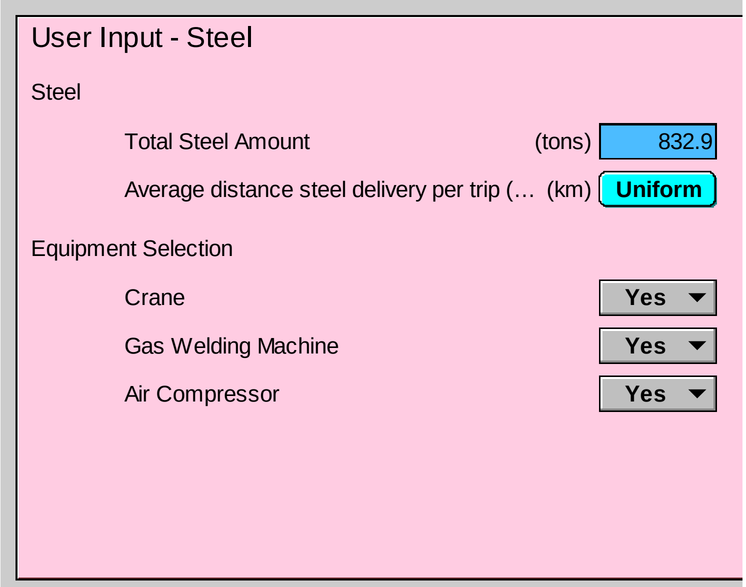
Number of Trips for Block Delivery 0

Reinforced Block? Reinf

Mortar Mixer for Non-Reinforced Block? No

Mortar Mixer Reinforced Block? No

Figure 131. User Input –Masonry– Steel Structure


User Input - Steel

Steel

Total Steel Amount (tons) 832.9

Average distance steel delivery per trip (… (km) Uniform

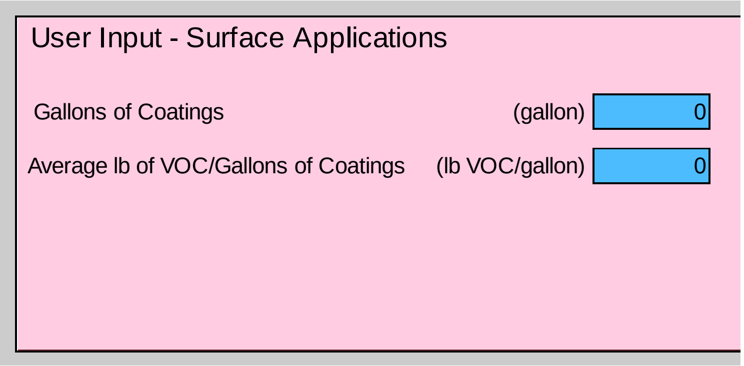
Equipment Selection

Crane Yes

Gas Welding Machine Yes

Air Compressor Yes

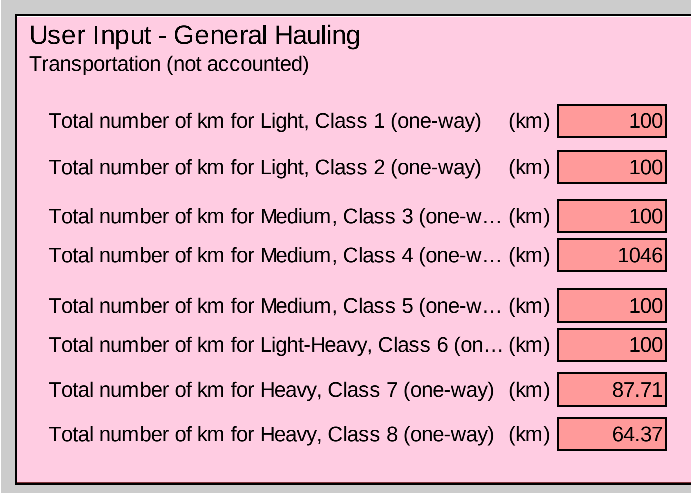
Figure 132. User Input –Steel– Steel Structure



User Input - Surface Applications

Gallons of Coatings	(gallon)	0
Average lb of VOC/Gallons of Coatings	(lb VOC/gallon)	0

Figure 133. User Input –Surface Applications– Steel Structure

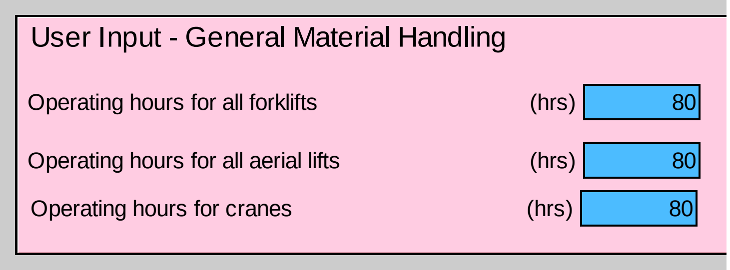


User Input - General Hauling

Transportation (not accounted)

Total number of km for Light, Class 1 (one-way)	(km)	100
Total number of km for Light, Class 2 (one-way)	(km)	100
Total number of km for Medium, Class 3 (one-w…	(km)	100
Total number of km for Medium, Class 4 (one-w…	(km)	1046
Total number of km for Medium, Class 5 (one-w…	(km)	100
Total number of km for Light-Heavy, Class 6 (on…	(km)	100
Total number of km for Heavy, Class 7 (one-way)	(km)	87.71
Total number of km for Heavy, Class 8 (one-way)	(km)	64.37

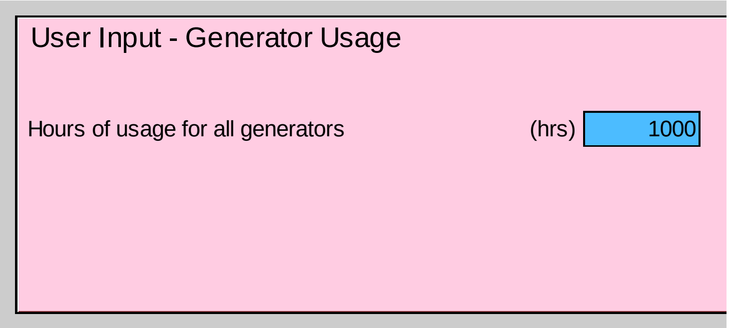
Figure 134. User Input –General Hauling– Steel Structure



User Input - General Material Handling

Operating hours for all forklifts	(hrs)	80
Operating hours for all aerial lifts	(hrs)	80
Operating hours for cranes	(hrs)	80

Figure 135. User Input –General Material Handling– Steel Structure



User Input - Generator Usage

Hours of usage for all generators (hrs) 1000

Figure 136. User Input –Generator Usage– Steel Structure

APPENDIX F. ADDITIONAL STEEL CASE STUDY RESULTS

ADDITIONAL STEEL CASE STUDY RESULTS

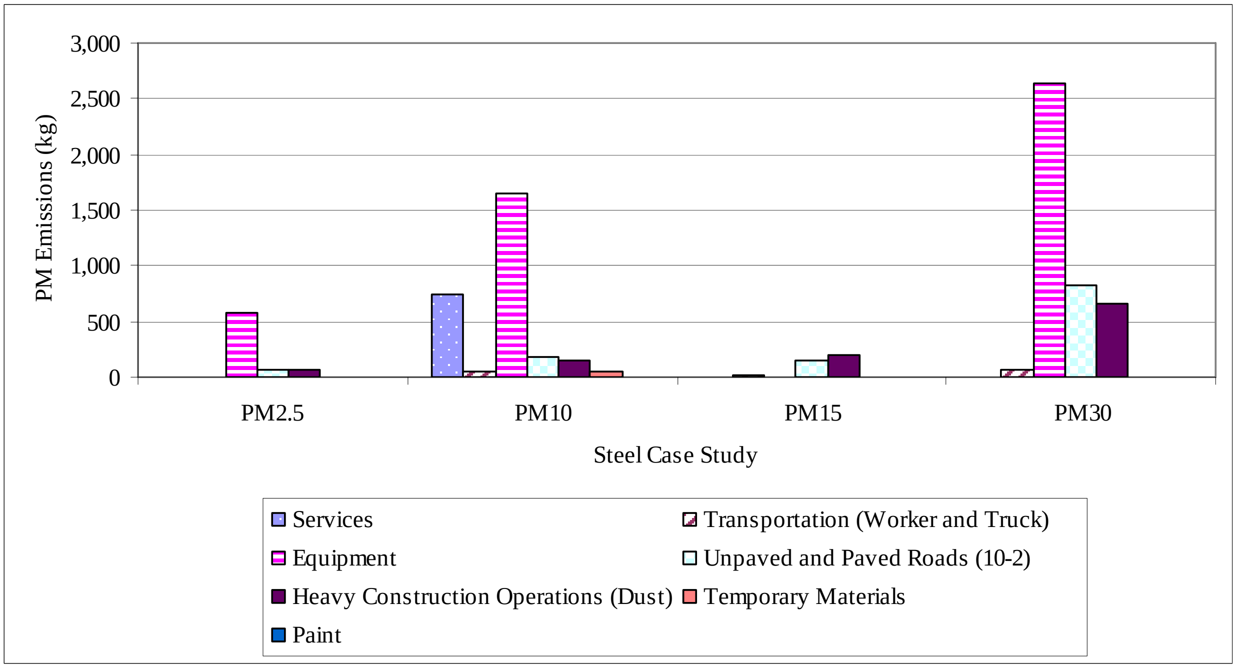


Figure 137. Broad Construction Impacts – PM Emissions – Steel (Mean Value)

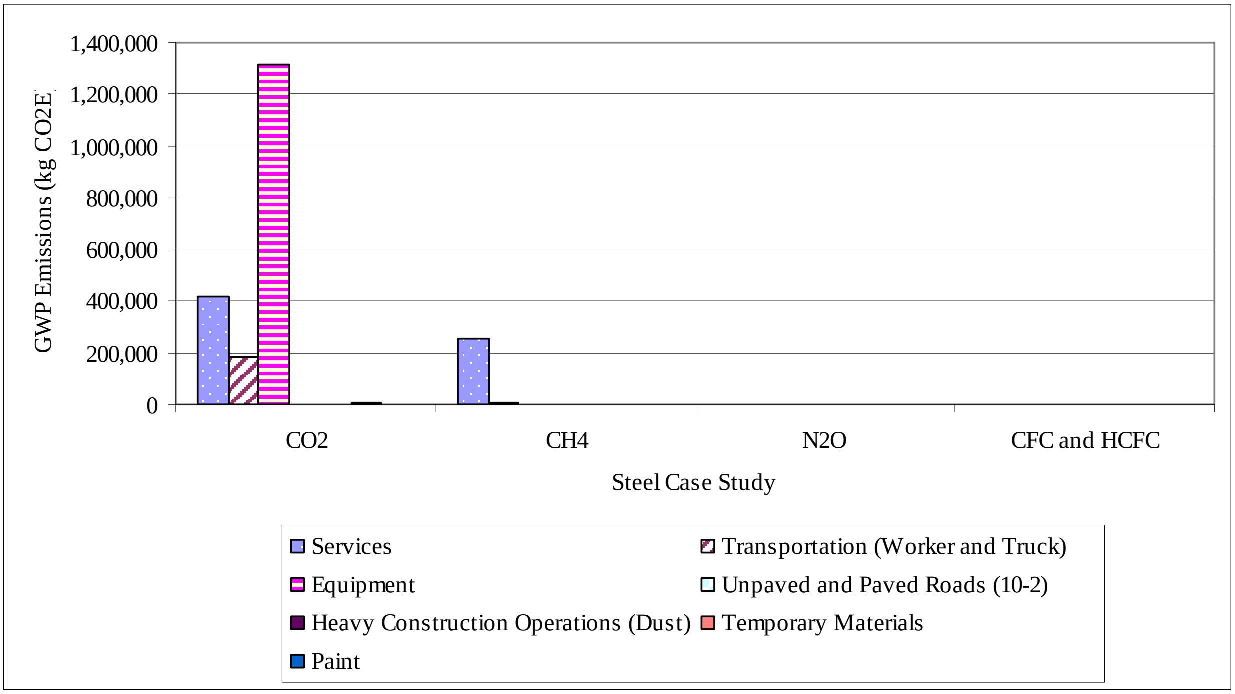


Figure 138. Broad Construction Impacts – GWP Emissions – Steel (Mean Value)

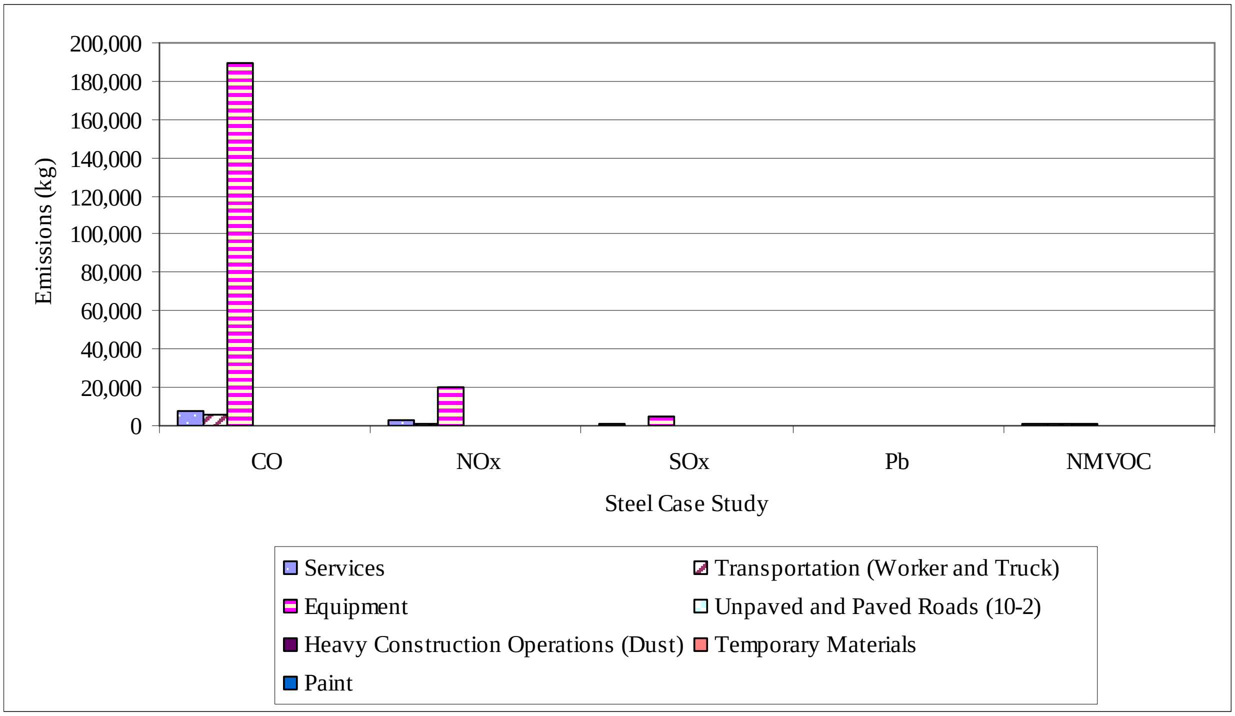
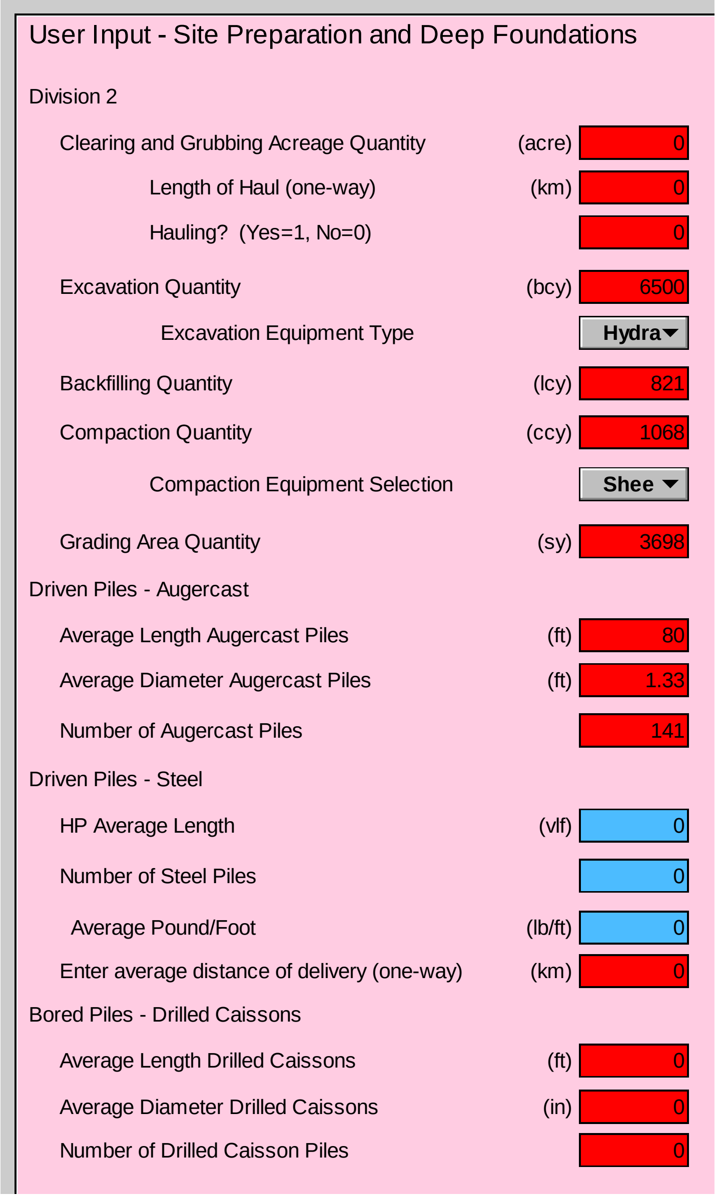


Figure 139. Broad Construction Impacts – Emissions – Steel (Mean Value)

APPENDIX G. INPUT INFORMATION PRECAST STRUCTURE CASE STUDY

INPUT INFORMATION PRECAST STRUCTURE CASE STUDY



User Input - Site Preparation and Deep Foundations

Division 2

Clearing and Grubbing Acreage Quantity	(acre)	0
Length of Haul (one-way)	(km)	0
Hauling? (Yes=1, No=0)		0
Excavation Quantity	(bcy)	6500
Excavation Equipment Type		Hydra
Backfilling Quantity	(lcy)	821
Compaction Quantity	(ccy)	1068
Compaction Equipment Selection		Shee
Grading Area Quantity	(sy)	3698

Driven Piles - Augercast

Average Length Augercast Piles	(ft)	80
Average Diameter Augercast Piles	(ft)	1.33
Number of Augercast Piles		141

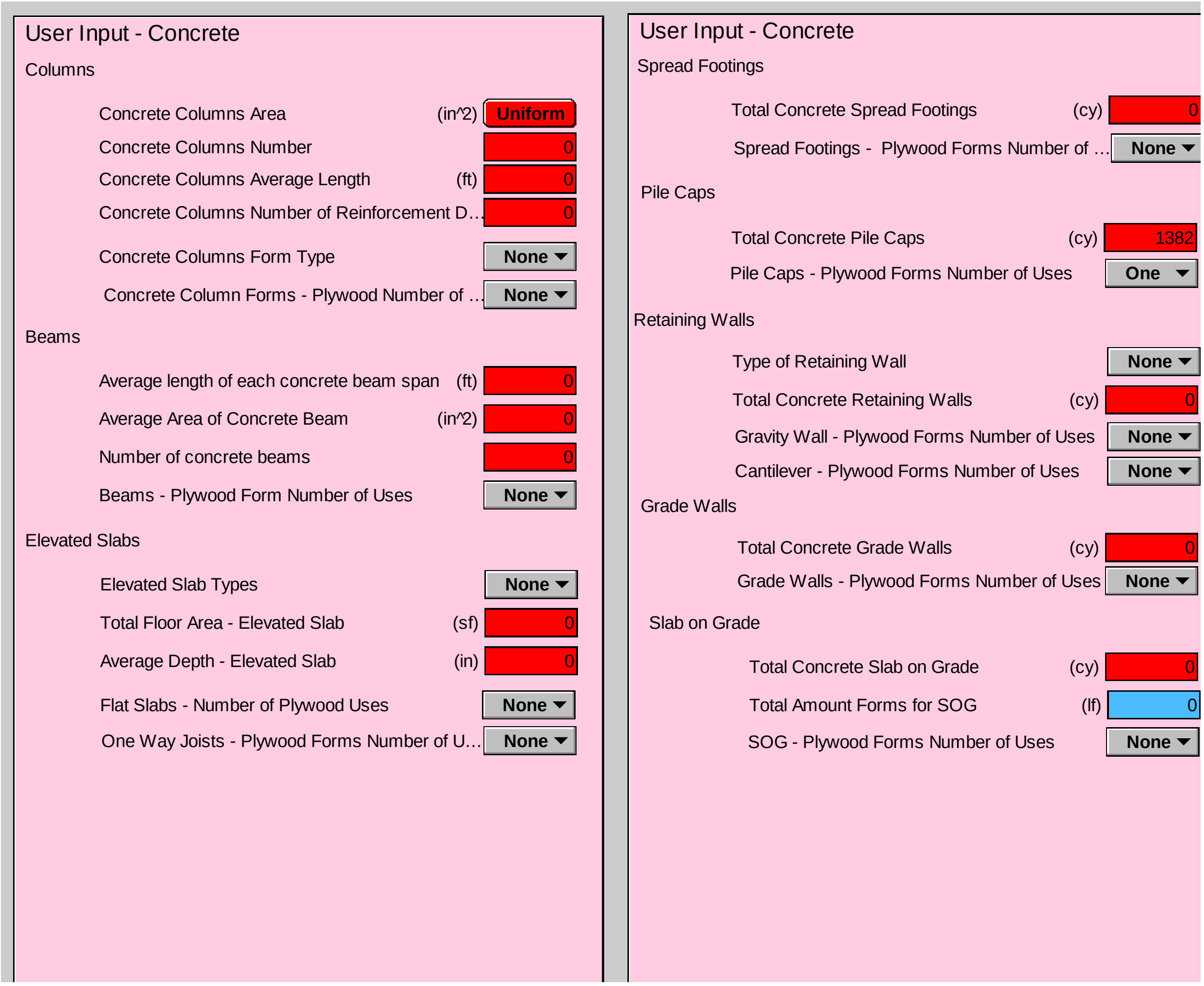
Driven Piles - Steel

HP Average Length	(vlf)	0
Number of Steel Piles		0
Average Pound/Foot	(lb/ft)	0
Enter average distance of delivery (one-way)	(km)	0

Bored Piles - Drilled Caissons

Average Length Drilled Caissons	(ft)	0
Average Diameter Drilled Caissons	(in)	0
Number of Drilled Caisson Piles		0

Figure 140. User Input - Site Preparation and Deep Foundations - Precast Structure



User Input - Concrete

Columns

Concrete Columns Area (in^2) Uniform

Concrete Columns Number 0

Concrete Columns Average Length (ft) 0

Concrete Columns Number of Reinforcement D… 0

Concrete Columns Form Type None

Concrete Column Forms - Plywood Number of … None

Beams

Average length of each concrete beam span (ft) 0

Average Area of Concrete Beam (in^2) 0

Number of concrete beams 0

Beams - Plywood Form Number of Uses None

Elevated Slabs

Elevated Slab Types None

Total Floor Area - Elevated Slab (sf) 0

Average Depth - Elevated Slab (in) 0

Flat Slabs - Number of Plywood Uses None

One Way Joists - Plywood Forms Number of U… None

User Input - Concrete

Spread Footings

Total Concrete Spread Footings (cy) 0

Spread Footings - Plywood Forms Number of … None

Pile Caps

Total Concrete Pile Caps (cy) 1382

Pile Caps - Plywood Forms Number of Uses One

Retaining Walls

Type of Retaining Wall None

Total Concrete Retaining Walls (cy) 0

Gravity Wall - Plywood Forms Number of Uses None

Cantilever - Plywood Forms Number of Uses None

Grade Walls

Total Concrete Grade Walls (cy) 0

Grade Walls - Plywood Forms Number of Uses None

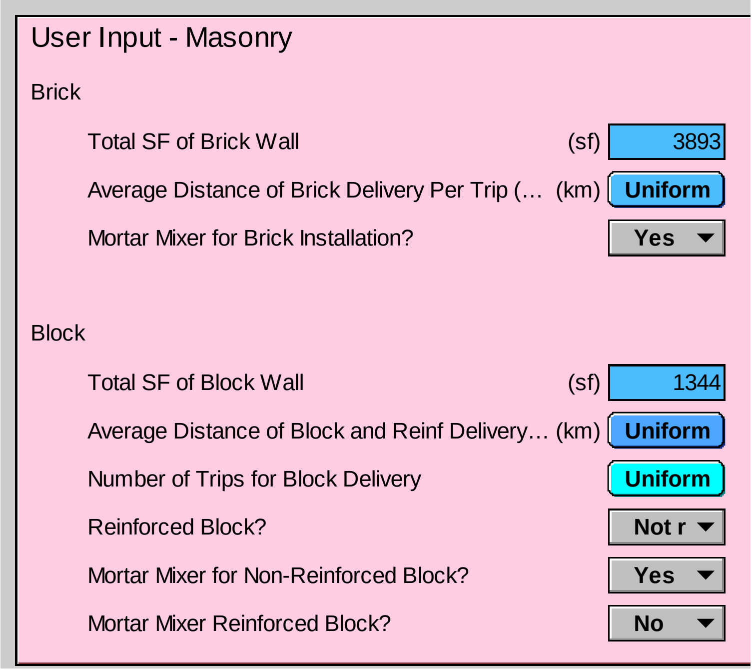
Slab on Grade

Total Concrete Slab on Grade (cy) 0

Total Amount Forms for SOG (lf) 0

SOG - Plywood Forms Number of Uses None

Figure 141. User Input - Concrete - Precast Structure



User Input - Masonry

Brick

Total SF of Brick Wall (sf) 3893

Average Distance of Brick Delivery Per Trip (… (km) Uniform

Mortar Mixer for Brick Installation? Yes

Block

Total SF of Block Wall (sf) 1344

Average Distance of Block and Reinf Delivery… (km) Uniform

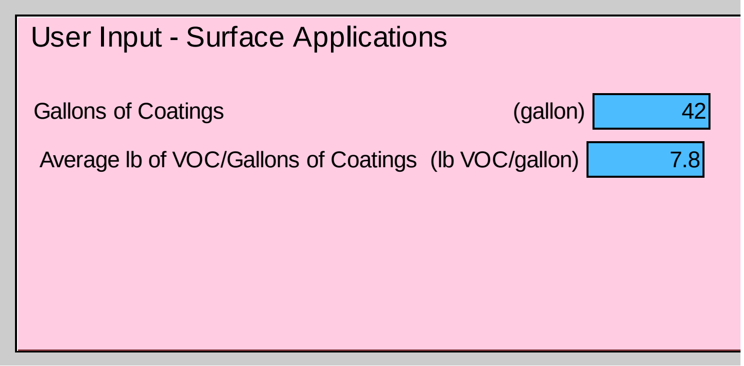
Number of Trips for Block Delivery Uniform

Reinforced Block? Not r

Mortar Mixer for Non-Reinforced Block? Yes

Mortar Mixer Reinforced Block? No

Figure 142. User Input – Masonry – Precast Structure

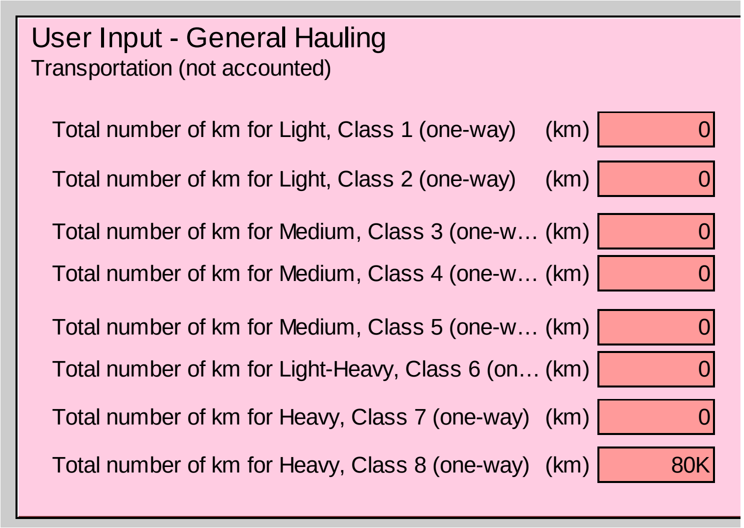


User Input - Surface Applications

Gallons of Coatings (gallon) 42

Average lb of VOC/Gallons of Coatings (lb VOC/gallon) 7.8

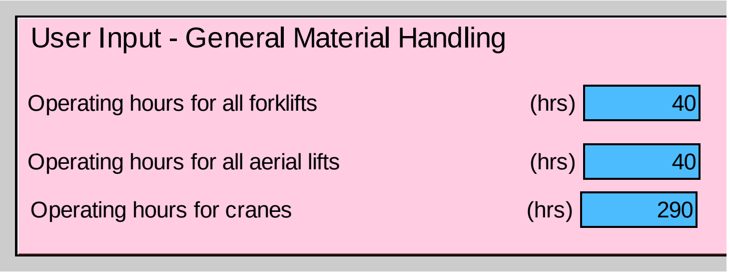
Figure 143. User Input - Surface Applications - Precast Structure


User Input - General Hauling

Transportation (not accounted)

Total number of km for Light, Class 1 (one-way)	(km)	0
Total number of km for Light, Class 2 (one-way)	(km)	0
Total number of km for Medium, Class 3 (one-w…	(km)	0
Total number of km for Medium, Class 4 (one-w…	(km)	0
Total number of km for Medium, Class 5 (one-w…	(km)	0
Total number of km for Light-Heavy, Class 6 (on…	(km)	0
Total number of km for Heavy, Class 7 (one-way)	(km)	0
Total number of km for Heavy, Class 8 (one-way)	(km)	80K

Figure 144. User Input – General Hauling – Precast Structure


User Input - General Material Handling

Operating hours for all forklifts	(hrs)	40
Operating hours for all aerial lifts	(hrs)	40
Operating hours for cranes	(hrs)	290

Figure 145. User Input - General Material Handling - Precast Structure

APPENDIX H. ADDITIONAL PRECAST CASE STUDY RESULTS

ADDITIONAL PRECAST CASE STUDY RESULTS

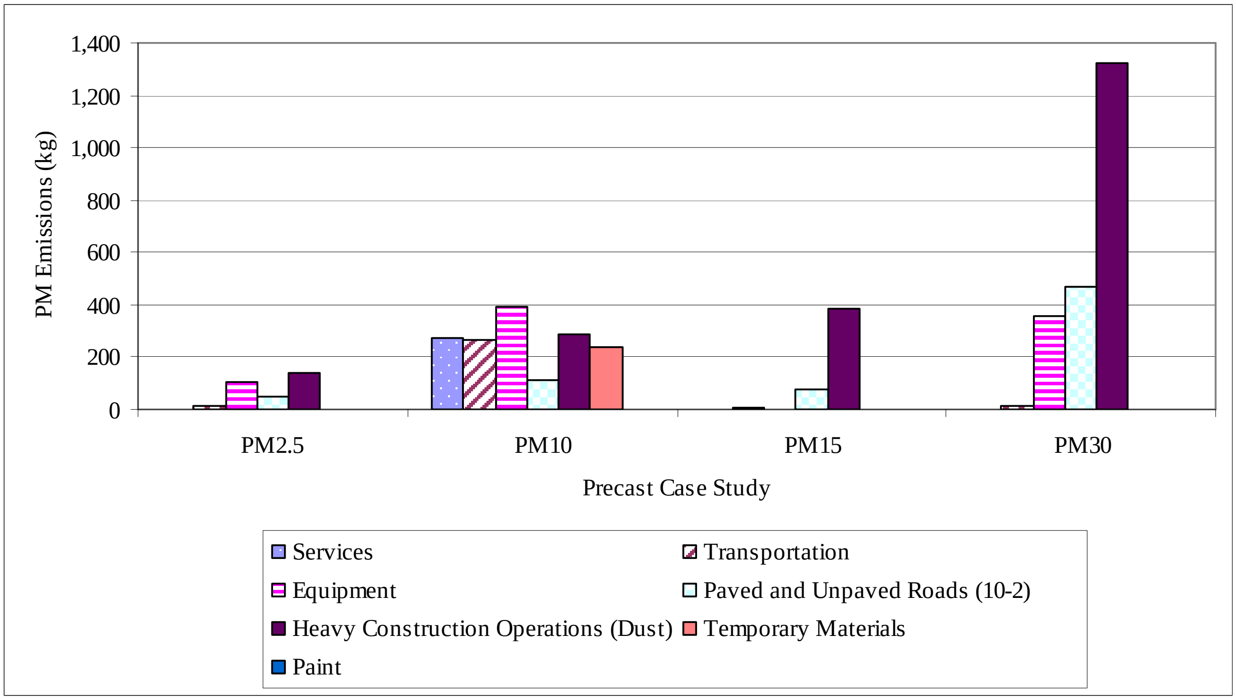


Figure 146. Broad Construction Impacts – PM Emissions – Precast (Mean Value)

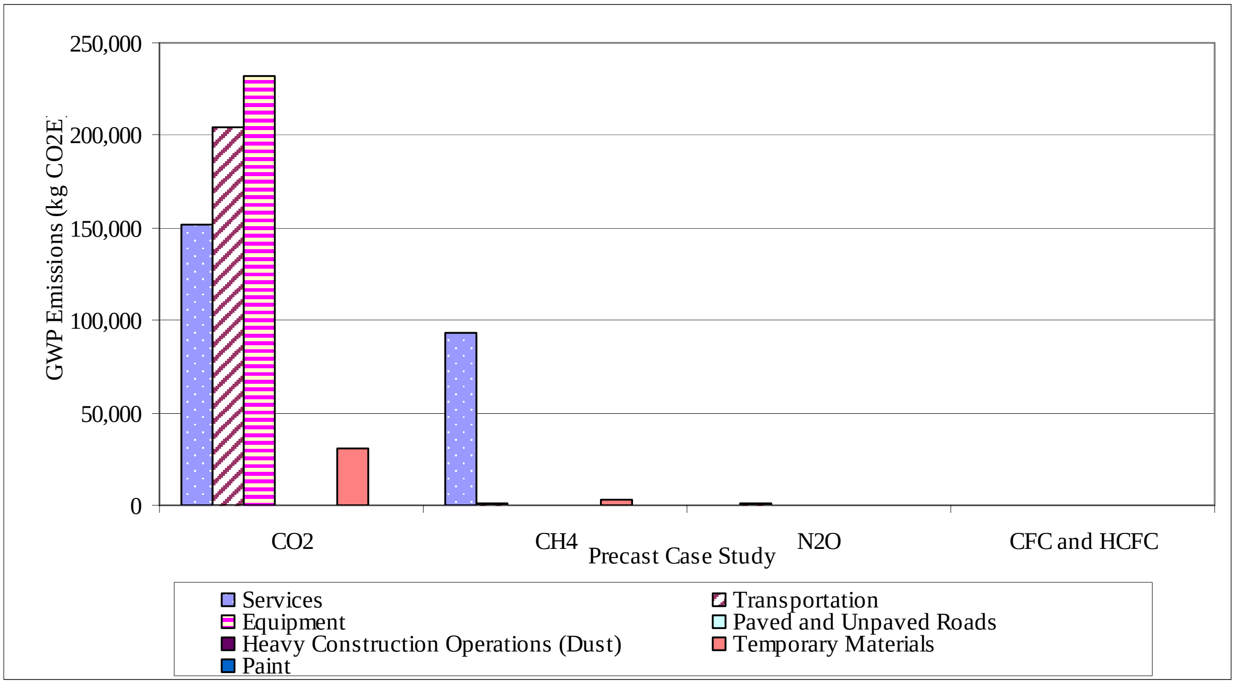


Figure 147. Broad Construction Impacts – GWP Emissions –Precast (Mean Value)

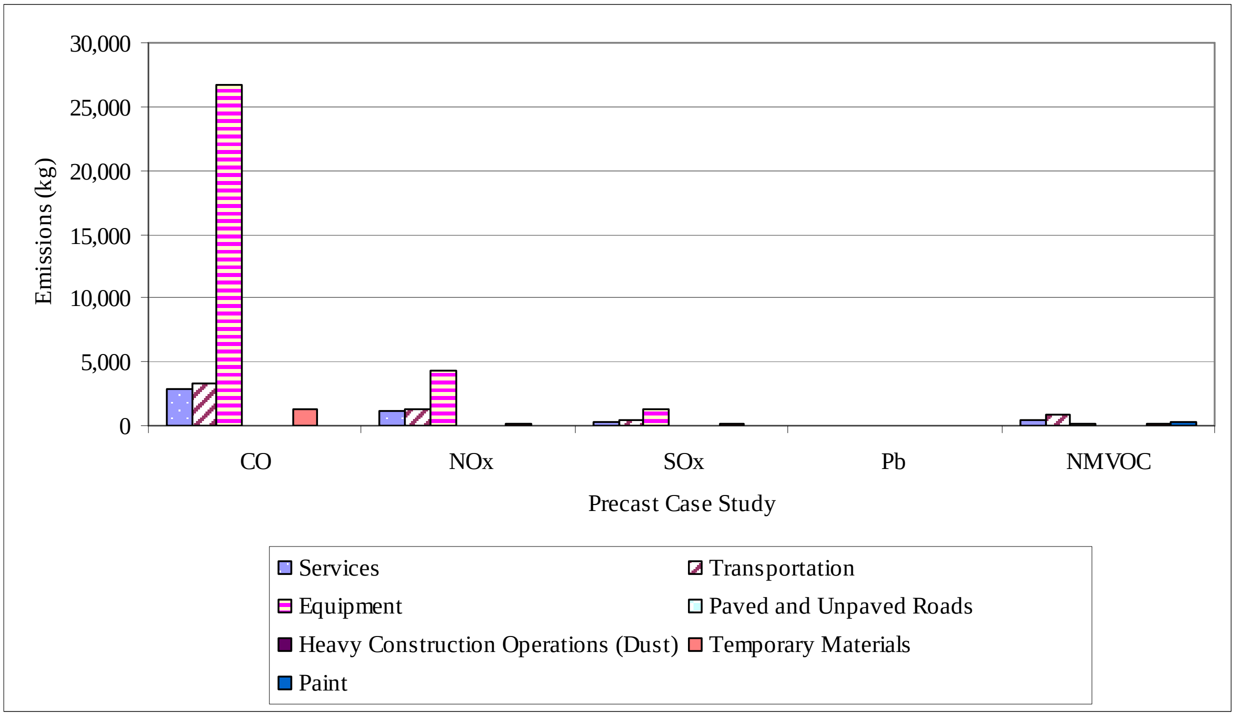


Figure 148. Broad Construction Impacts –Emissions –Precast (Mean Value)

APPENDIX I. COMPARATIVE RESULTS BETWEEN CASE STUDIES

COMPARATIVE RESULTS STEEL AND PRECAST CASE STUDIES

Table 54. Total Energy and Waste - Steel and Precast

	Energy (TJ)	Solid Waste (tons)	Liquid Waste (gallons)
Steel	20	91	2,709
Precast	8	172	1,386

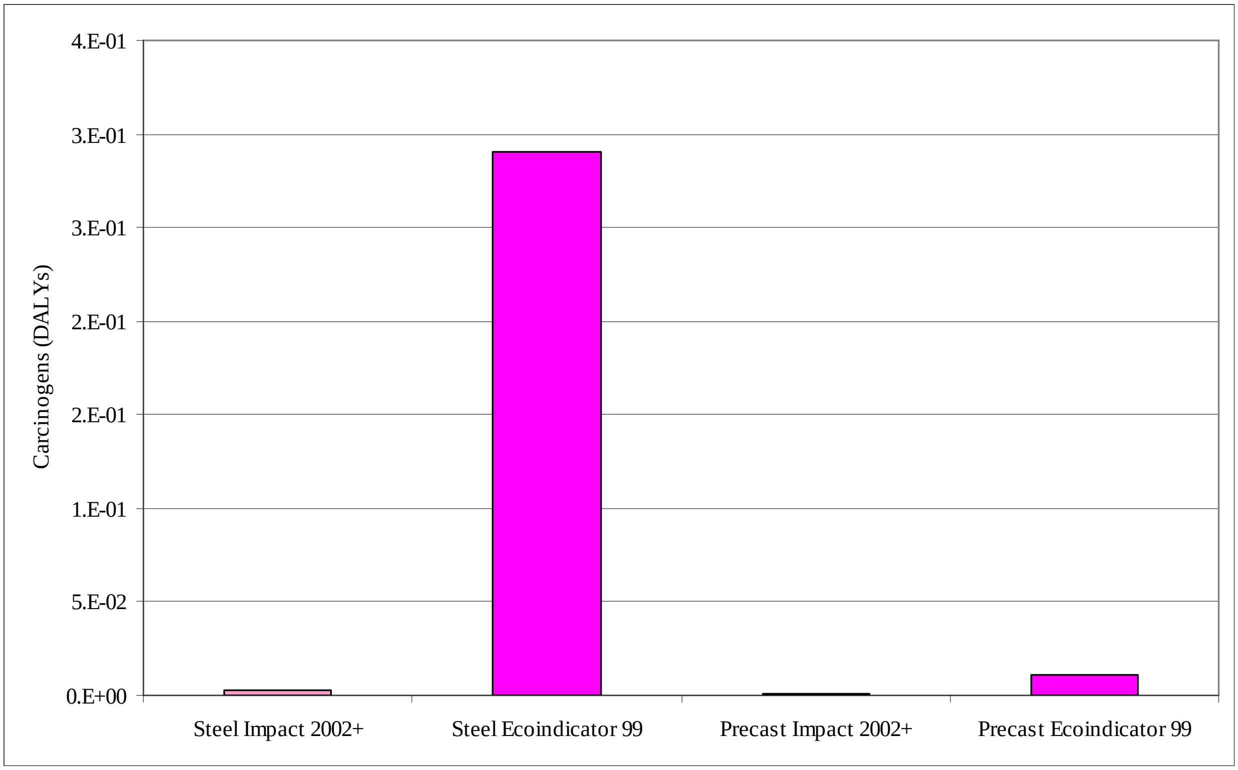


Figure 149. Carcinogens - Total LCIA – Steel and Precast (Mean Value)

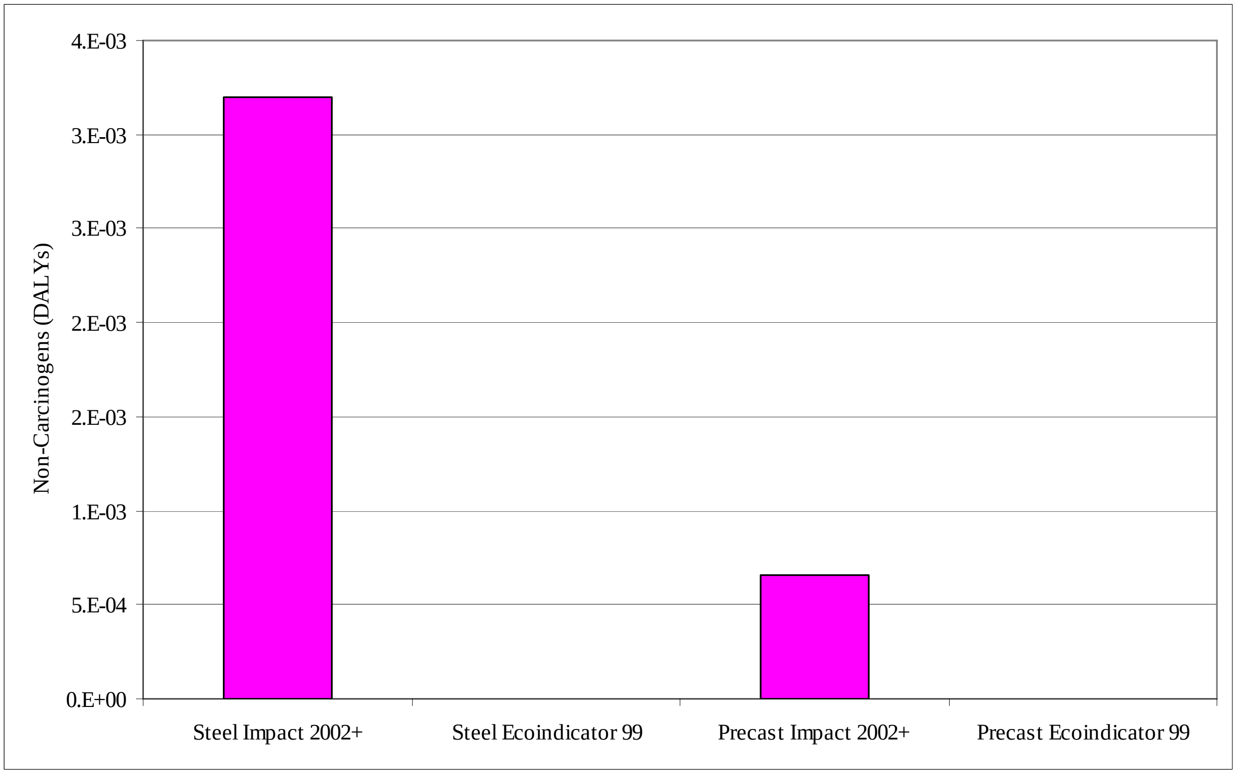


Figure 150. Non-Carcinogens – Total LCIA – Steel and Precast (Mean Value)

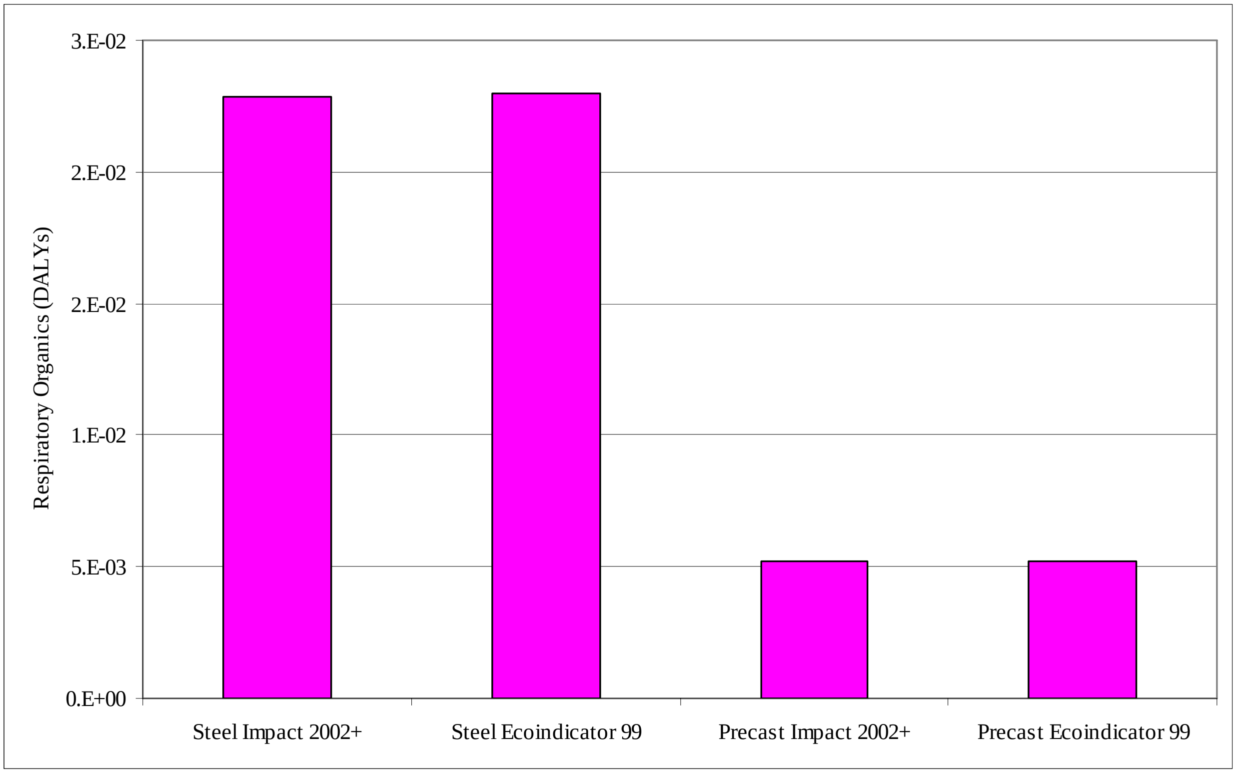


Figure 151. Respiratory Organics – Total LCIA – Steel and Precast (Mean Value)

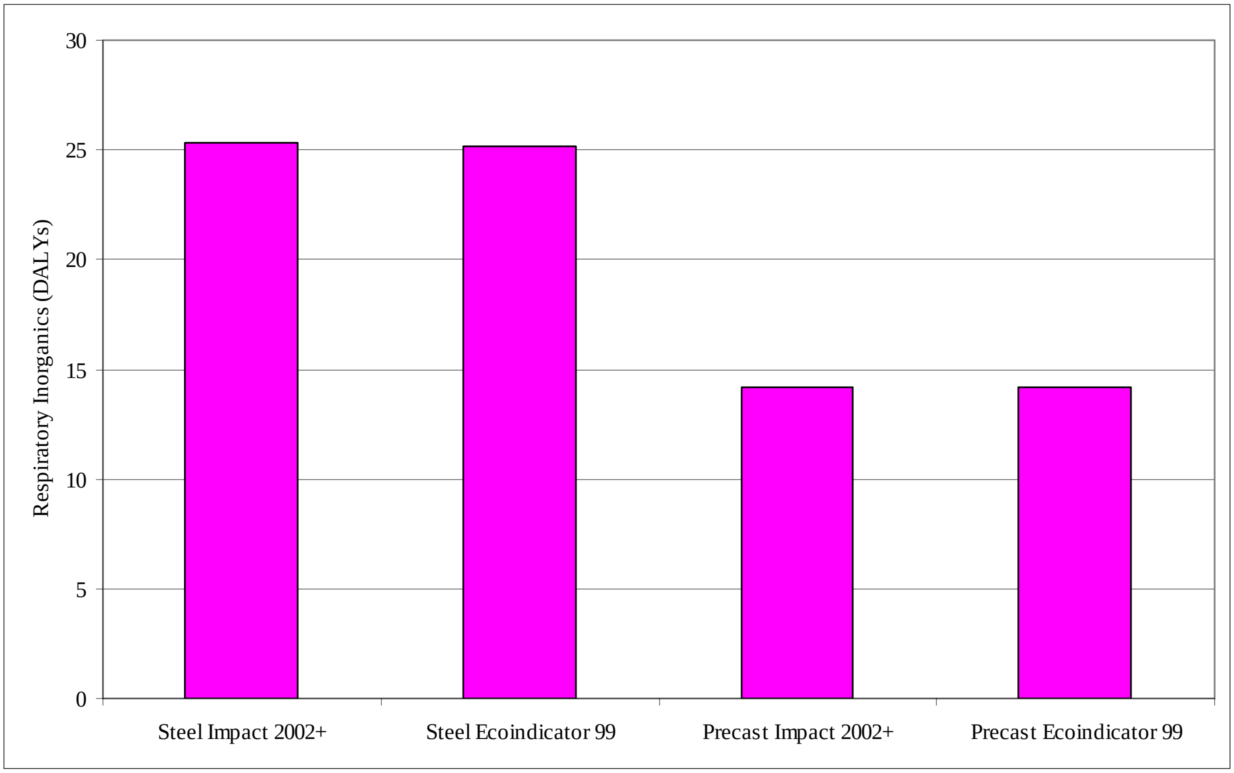


Figure 152. Respiratory Inorganics – Total LCIA – Steel and Precast (Mean Value)

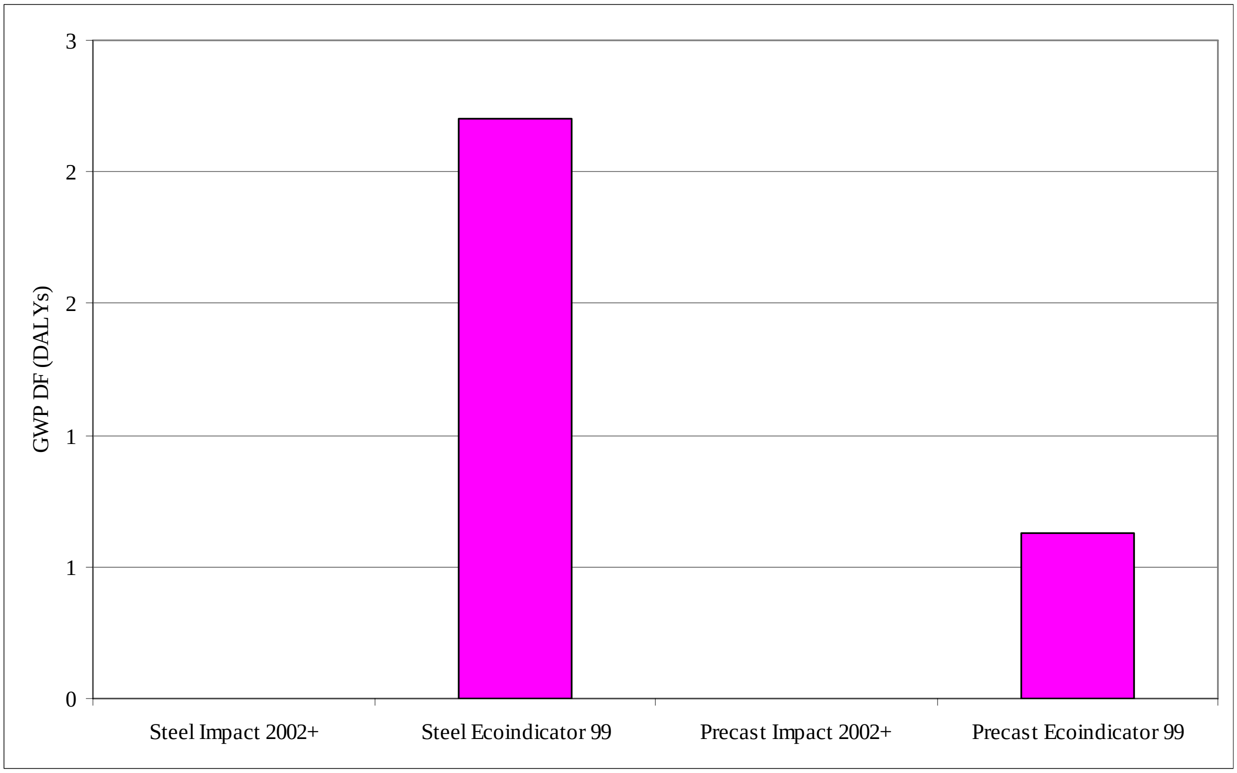


Figure 153. GWP DF – Total LCIA – Steel and Precast (Mean Value)

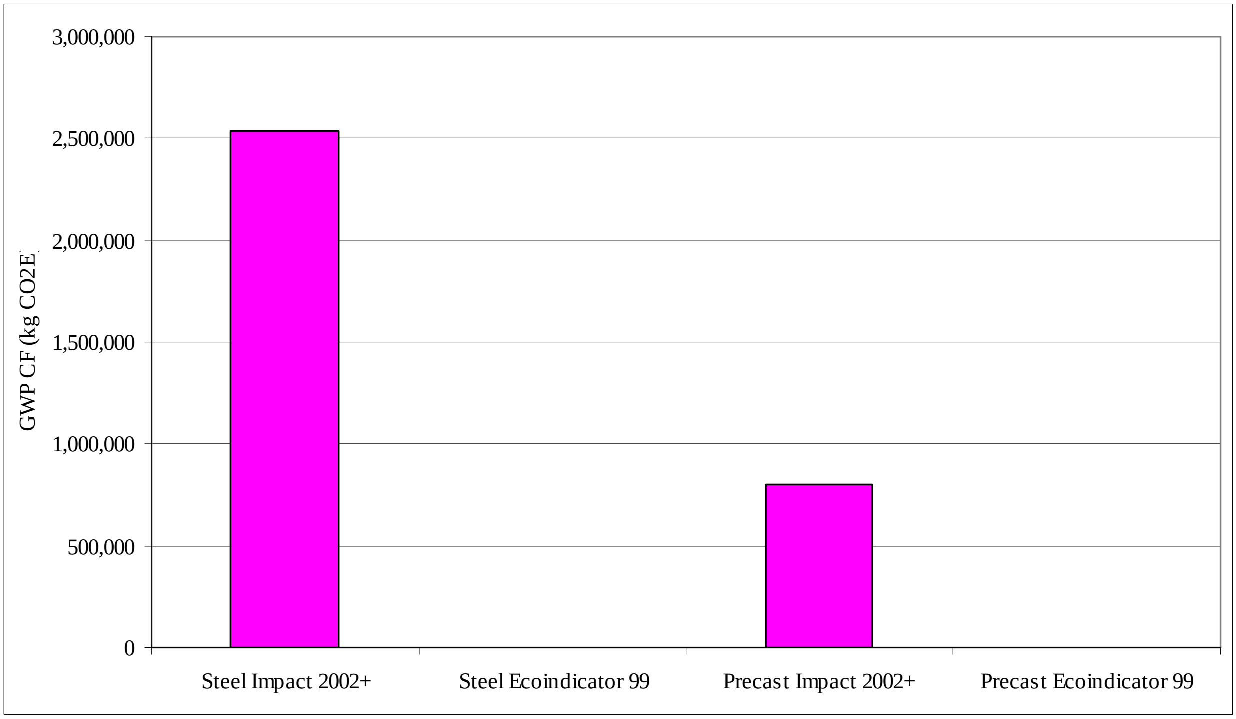


Figure 154. GWP CF – Total LCIA – Steel and Precast (Mean Value)

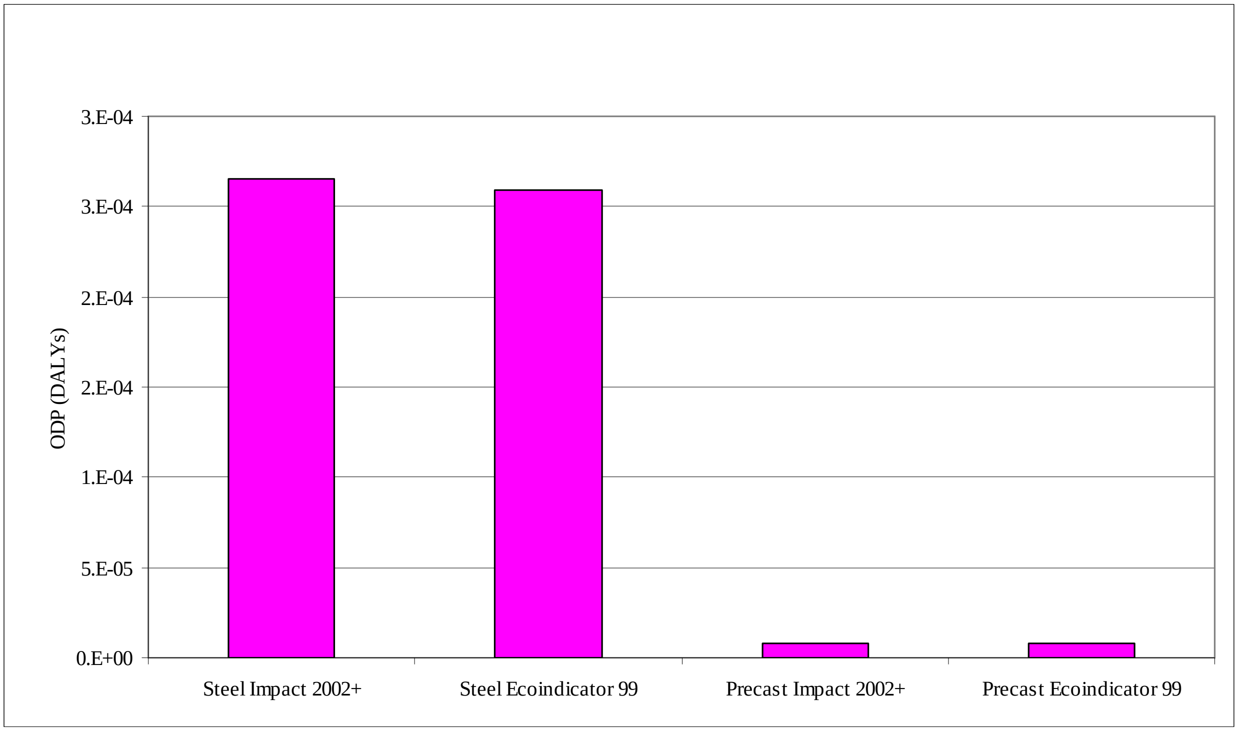


Figure 155. ODP – Total LCIA – Steel and Precast (Mean Value)

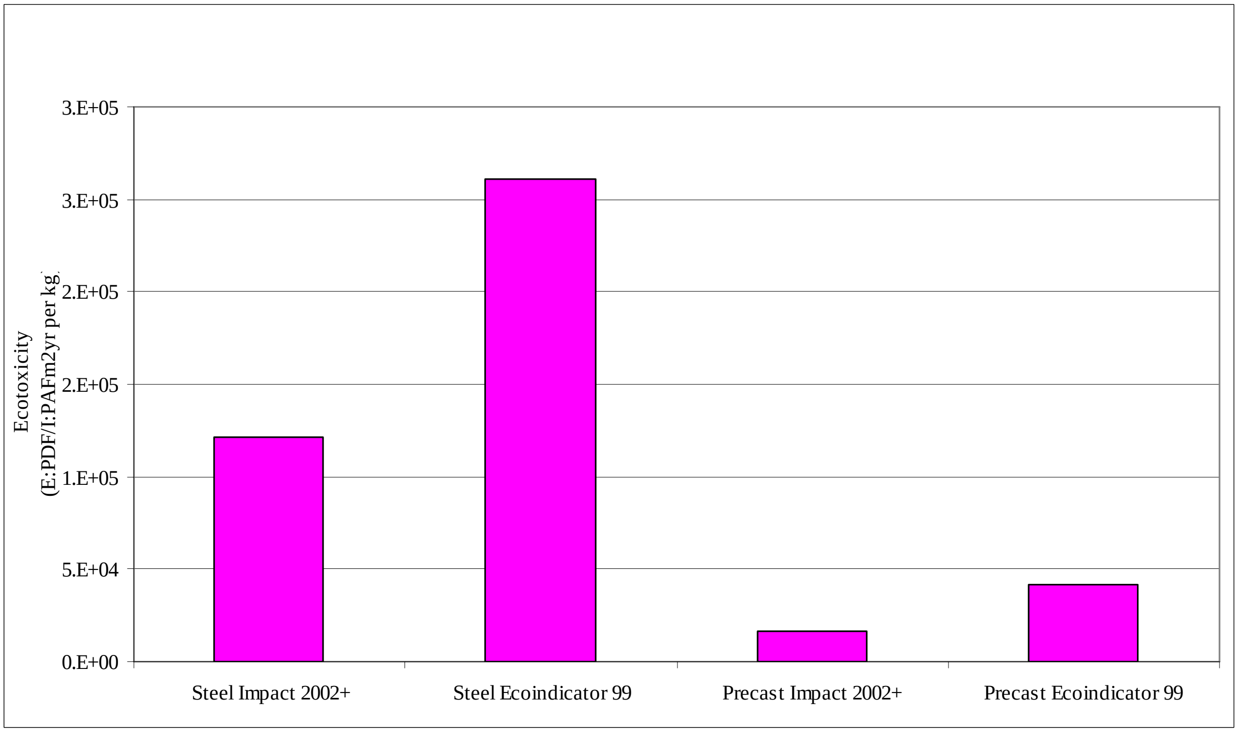


Figure 156. Ecotoxicity – Total LCIA – Steel and Precast (Mean Value)

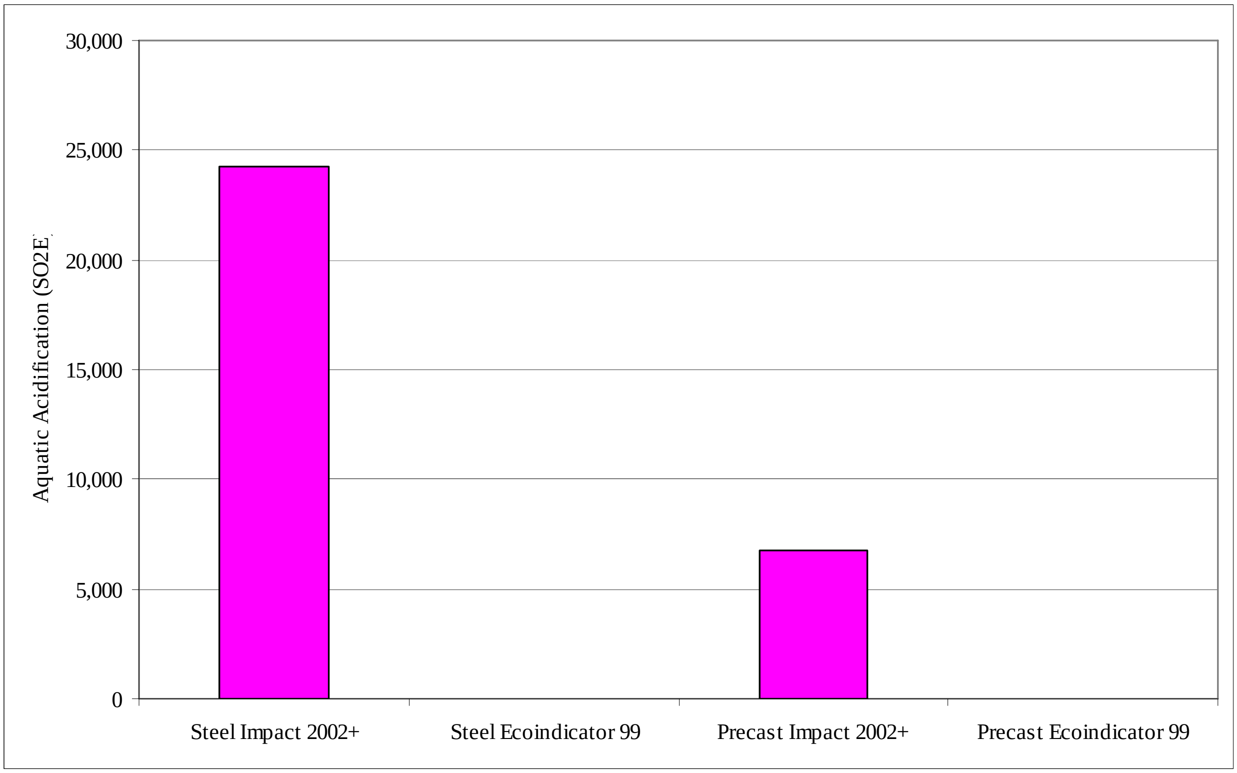


Figure 157. Aquatic Acidification – Total LCIA – Steel and Precast (Mean Value)

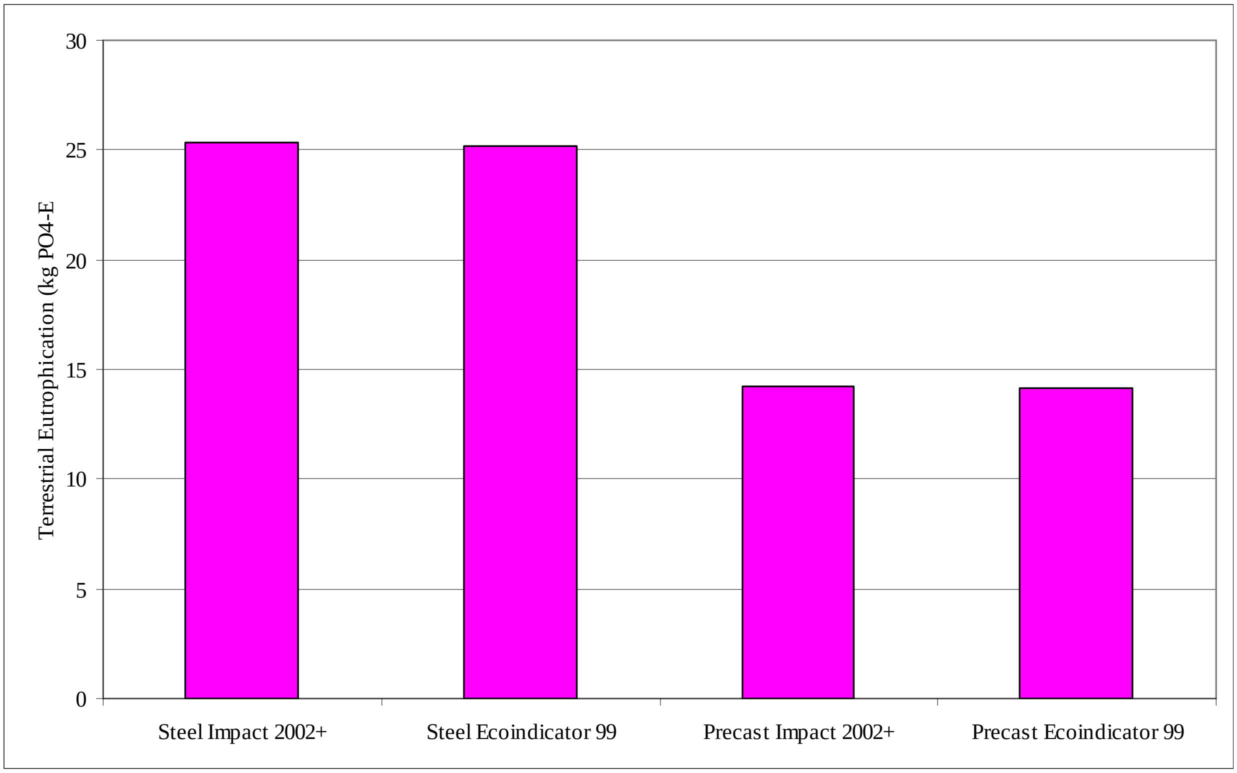


Figure 158. Terrestrial Eutrophication – Total LCIA – Steel and Precast (Mean Value)

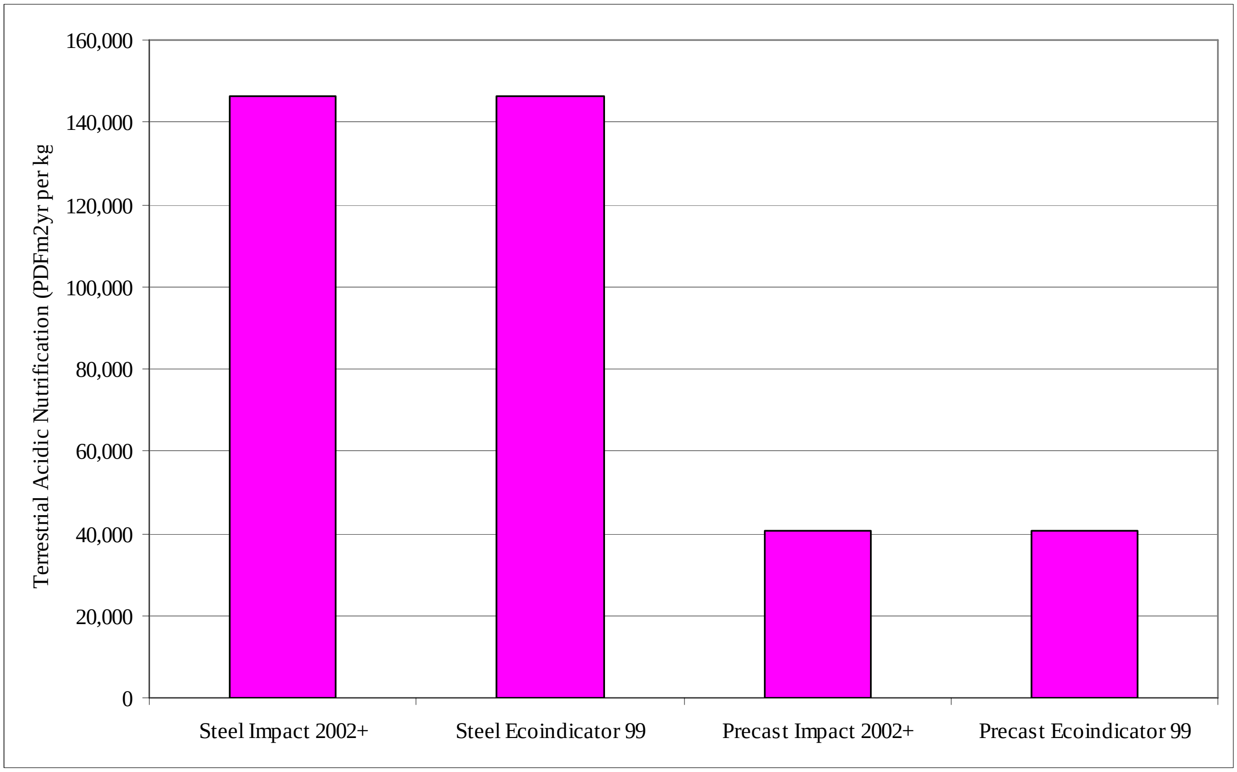


Figure 159. Terr. Acid. and Nutr. – Total LCIA – Steel and Precast (Mean Value)

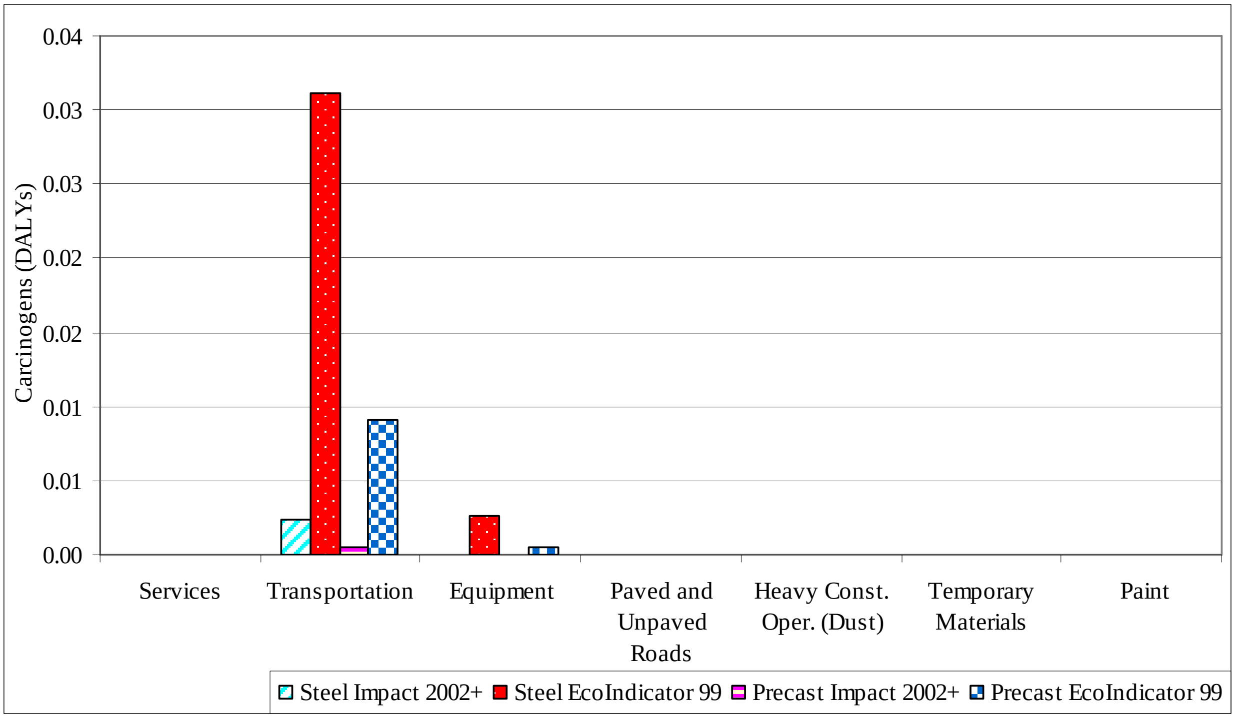


Figure 160. Carcinogens – Broad Construction LCIA – Steel and Precast (Mean Value)

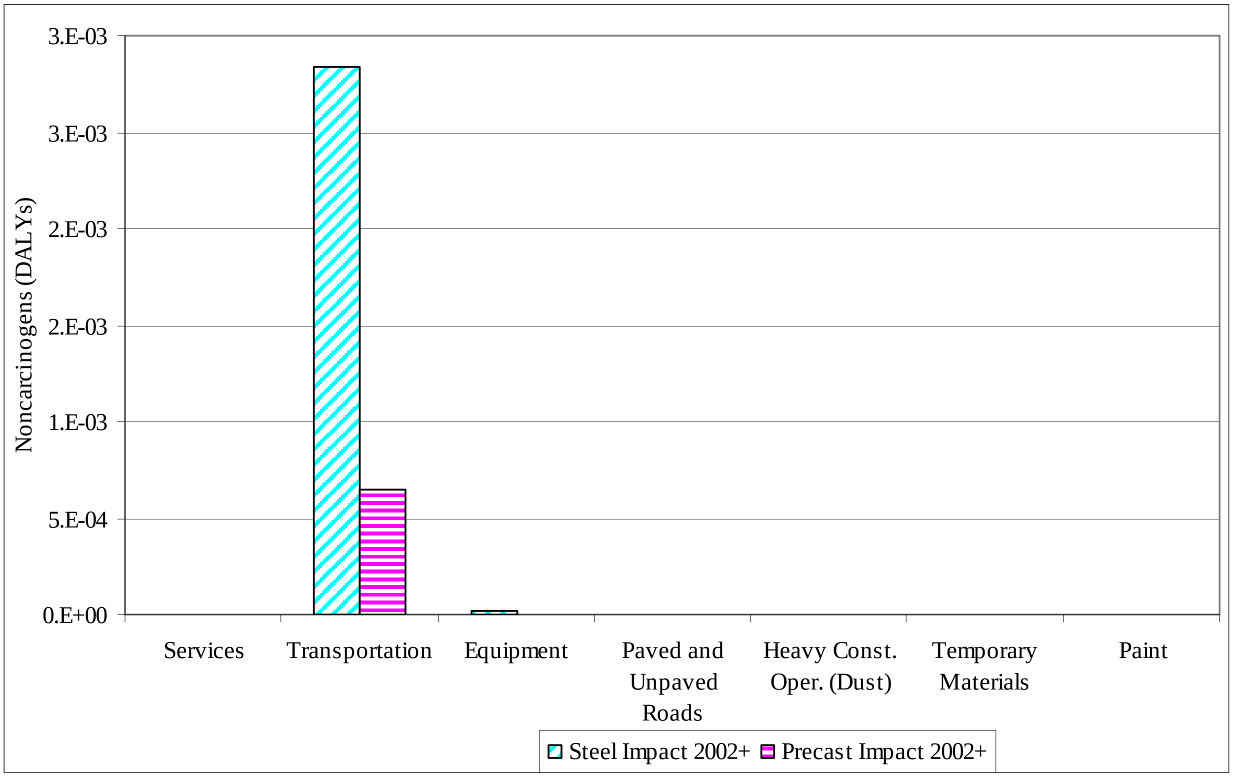


Figure 161. Non-Carcinogens – Broad Construction LCIA – Steel and Precast (Mean Value)

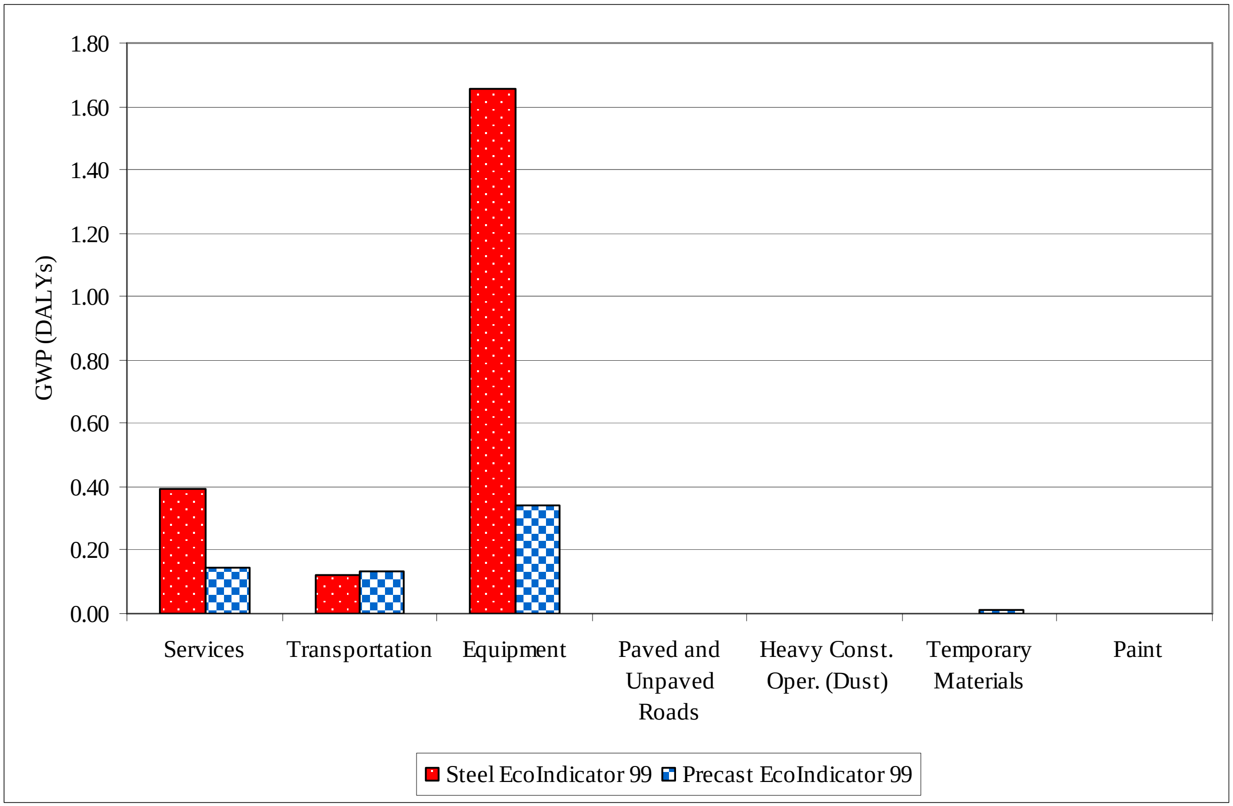


Figure 162. GWP DF – Broad Construction LCIA – Steel and Precast (Mean Value)

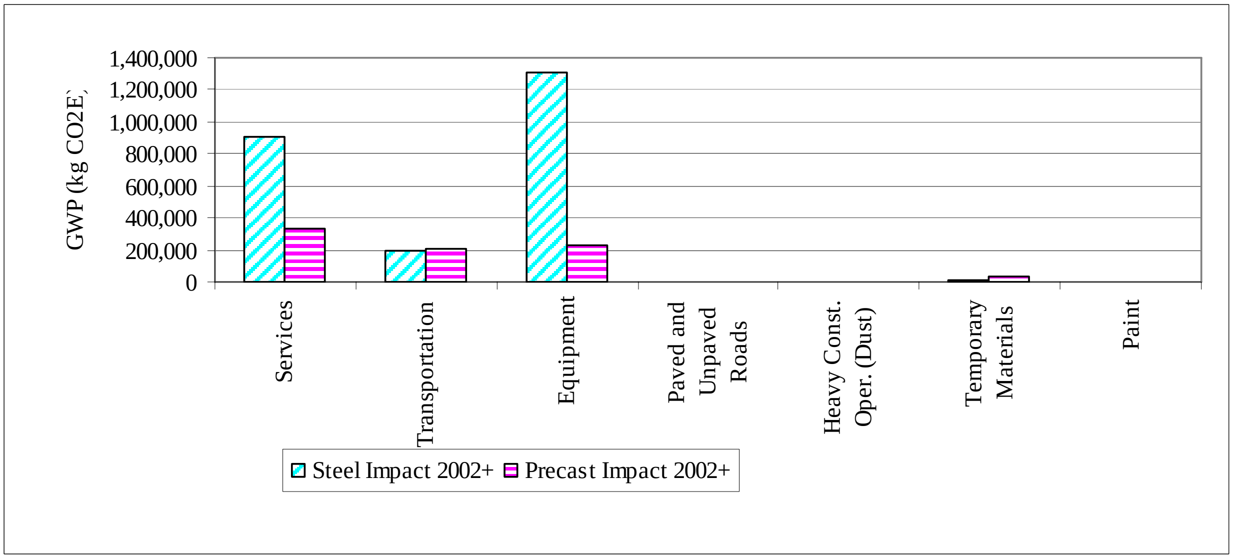


Figure 163. GWP CF – Broad Construction LCIA – Steel and Precast (Mean Value)

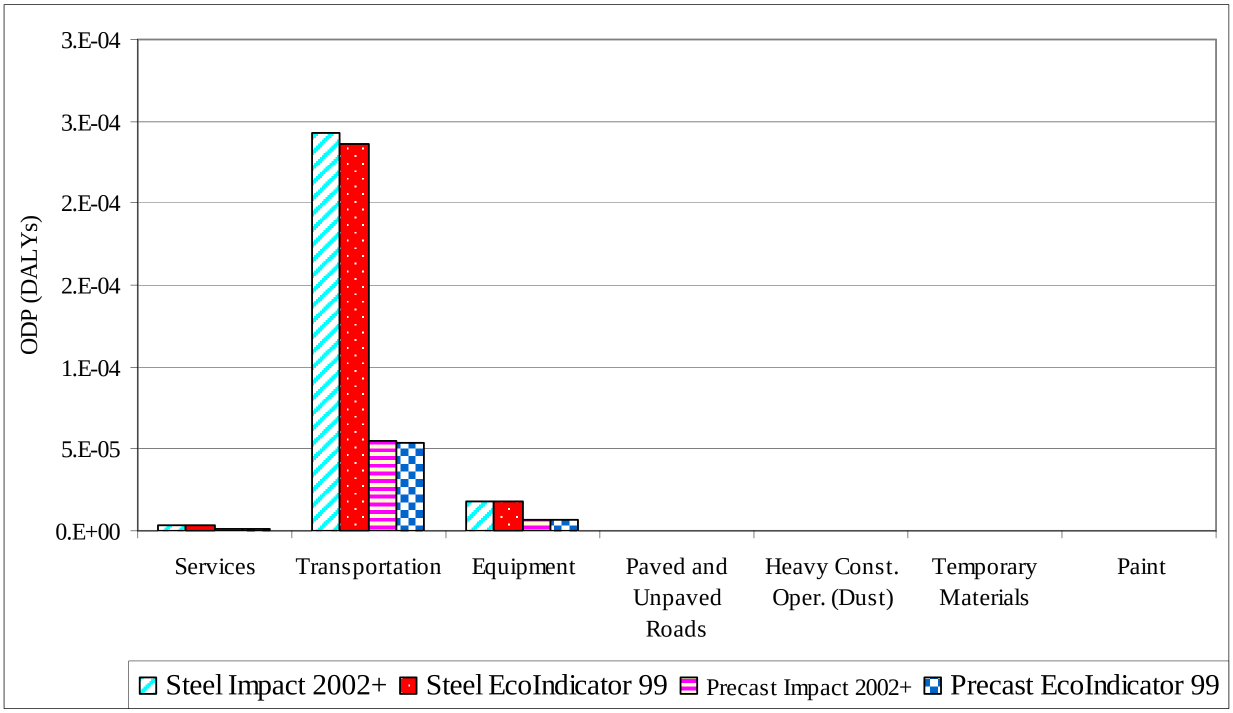


Figure 164. ODP – Broad Construction LCIA – Steel and Precast (Mean Value)

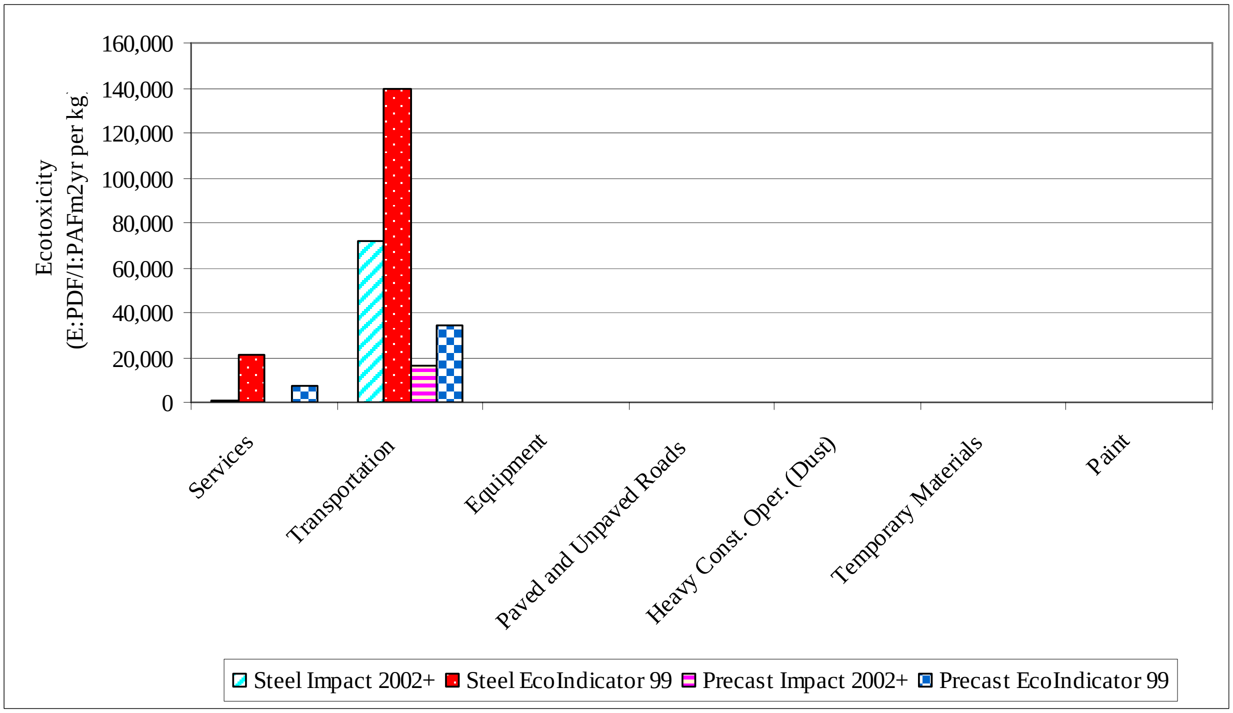


Figure 165. Ecotoxicity – Broad Construction LCIA – Steel and Precast (Mean Value)

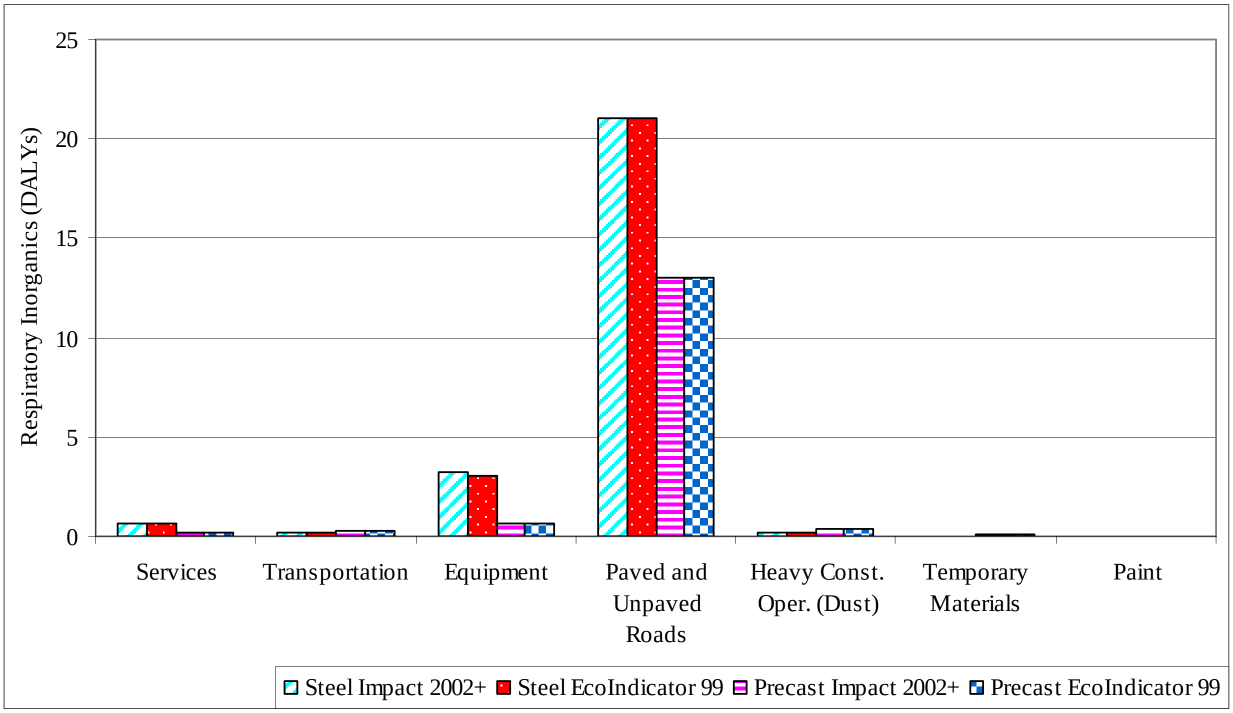


Figure 166. Resp. Inorganics – Broad Construction LCIA – Steel and Precast (Mean Value)

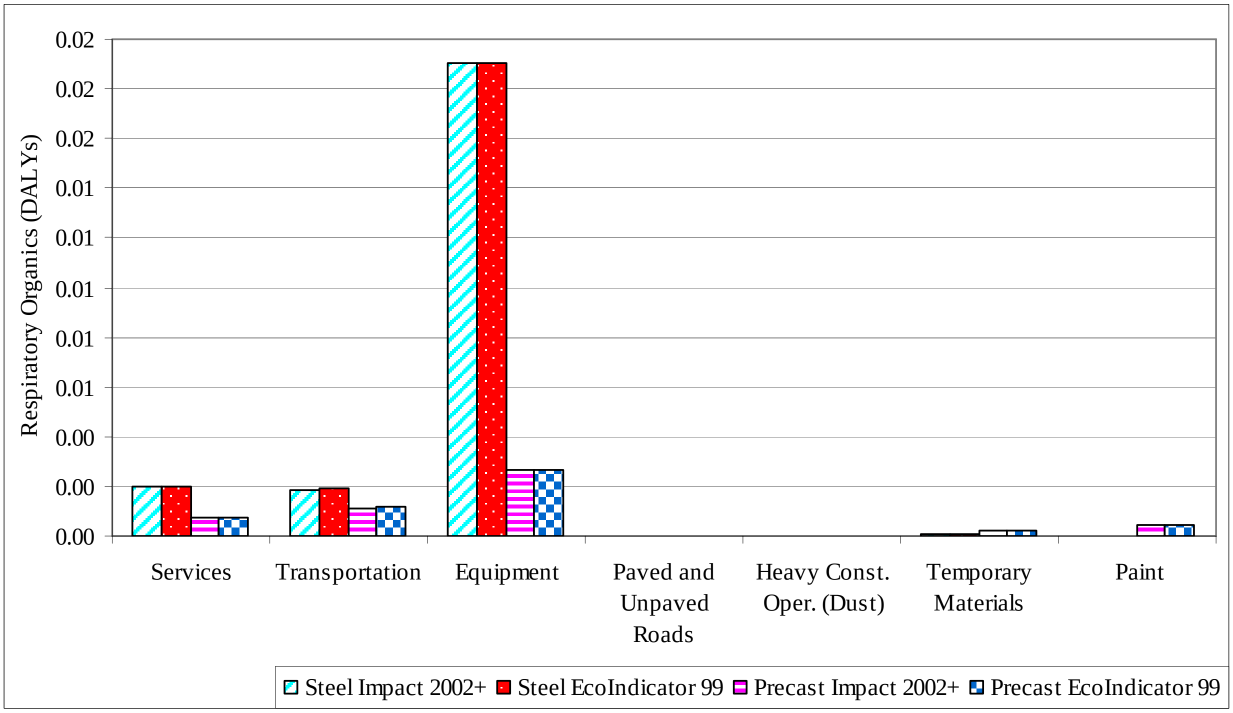


Figure 167. Resp. Organics – Broad Construction LCIA – Steel and Precast (Mean Value)

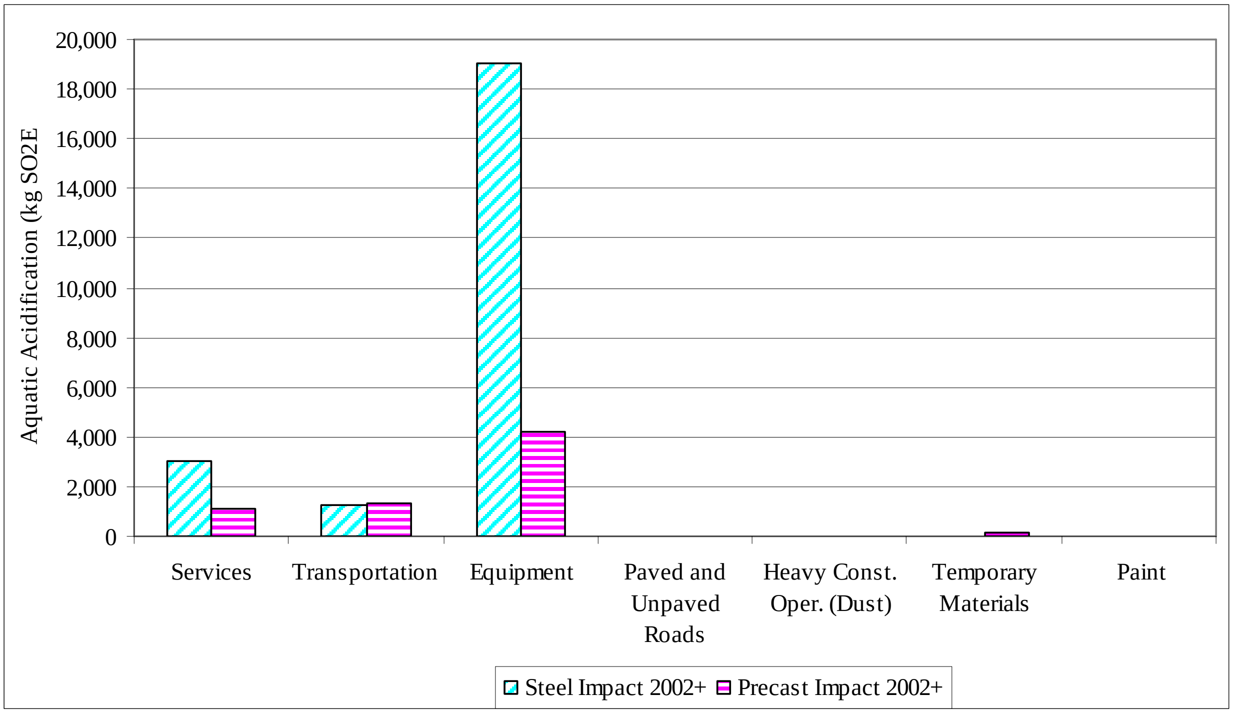


Figure 168. Aquatic Acid. – Broad Construction LCIA – Steel and Precast (Mean Value)

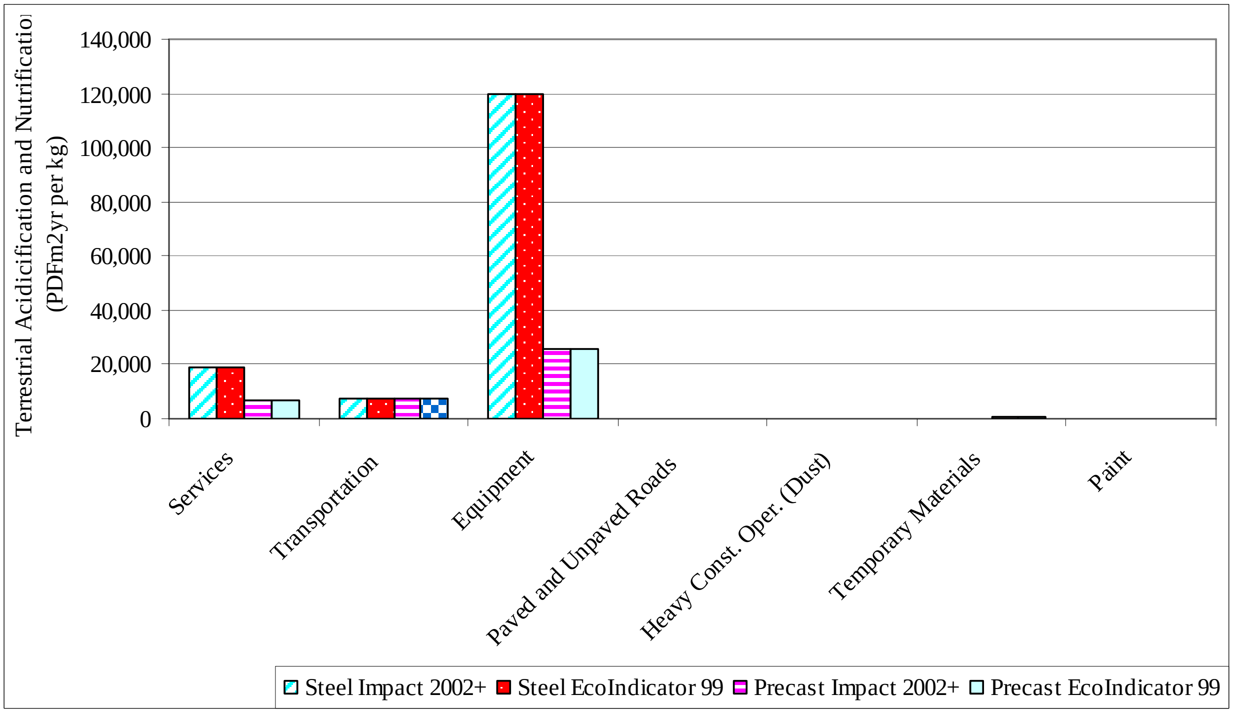


Figure 169. Terr. Acid. & Nutr. – Broad Const. LCIA – Steel and Precast (Mean Value)

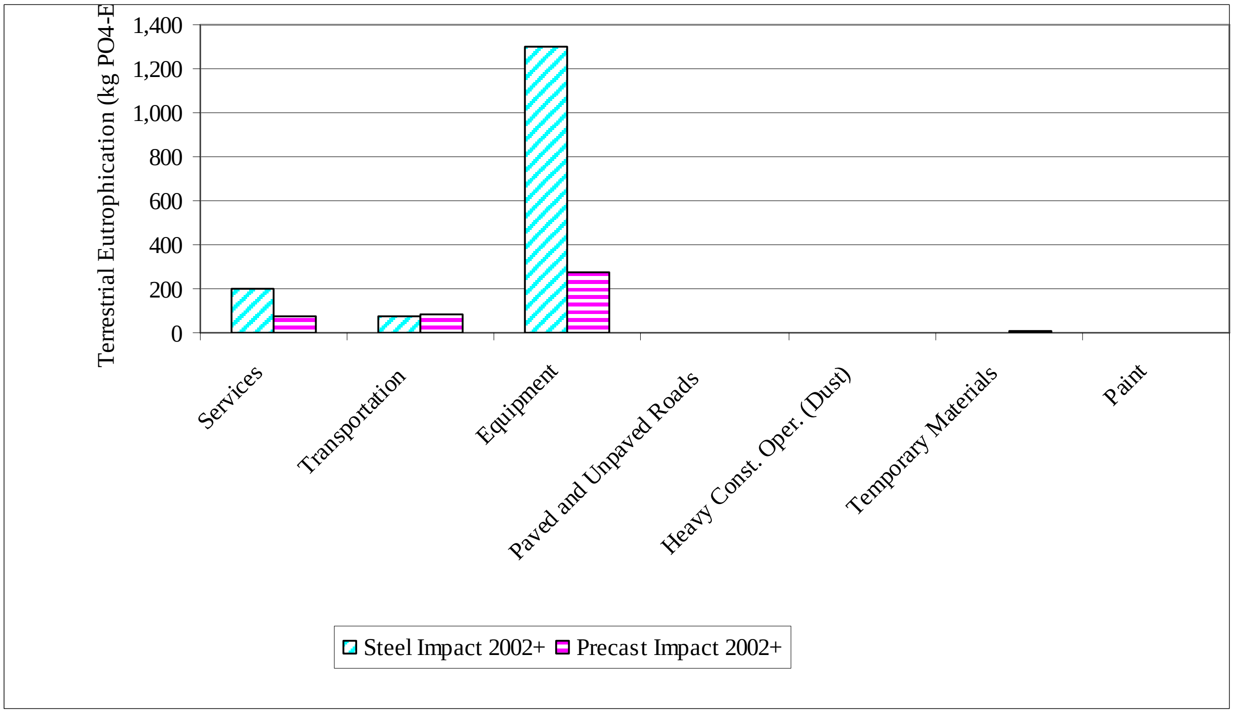


Figure 170. Terr. Eutr. – Broad Construction LCIA – Steel and Precast (Mean Value)

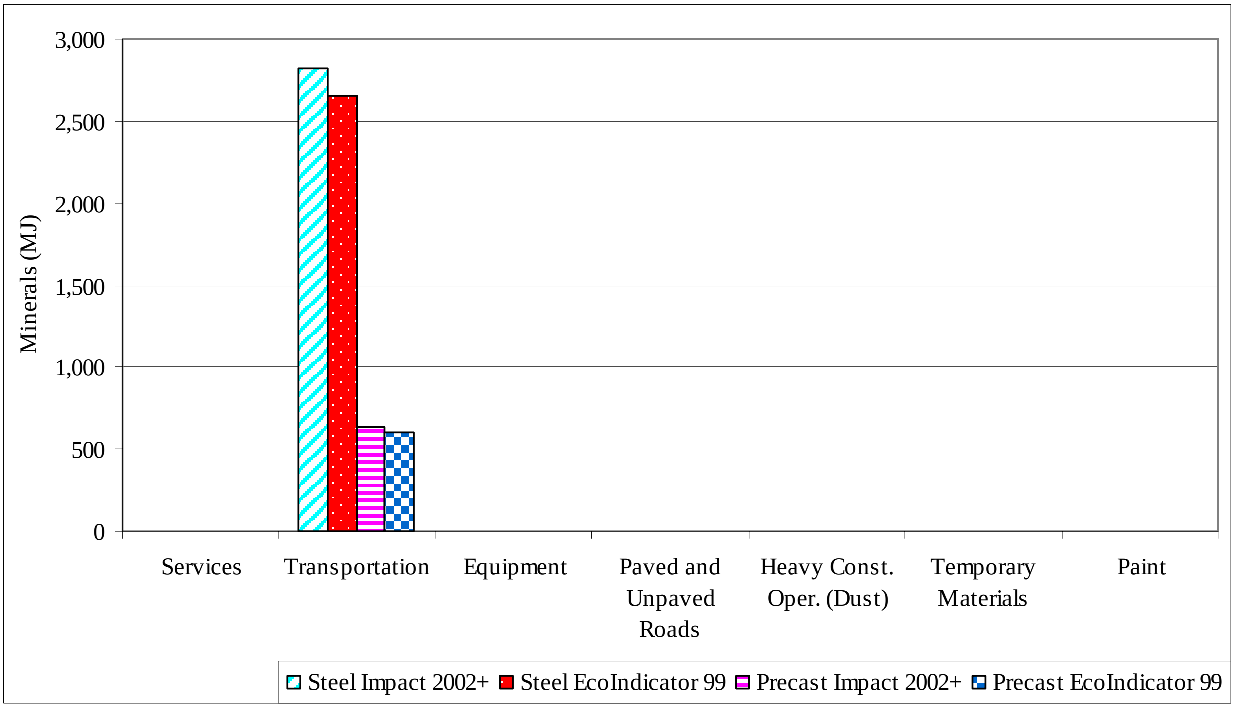


Figure 171. Minerals – Broad Const. LCIA – Steel and Precast (Mean Value)

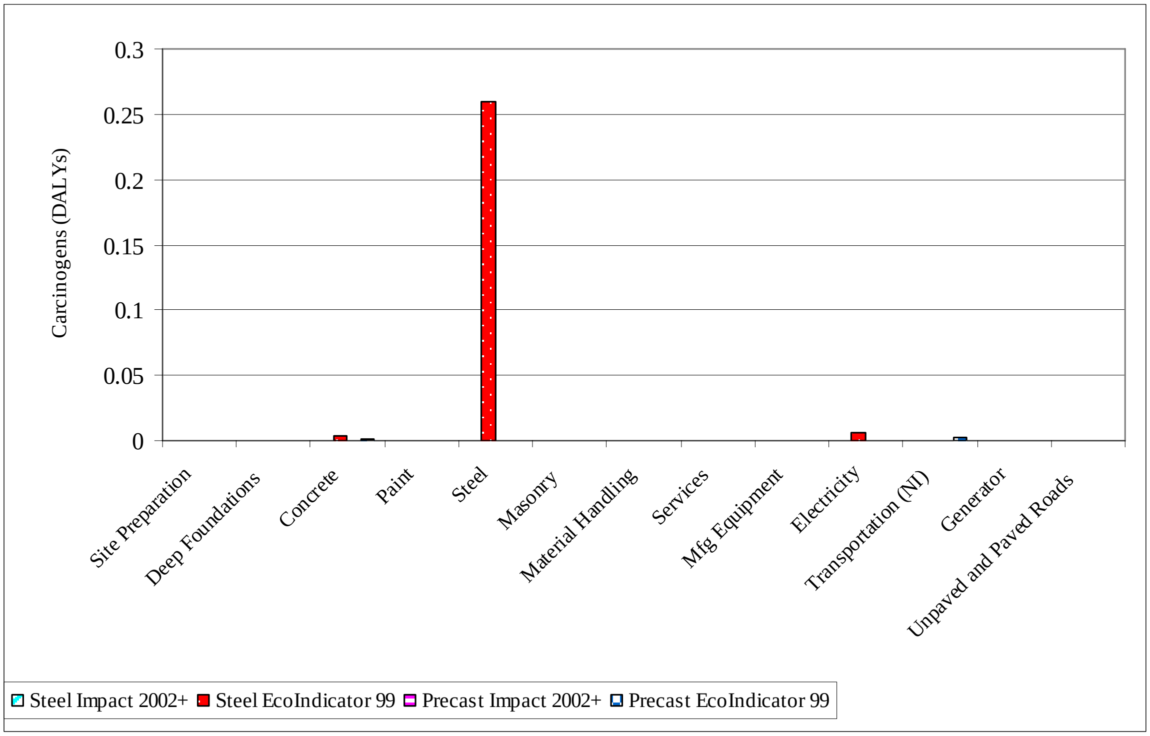


Figure 172. Carc. – Aggr. Const. Processes LCIA – Steel and Precast (Mean Value)

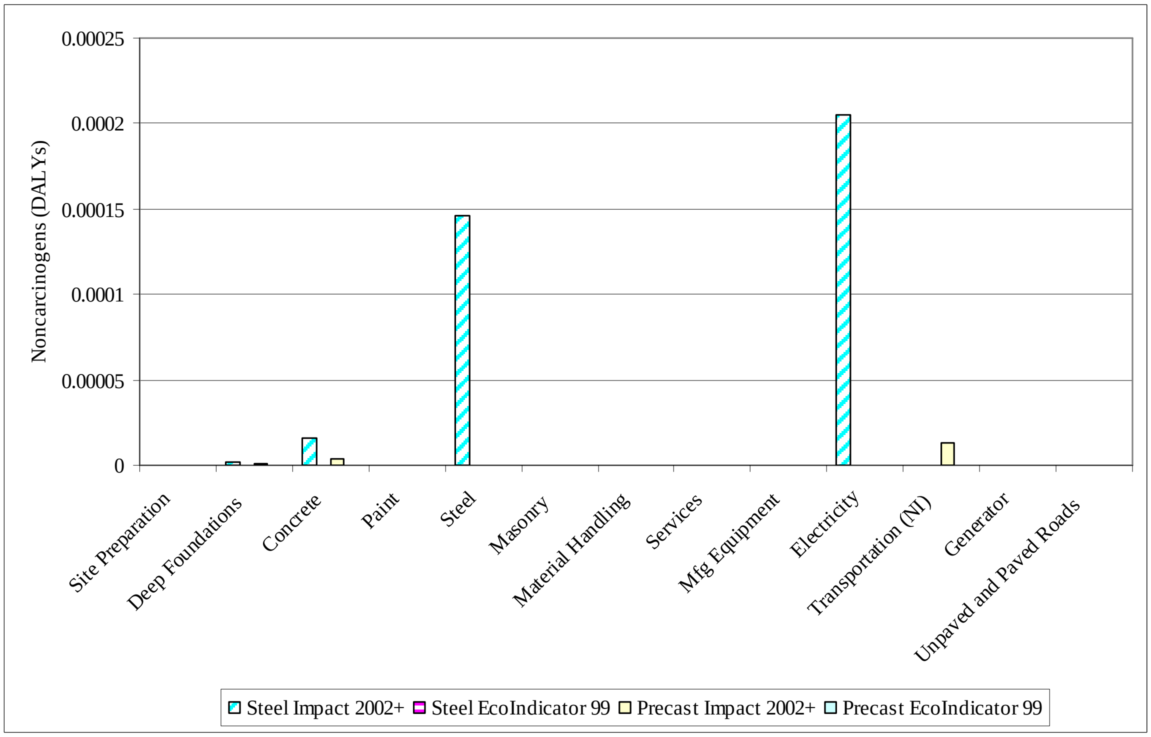


Figure 173. Noncarc. – Aggr. Const. Processes LCIA – Steel and Precast (Mean Value)

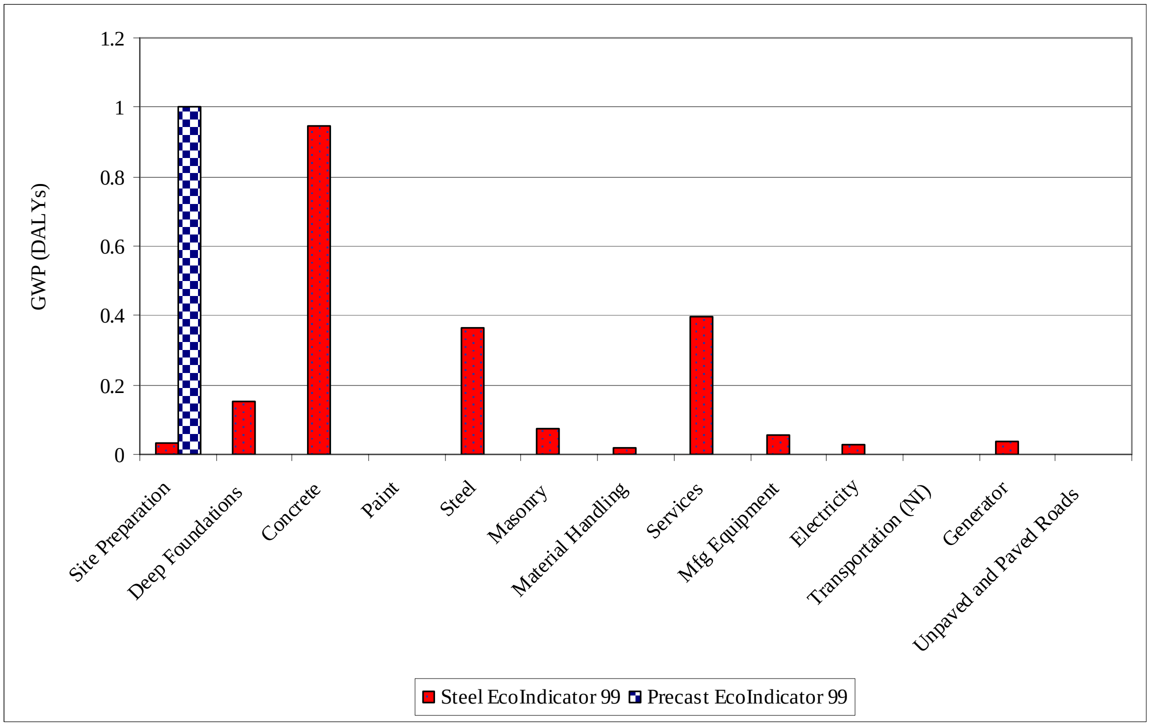


Figure 174. GWP DF – Aggr. Const. Processes LCIA – Steel and Precast (Mean Value)

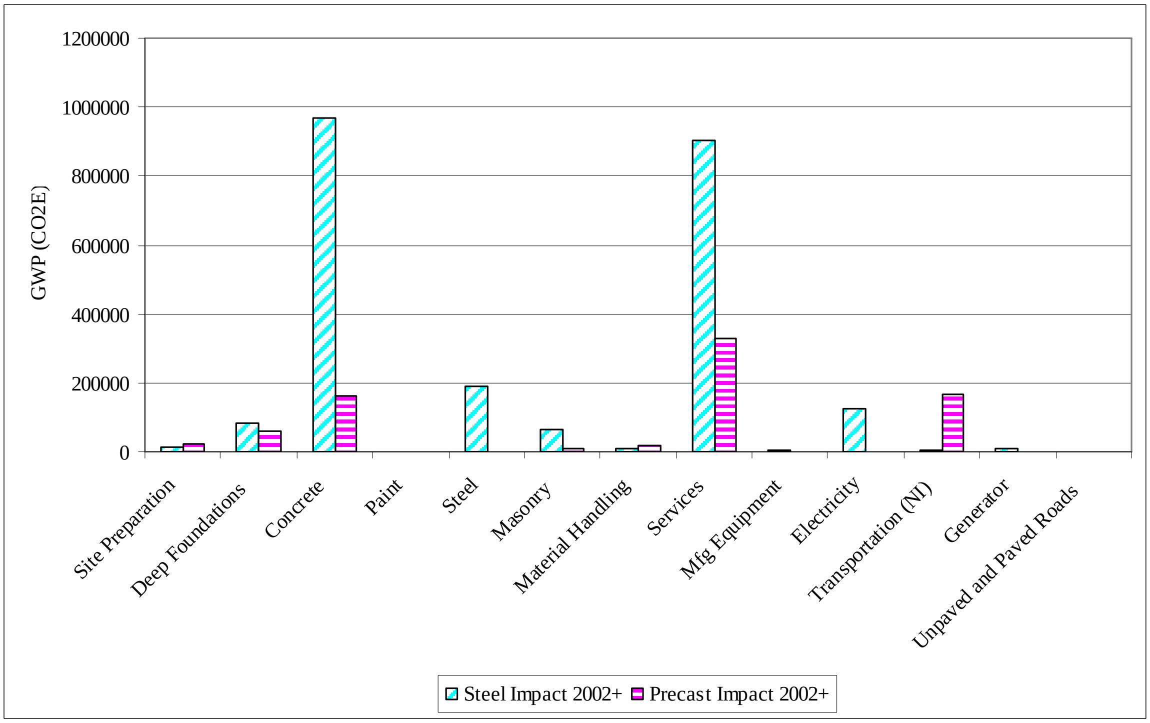


Figure 175. GWP CF– Aggr. Const. Processes LCIA – Steel and Precast (Mean Value)

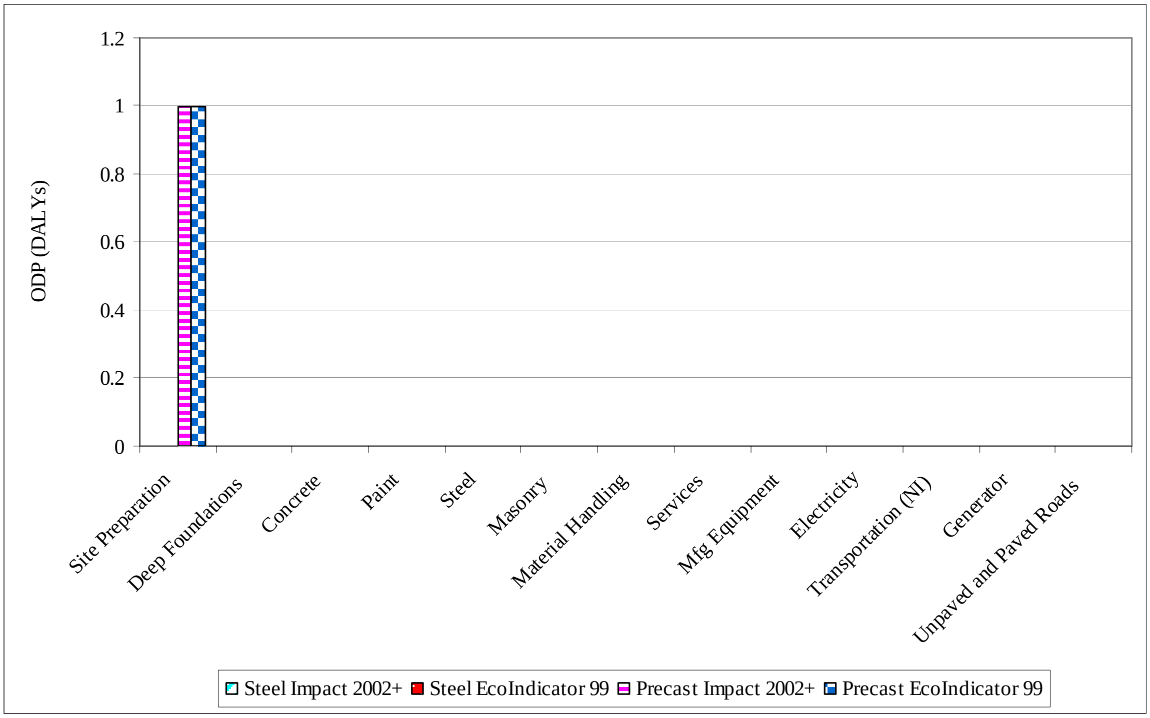


Figure 176. ODP – Aggr. Const. Processes LCIA – Steel and Precast (Mean Value)

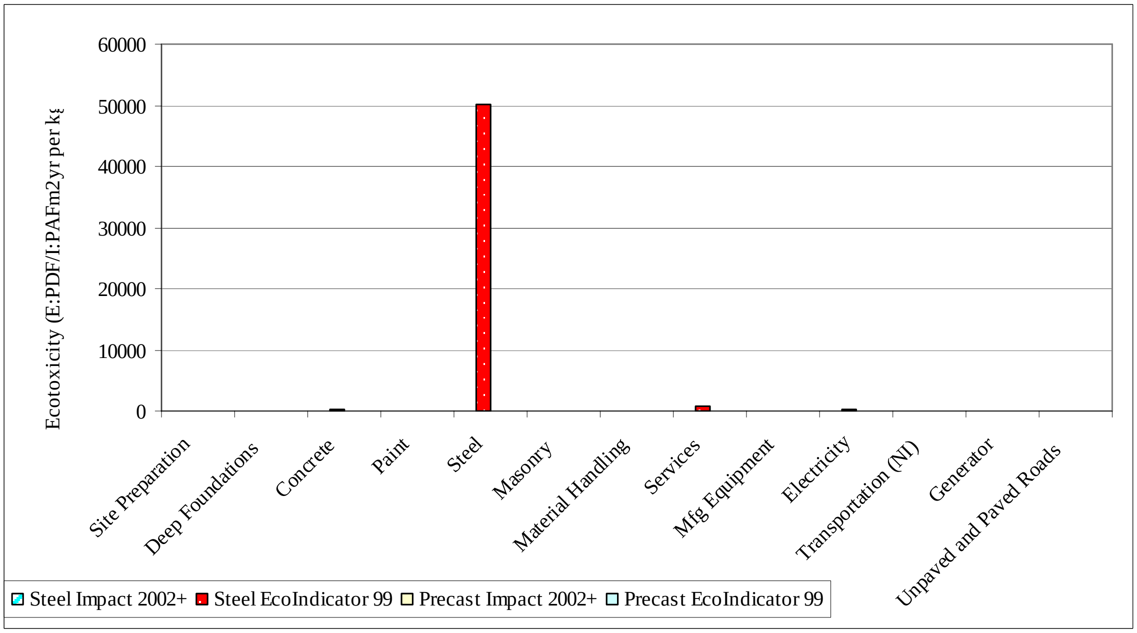


Figure 177. Ecotox.– Aggr. Const. Processes LCIA – Steel and Precast (Mean Value)

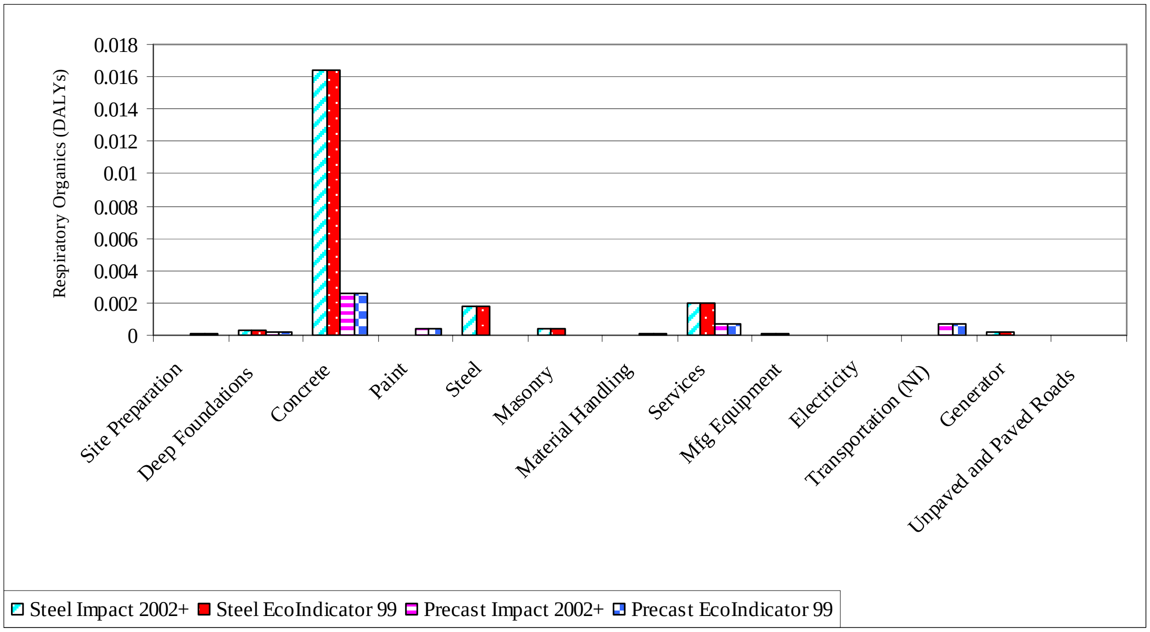


Figure 178. Resp. Organics– Aggr. Const. Processes LCIA – Steel and Precast (Mean Value)

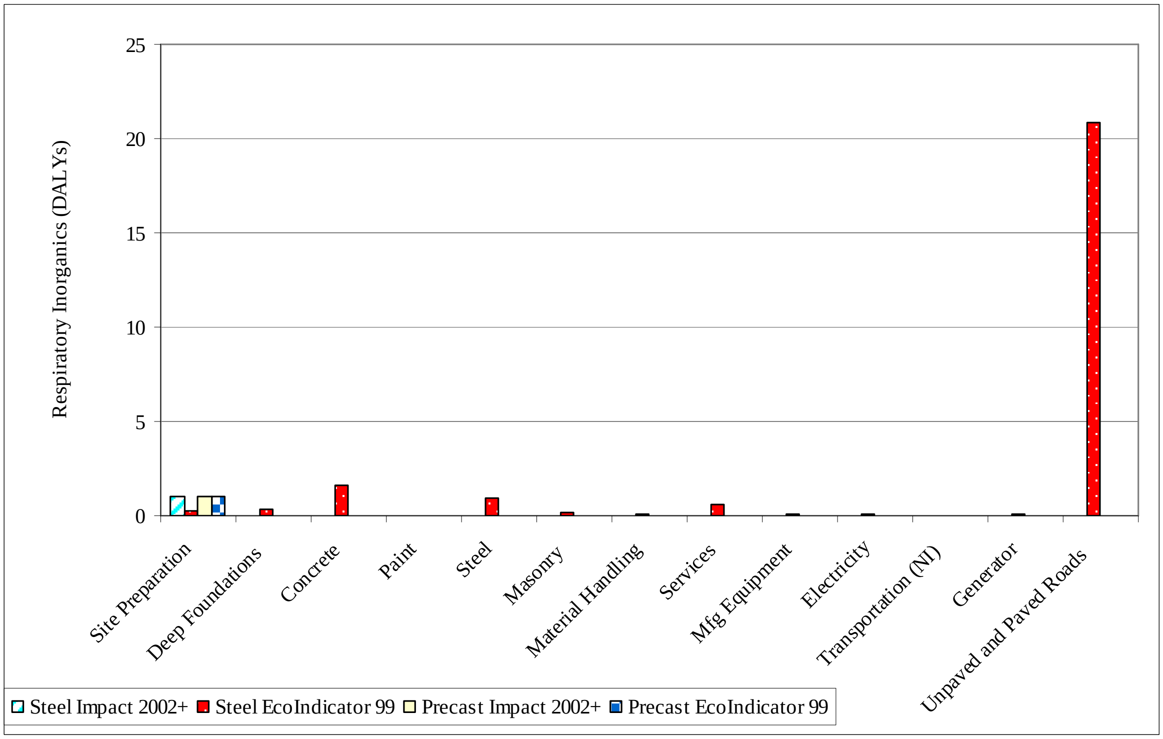


Figure 179. Resp. Inorganics– Aggr. Const. Processes LCIA – Steel & Precast (Mean Value)

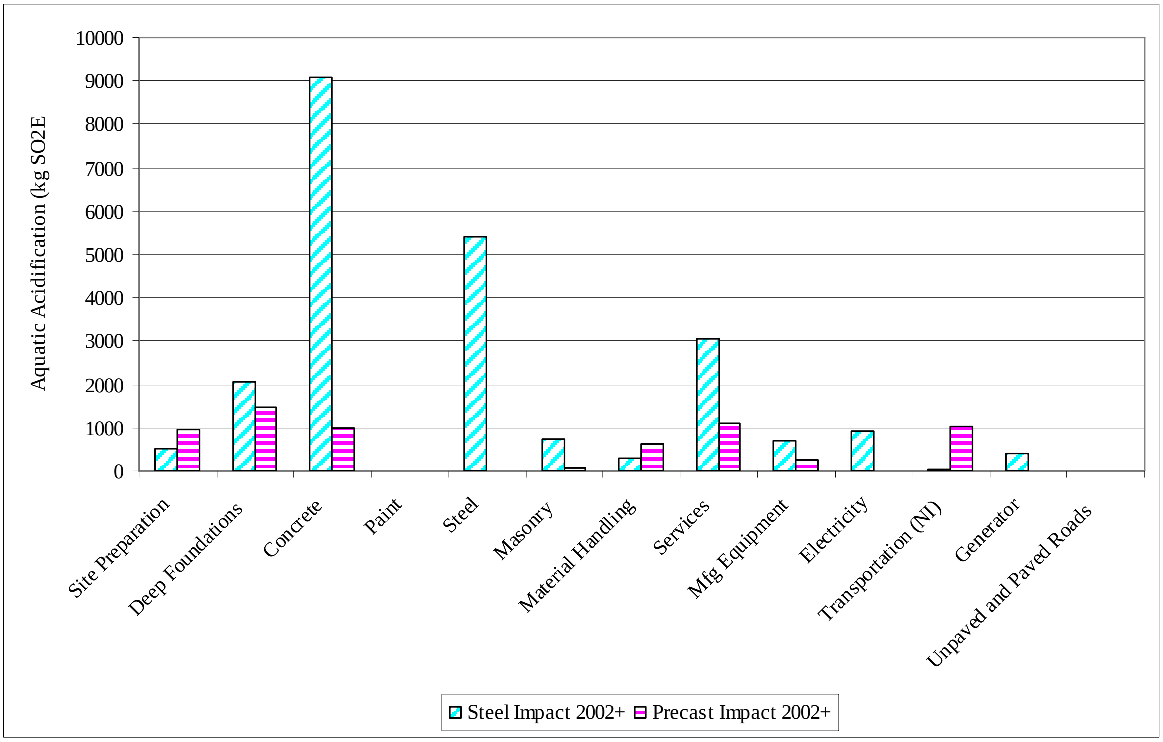


Figure 180. Aquatic Acid.– Aggr. Const. Processes LCIA – Steel and Precast (Mean Value)

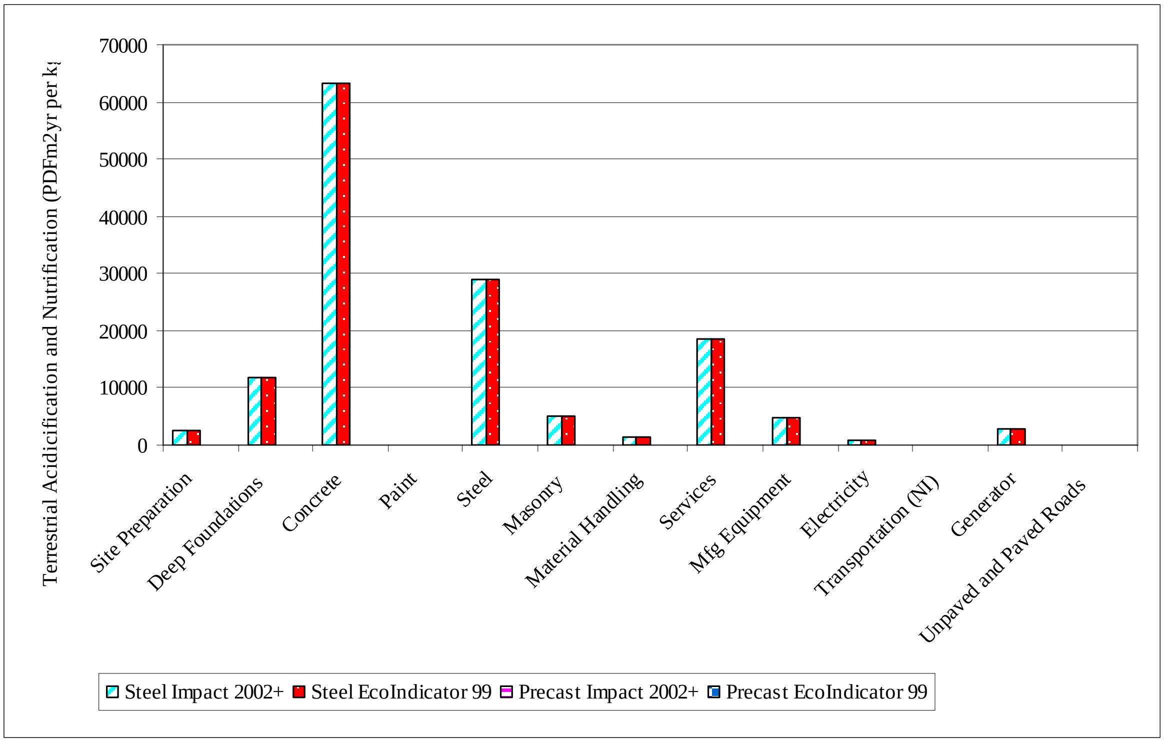


Figure 181. Terr. Acid. & Nutr. – Aggr.. Processes LCIA – Steel & Precast (Mean Value)

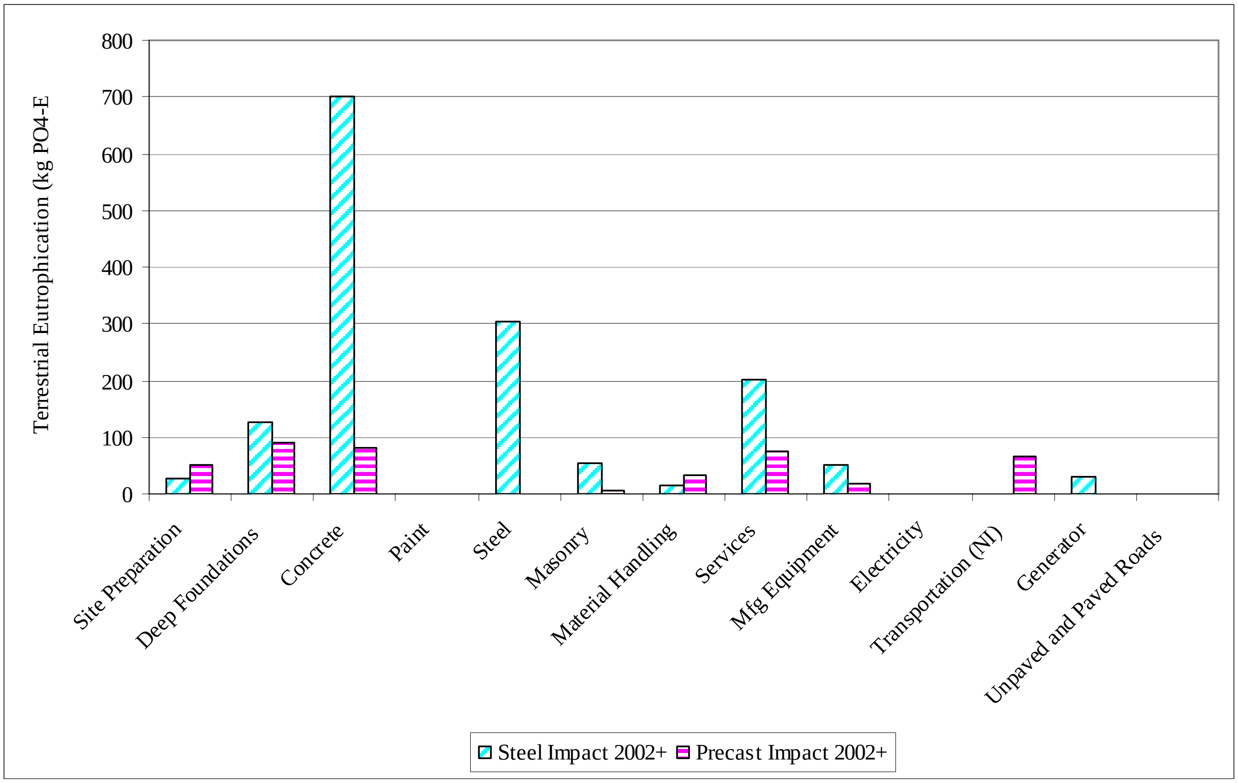


Figure 182. Terr. Eutr. – Aggr. Const. Processes LCIA – Steel and Precast (Mean Value)

APPENDIX J. PROJECT DELIVERY AND GREEN DESIGN

PROJECT DELIVERY AND GREEN DESIGN

Communication, coordination, and contracts between the owner, contractor, and designer are important for project success. Selection of the project delivery method (PDM) should be based on many factors, including the owner's experience; administrative constraints; funding restrictions; schedule and completion requirements; and legal limitations. Another criterion for selection of a PDM can be its relative success in implementing the project's green design and sustainability goals. With the increasing number of sustainable and green projects as evidenced by the growing use of the United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) green building rating system, it is important that the relationship between the PDM and green design goals is better understood by designers, owners, and the construction industry.

Given the definitions of green design and the design-build PDM, it reasonable to consider a complementary relationship between the two: both green design and design-build are intended to create an integrated, holistic, team-based collaborative project. Additionally, it is also possible that relationships exist between green design and other PDMs, namely design-bid-build (DBB) and construction management (CM). A preliminary investigation between selected PDMs and green design is explored in this research with a focus on public sector projects. The study was limited to public sector projects to narrow the initial research scope and respond to the increasing number of federal, state, and local agencies mandating green buildings.

Preliminary research focused on two areas – completing a literature review that focused on PDMs and project success factors, independent of green design; and conducting a qualitative, structured interview of owners, contractors, and designers with experience in both public sector projects and green buildings. Upon completion of the interviews, the responses were reviewed for green design project characteristics and the relationship to the PDM used in the project. Next, the correspondence between existing research on critical project success factors reported in the literature and the survey responses were made to develop initial insights into possible unique aspects related to green design projects. Quantitative analysis was not conducted in this phase of research, but is anticipated in future work.

The section begins with a brief description of some project delivery methods, then continues with a description of research approach, the literature review, the preliminary findings, and concludes with future research directions.

J.1 PROJECT DELIVERY METHODS

While several types of project delivery methods (PDMs) and their respective variations exist, this research focuses on three methods: design-bid-build (DBB), design-build (DB), and construction management (CM).

J.1.1 Design-Bid-Build

DBB is a traditional project delivery method prevalently used in public projects. With this method, the owner contracts separately with the designer and the contractor. A direct contractual relationship between the designer and contractor does not exist, although a working relationship is typically established. The schedule progression is typically linear; that is, the designer completes the design, the owner solicits bids for the project, and then the contractor builds the project. Perceived advantages of this approach are typically clearly defined roles; the owner has significant control over the process; and the checks and balances between the three parties lead to a higher quality project.

While DBB is a frequently used method, several drawbacks exist. Since a contractual relationship does not exist between the contractor and designer, a non-productive adversarial relationship between the parties can develop because the individual entities are mainly protecting their respective interests. It is commonly believed that the DBB projects have extended schedules often caused by relatively long procurement processes; for example, most federal, state, and local projects require a minimum three week bidding period. Perhaps the greatest disadvantage of DBB is that the budget, schedule, and ultimately the perceived success of the project rely heavily on the completeness of the contract documents. Design omissions and errors equate to change orders and possibly schedule delays. Often for public projects, the use of DBB is dictated by the funding source, associated legislation, and procurement laws; public agencies may not have a choice regarding the project delivery method. Efforts to improve DBB include an owner's concerted efforts to ensure accurate contract documents, pre-qualifying bidders, and commitments through partnering (Mulvey 1998).

J.1.2 Design-Build

In the DB project delivery system the owner contracts with a single venture to perform both the design and construction phases of a contract, offering the owner a sole contract with a single point of contact and responsibility. DB use is increasing, especially in the private sector. DB often appeals to the owner due to a single-source of contact along with responsibility, decrease in contract administration efforts, and often a decrease in the project schedule due to the overlapping design and construction phases. Variations of DB are as follows:

1. Multiple DB: Design construction phases coincide; owner contracts with separate DB firms for different phases or aspects of the projects.
2. Turnkey: Design and construction phases coincide; owner contracts with one turnkey contractor who is responsible for design, construction, and commissioning.
3. DB Bridging: Detailed description below.

Some of the perceived disadvantages associated with DB include the owner's potential reduced level of control over the final project and quality. DB owners often believe that quality may be compromised because DB lacks the checks and balances typical in DBB. Most DB firms or joint ventures are headed by the contractor, possibly due to bonding capacity, with the designer as the subconsultant. With the contractor as the lead and ultimately responsible for the bottom line, the designer's recommendation with respect to quality may be 'over-ruled' due to budget issues. Another important issue faced by owners in DB is the importance of the selection of a capable design-build team. In an attempt to take advantage of positive elements of both DB and DBB, a hybrid known as ‘Design-Building Bridging,’ or simply, Bridging, was created in 1982 by George Heery (Brookwood 2006). In Bridging, the owner with a designer establishes a strong set of documents, typically comparable to the design development phase, and then works to award a contract with a DB firm. As will be subsequently discussed, several U.S. government agencies are using DB Bridging, along with additional modifications.

J.1.3 Construction Management

Several varieties of construction management (CM) exist with two common variations being CM at risk (CMR) and agency CM. Both methods offer the advantages of engaging a contracting firm at the onset of a project and benefiting from the CM firm’s expertise in scheduling, budgeting, and value engineering. CMR is a method where the owner contracts with both a designer and a construction manager. The CM firm, typically selected on qualifications, functions in a dual role responsible for both construction management services and construction activities. While definitions of CMR vary, this method typically uses a Guaranteed Maximum Price (GMP). At a certain point in the design process, which varies according to project, the CM develops a GMP based on the contract documents. The CM and the owner enter into a contract based on the GMP. ‘At-risk’ depends on whether it is from the perspective of the owner or the CM. From the owner’s perspective, ‘at-risk’ is any substantial changes to the design subsequently resulting in a legitimate change to the GMP. From the CM’s perspective, ‘at-risk’ means that any minor changes in the contract documents do not change the GMP.

An agency CM functions as an extension of the owner’s staff, and offers advice on budgeting, scheduling, and daily construction activities. While the owner typically holds both the design and construction contracts, the agency CM supports the owner to make educated and practical construction decisions. The contract between the owner and agency CM is often either a percentage of the construction contract or based on hourly staffing requirements.

The advantages of the CM methods are flexibility, especially when the project scope and program is not well-developed; control over schedule and budget when several contractors are involved; and a professional, single-source liaison with the owner. Some disadvantages are the number of people involved in resolving disputes, and disagreement over legitimate scope changes that may or may not affect the GMP. With an agency CM, if the agency CM is also a general contractor, then the agency CM may have difficulty understanding and protecting the owner's interest because of having more experience and perspective from the contractor's standpoint.

J.1.4 Research Approach for Preliminary Results

The preliminary research involved two components: a structured qualitative survey and a literature review focused on PDMs. The research approach is to some extent a simplified version of that used by Songer and Molenaar (1997) in developing project characteristics. This section mainly focuses on the survey. The first step in the survey was developing a database of contacts. The four main sources that comprised the database were the USGBC's (2006) website, Design Build Institute of America's (2006) website, contact with the Associated General Contractors (AGC), and web searches. Only completed projects were included in the database. The DBIA's website lists all DBIA registered projects which used DB as a PDM. All public sector building related projects were extracted and included in the database. The AGC was contacted and subsequently sent an email to selected members. A list of the interested members was forwarded and included in the database. Finally, web searches were not only used to obtain information on contacts within government agencies, but also to provide additional knowledge on specific projects. For example, if an architect was contacted about Project X, then a web search was done on Project X to determine the owner and contractor so additional information could be obtained. The database, not including web results, includes about 250 contacts. The intent behind this preliminary research was not rigorous quantitative analysis, but to develop a general understanding of the current state of operations with respect to PDMs, green design, and project success through structured interviews.

The initial approach included a two-step process of data collection. Two sets of questions were developed, one for contacts developed from the USGBC's website and one for contacts from the DBIA. Two different sets of questions were needed because the USGBC projects were known to be green, but the PDM was not known; conversely, it was known that the DBIA projects used DB, but it was not known if the project was green. Web searches and AGC contacts used a combination of the two sets of questions. Flowcharts of question sequences were used to ensure the interviews were conducted in a structured and consistent manner. Next, a questionnaire was developed that focused on quantitative aspects and quality. The interview covered both green project characteristics as well as PDMs. The questions included:

- What project delivery method was used?
- Was the project successful, why or why not?
- Do you think the PDM had an effect, either positive or negative, on the project? How?
- What PDM do you think should be used for green projects?
- Can you recommend some best practices for PDM on green projects?

The intent of the phone interviews was the structured interview, but it was also used to determine if the questionnaire should be sent. If the project was appropriate, then the questionnaire was sent to the interviewee via the preferred method of email, fax, or mail. Finally, the interviewee was to return the questionnaire. For the phone interview process, approximately 75 contacts were called. During the initial phase of the phone interviews, the majority of the interviewees was not interested in the questionnaire portion and indicated that decision during the phone interview or did not return the questionnaire. Due to the low response rate on the questionnaire, it was not possible to conduct analysis of the responses.

In total, 88 individuals were contacted either via telephone or email, and 21 interviews were conducted. During the 21 interviews, several individuals discussed more than one project, so 26 projects are included in the study. The response rate was 24% on an actual interview basis, and 30% on a project basis. Owners represented about one-half of the respondents; DB projects were about one-half (14); DBB were about one-third (8); and the remainder (4) were CM. The information presented in the preliminary findings section was not normalized or adjusted based on the respondent or PDM type. Six respondents completed the questionnaire. Since only a small number of questionnaires were completed, the results are not reported here. The majority of the projects were commercial buildings. After the interviews were completed, responses were tabulated, evaluated, and organized into common project characteristics and the associated PDM.

J.1.5 Literature Review

A relatively large amount of research has been conducted regarding PDMs in projects in general compared to research of PDMs with green design projects. Therefore, a literature review was conducted of project delivery systems irrespective of the relationship with green design. The literature review focuses on the following aspects:

- Quantitative studies related to PDMs to report advantages and disadvantages of the associated method;
- Project characteristics that complement DB;
- The owner's role in DB projects;
- The public sector's perspective on DB; and
- Characteristics of successful projects.

J.1.6 Quantitative Studies of Project Delivery Methods

The goal of the literature review was to understand the current state of knowledge on PDMs, looking more specifically at DB, and develop a comprehensive list of successful project features. There has been a relatively large amount of research on PDMs in projects in general compared to research on PDMs with green design projects. Therefore, a literature review was conducted of project delivery methods irrespective of the relationship with green design. The literature review focuses on the following aspects with emphasis on DB:

- Quantitative studies related to PDMs to report advantages and disadvantages of the associated method;
- Project characteristics that complement DB;
- Owner's role in DB projects;
- Public sector's perspective on DB; and
- Characteristics of successful projects.

Quantitative studies on PDMs report positive, negative, and neutral findings on DB. Konchar and Sanvido (1998) collected project specific data from 351 U.S. building projects to empirically compare cost, schedule, and quality with respect to CMR, DB, and DBB. Univariate results indicated that DB projects performed equally or better than DBB and CM@R.

Ibbs et al. (2003) examined the effectiveness of 67 projects related to DB and DBB. The study quantitatively analyzed the impact of different PDMs on changes in cost, changes in schedule, and productivity. This research differs from Konchar and Sanvido (1998) in that Ibbs et al. (2003) also included productivity, which leads to changes in cost and schedule. The authors concluded that the reported cost savings associated with the DB method were not fully substantiated by this set of data with univariate statistical analyses. Relative to schedule, DB projects experienced a 7.7% change whereas DBB were at 8.4%. The authors note that while it is important to understand PDMs in concert with cost and schedule, the significant indicator is productivity. Productivity was analyzed as a function of cost and schedule changes by calculating best fit regression equations. The authors observed that the effects on productivity were difficult to predict and ultimately may depend on the functionality of cost or schedule versus productivity. To summarize, this study found that DB did not perform significantly better than DBB.

The literature review also focused on project success to better understand the potential relationship of green design project success and PDMs. Understanding and defining not only characteristics of successful projects but also key project characteristics with respect to PDMs is critical for selecting the appropriate PDM for a project.

Songer and Molenaar (1997) examined 88 public sector projects to identify project characteristics that are critical for success. Criteria of success is staying on budget, conforming to user's expectations, and staying on schedule. This study found that the top five DB characteristics for successful DB projects are (1) well-defined scope, (2) shared understanding of the project scope, (3) adequate owner staffing, (4) owner's construction sophistication, and (5) established budget. With the project characteristics established, Molenaar and Songer (1998) then tested the above characteristics by attempting to predict the relationship between the characteristics and project success for public sector projects using DB. Results indicated that the most critical element to project success is the owner. The owner's critical roles are developing accurate request for proposals (RFP) and active involvement in the design phase. These results are important because they are contrary to the perceived belief that DB projects have a lower administrative burden.

Several other studies have also attempted to define successful project characteristics. Alkhathami (2004) summarizes several key project success factor studies. For example, Ashley et al. (1987) developed a comprehensive, filtered, and statistically significant list of project success factors:

1. Construction and design planning effort
2. Project manager goal commitment
3. Project team motivation
4. Project manger technical capabilities
5. Scope and work definition
6. Control systems

Additional research on project success factors was done by Sanvido et al. (1992). The researchers found four critical factors that determine project success:

1. A well-organized, cohesive facility team to manage, plan, construct, and operate the facility.
2. A series of contracts that allow and encourage the various specialists to behave as a team without conflict of interests and differing goals.
3. Experience in the management, planning, design, construction, and operations of similar facilities.
4. Timely information from the owner, user, designer, contractor, and operator in the planning and design phase of the facility.

Chua et al. (1999) used analytical hierarchy process (AHP) with subjective expert judgments to identify critical success factors (CSFs) with respect to budget, schedule, quality, and overall performance. A summary of the CSFs based on overall performance includes:

1. Adequacy of plans and specifications
2. Constructability
3. PM commitment and involvement
4. Realistic obligations/clear objectives
5. PM competency
6. Contractual motivation/incentives
7. Site inspections
8. Construction control meetings
9. Formal communication (construction)
10. Economics risks

In summary, while some research has concluded that the hypothesized benefits of DB are not conclusively demonstrated, the majority of research has reported that DB is an effective PDM given a project with appropriate characteristics. Secondly, with respect to the public sector, as the use of DB increases and the owner's experience with DB increases, some of the reported administrative burden should be reduced. A substantial amount of research exists on project success factors, and a representative sampling was described. The successful project characteristics from these studies are compared to characteristics of green design projects in the subsequent section.

J.1.7 Review of Preliminary Findings

Two major aspects of the preliminary research are summarized in this section. First, green project characteristics as they relate to PDMs are discussed, and then a comparison of those characteristics with existing project success factors was evaluated.

The interviews were summarized and evaluated in a structured manner and common "green project characteristics" were identified. The "green project characteristics" are often not mutually exclusive. One example is with number 4, Clear definition of scope of work, and number 5, Adequate budget and funding limitations, because an overly ambitious scope of work can strain a fixed budget. Each of these characteristics have been examined in relation to the survey responses and other related published work to determine if the characteristic is more relevant or associated with a particular PDM, if it is generally regarded as a good practice, or if it is both. The seven important project characteristics that emerged from the structured interviews follow:

1. Collaboration
2. Team Experience
3. Leadership
4. Clear definition of scope of work
5. Adequate budget and funding limitations
6. Complexity and Flexibility
7. Control and Accountability

Collaboration

Project team collaboration early in the design and construction process is an important aspect of green projects. Several interviewees strongly suggested that one key to project success for green design projects was collaboration. Collaboration is cooperation among the owner, contractor, designer, or design-builder. From the survey results, collaboration early in the project was recommended by six of the respondents; integrated team was recommended by four of the respondents. One respondent emphasized both collaboration and an integrated team. With respect to this feature and PDMs, collaboration was considered somewhat more important in projects that used DB. Five of fourteen DB projects, three of eight DBB projects, and one of four CMR projects stressed that collaboration was an important feature for project success. Collaboration was a slightly more prevalent feature in DB projects, but also considered important in DBB projects. The conclusion, therefore, is that collaboration is important on all green design projects, and is an important characteristic of green design projects that use DB.

Team experience

Team experience is important on all green design projects independent of the PDM. Owners should use a ‘best value’ selection process, which is more prevalent in DB projects, and include team experience as a criterion. The owner’s role is critical with DB. The experience of the designer, contractor, and owner is an important feature of green design projects. From the interviews, six respondents believed that team experience was an important characteristic in a green design project. Of those six, four projects were DB, while two projects were DBB. Experience with the LEED rating system and its credits are important characteristics for all parties. One of the critical characteristics in a successful DB project is the role of owner. The owner’s experience is central early in the project, in particular, the owner’s development of the RFP in the initial design phase (Molenaar and Songer 1998). The experience of the contractor’s project manager was also noted as an important characteristic in this survey, and it is corroborated by existing research.

Leadership and Contractual Incentives

Leadership is an important characteristic for all contracting parties involved in green design projects and it is a dominant characteristic in DB projects. The importance of leadership was discussed during seven interviews. Six of those interviews were associated with DB projects, and one was associated with a DBB project. Leadership, as discussed during the interview process, was fairly broad and depended on the person’s perspective. For example, a contractor recommended that a contractor should lead the DB team. On the other hand, a designer recommended that the designer should lead the DB team. The contractor believed construction companies remained more focused on budget and schedule. The designer believed that they were able to guide the project to achieve higher LEED ratings and maintain a higher level of quality standards for the projects. One owner mentioned that he was considering a project delivery method that would put the contractor and designer on an equal footing, or have the designer as the lead. This owner explained that with DB, "…the contractor typically holds cost first, quality second. Conversely, the A/E firm holds quality first, and cost second. But, because the contractor typically holds the DB contract, cost usually wins."

The owner's leadership is critical in setting the tone of the project and setting a clear direction, not only in the scope of work, but also during construction as issues arise. During three of the interviews, the importance of owner's leadership was discussed in terms of setting and remaining focused on the budget and LEED goals. For green design projects, it is most commonly the owner's decision that a project will have green design features, and then often determines the LEED rating range or state that the project will be LEED silver, for example. One interviewee pointed out that one successful characteristic in a DB project was that the owner not only set an attainable LEED rating but also established a good and realistic budget to achieve the LEED goal. Another interviewee thought that the owner's focus on the budget helped to achieve a successful project.

Agencies that are using DB, such as the Pentagon to name just one, have found it effective to include award and incentive fees to the design-builder. An award fee, typically 10% of the contract award, provides the design-builder with an up-front incentive and starts the project in a positive manner. The award fee not only acts as an effective relationship builder, but also assists in paying some of the designer's fees. With respect to the incentive, if there is a savings, then a split is shared between the DB firm and the owner. If there is an overrun, then an established not to exceed split is also shared between the DB firm and the owner. The Pentagon also uses quarterly progress reports which are associated with incentive fees. Contractual incentives in turn create contracts with complementary goals, all project success factors cited by Chua et al. (1999), Alkhathami (2004), and Sanvido et al. (1992).

Clear definition of scope of work

A well-defined scope of work is important on all projects. Having a clear scope of work was mentioned during five interviews. Four of the five interviews were related to DB projects. In the case of DB, bridging helps improve quality and the owner's control; and using performance specifications to attain a LEED certification has been an effective contract administrative technique. A clear scope of work minimizes change orders and schedule delays in all PDMs. A clear scope of work is a project success factor in Ashley et al. (1987).

In Design-build bridging, the owner produces a set of documents and establishes an RFP based on the bridging documents. The selected design-builder incorporates the bridging document into the final design and project. It should be noted that one interviewee mentioned that a potential problem with bridging is that the architect of record is the architect from the design-build company, which may become an issue when the bridging documents are incorporated from a different architectural firm. Bridging was mentioned during several of the interviews, and several respondents stated that bridging is recommended and used by the United States General Services Administration (GSA). DB bridging is used to maintain the owner's level of control and meet quality standards, two aspects of DB that are often cited as disadvantages. DB bridging appears to work well with green design because it allows the project team flexibility during the design and construction phases to experiment and meet LEED requirements, and ensures attainment of the owner's project goals and quality level.

Regardless of the PDM, several interviewees mentioned that specifying green design elements as performance specifications, such as the project shall meet or exceed a specified LEED rating, was effective to realizing green design goals. Performance specifications set clear goals and shifted some of the responsibility from the owner and designer to the contractor. Since a significant number of LEED credits are managed or driven by the contractor, this approach assisted in obtaining the owner's overall green project goals. Some owners who use DB are using design competitions to assist them in the selection process. The owner gives the short-listed firms design fees or a stipend to compete in the selection process, which is a two-fold advantage because the firms are compensated for their proposals while the owner is given the opportunity to further define and solidify the project's scope of work before entering into a DB contract.

Adequate budget and funding limitations

Having adequate funding and budget for the given scope of work is particularly important in a green design project. Public funding restrictions may not allow the use of certain PDMs, and the nature of public funding streams may make non-traditional PDMs more difficult. Based on observations in this research, the use of non-traditional PDMs seems to decrease as one moves from federal, to state, to local levels. The federal government uses more DB than the local governments with the state's usage in-between. On the other hand, one federal employee noted that the GSA's program requirements changed often, so DB may not work well due to shifts in the program. Also, the funding allocation is often separated between the design and construction phases making the option to pursue DB more administratively difficult. One interviewee noted that DBB must be used due to funding and legal constraints.

Two respondents cited the importance of the owner's expectations in conjunction with the budget and LEED goals. Incorporating green design early in the design process in the Pentagon renovation projects resulted in spending less money on green aspects while achieving a higher LEED certification (Pulaski et al. 2003).

Complexity and Flexibility

Project complexity and flexibility is a project characteristic that is more positively associated with DB. Flexibility and complexity are included in the same category because during the interview process the two features were often intertwined; for example, a complex project required flexibility from all team members to produce a successful project. Complexity and flexibility were discussed in six of the interviews; three were associated with DB projects, two with DBB projects, and one interviewee based on experience. These combined characteristics appear to be more prevalent in green design projects, as they are minimally mentioned in existing research reviewed herein, but Molenaar and Songer (1998) do include project complexity as a success factor for DB projects. Interviewees said that they decided to use DB because it allowed them to be more flexible and allowed the team to refine the design without affecting the schedule. DB's flexibility fostered a collaborative effort that resulted in an end-product with many owner or tenant requested features. This aspect is important when the project is being built by a developer with a long-term lease tenant who has specific space requirements.

Administratively, it was more difficult with DBB to make changes because the change order process was difficult and time-intensive causing additional costs and schedule delays. However, one interviewee believed that sustainable design was too complex to achieve with a traditional design-build PDM.

Control and Accountability

Control and accountability are related problems and are associated with DB to a greater degree than with DBB. Project controls are instituted to provide for the accountability of the project team. Control and accountability are not specific to green design projects, and as discussed earlier, DB Bridging can be used to offset the lack of control with traditional DB. With the owner's level of project control potentially reduced when using DB, accountability of the DB team to the owner can be lost as well. This issue was discussed in four interviews; two were DBB projects, one was a DB project, and one was speaking based on experience. The two DBB interviewees both believed that DBB was the best option when the owner desired a great deal of project input and control. One architect interviewed believed that DB diminished owner's participation, and that the architect's access to the owner was limited. On the other hand, one interviewee that participated in a DB project thought that DB was the better approach when green design was involved because of the project team's continuity.

A consistent relationship between green design projects and a particular PDM did not emerge from this preliminary research. However, based on the limited survey data and consistent with other research, it is concluded that, rather than identifying one PDM that should be used for all green design projects, individual project characteristics should be the basis for PDM selection for green design projects. Future research will further investigate the relationship between the identified green design project characteristics and PDMs.

Second, some green design project success factors were identified that may be unique to green design projects. Project success factors from Ashley et al. (1987), Sanvido et al. (1992), and Chua at al. (1999) are shown in Table 55, along with the green design project characteristics identified from this work. Of the seven green design project characteristics, three characteristics – Leadership, budget and funding, and complexity and flexibility – were not identified in previous research as critical project success factors.

Table 55. Literature Critical Success Factors& Research Green Design Characteristics

Existing Literature Project Success Factors			Green Project Characteristics
Ashley et al. (1987)	**Sanvido et al. (1992)**	**Chua et al. (1999)**	**Bilec and Ries**
-	-	Adequacy of plans and specifications	-
Scope and work definition	-	-	Scope and work definition
-	-	Constructability	-
Project manager goal commitment	-	PM commitment and involvement	-
-	-	Realistic obligations/clear objectives	-
Project manager technical capabilities	-	PM competency	-
-	-		-
-	-	Site inspections	-
Control systems	-	Construction control meetings	Control and accountability
-	-	Formal communication (construction)	-
-	-	Economics risks	-
-	Well-organized, cohesive facility team	-	Collaboration
-	Contracts with complementary goals	Contractual motivation/incentives	Contractual incentives
-	Team experience	-	Team experience
-	Timely, valuable, optimization information	-	-
Planning effort (construction and design)	-	-	-
-	-	-	-
Project manager motivation	-	-	-
-	-	-	Leadership
-	-	-	Budget and Funding
-	-	-	Complexity and Flexibility

J.1.8 PDM Conclusion

The intent of this research was to examine the relationship between project delivery methods and green design projects in order to assist the public sector in the selection of a PDM appropriate for a green design project. This research is relevant and timely since an increasing number of Federal, State, and local agencies are mandating green buildings.

This preliminary research used qualitative survey analysis and structured interviews. Further, literature reviews were conducted on the effectiveness of PDMs and on project success factors in general, without considering green or sustainable aspects. The most important finding is that the PDM selection decision for green design projects should be based on project characteristics. The green design project characteristics identified in this research are as follows:

1. Early team collaboration is an important aspect of green design projects, and even more significant in DB projects.
2. Not only is the experience of the designer and contractor important, but also the owner's role and experience is critical. This finding is independent of the PDM.
3. Leadership is an important feature for all contracting parties involved in green design projects, and is particularly important in DB projects.
4. A well-defined scope of work is important on all green design projects. For DB projects, DB Bridging helps improve the owner's control and quality.
5. Adequate funding and budget for the given scope of work is significant for green design projects. Public funding restrictions may not allow the use of certain PDMs, and the nature of public funding streams may make non-traditional PDMs more difficult.
6. Project complexity and flexibility is a project feature that is more specific to green design projects and DB may handle this characteristic better than other PDMs.
7. Control and accountability is a problem associated with DB more than with DBB. It is not specific to green design projects. As with scope of work, DB Bridging can be used to offset the lack of control with traditional DB.

A relationship between DB and green design did not explicitly emerge, but several broad characteristics related to PDMs and green design did emerge which may assist the owner in making the appropriate PDM decision. Further, when using DB on a green design project, the main recommendations were to use DB Bridging with award and/or incentive fees and performance specifications.

Additional research is needed to further investigate the relationship between green design and PDMs. Future research will further develop the identified green design project characteristics and relate those characteristics to both PDMs and project success. The research approach is anticipated to be a more extensive survey allowing statistical analysis of the results.

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