Hybrid life cycle assessment of low, mid and high-rise multi-family dwellings with development of knowledge-based uncertainty bounds

Kimberly Bawden
krbp2i@rit.edu

Follow this and additional works at: http://scholarworks.rit.edu/theses

Recommended Citation
Hybrid Life Cycle Assessment of Low, Mid and High-Rise Multi-Family Dwellings with Development of Knowledge-Based Uncertainty Bounds

by

Kimberly R. Bawden

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Sustainable Systems Department of Sustainability Golisano Institute for Sustainability

Rochester Institute of Technology Rochester, NY August, 2013
By
Kimberly R. Bawden
Submitted by Kimberly R. Bawden in partial fulfillment of the requirements for the degree of Master of Science in Sustainable Systems and accepted on behalf of the Rochester Institute of Technology by the thesis committee. We, the undersigned members of the Faculty of the Rochester Institute of Technology, certify that we have advised and/or supervised the candidate on the work described in this thesis. We further certify that we have reviewed the thesis manuscript and approve it in partial fulfillment of the requirements of the degree of Master of Science in Sustainable Systems.

Approved by:
Dr. Eric D. Williams: _______________________________ Date
(Committee Chair and Thesis Advisor)

Dr. Callie Babbitt: _______________________________ Date
(Committee Member)

Mr. Jules Chiavaroli: _______________________________ Date
(Committee Member)

SUSTAINABLE SYSTEMS PROGRAM
ROCHESTER INSTITUTE OF TECHNOLOGY
AUGUST 2013
Abstract

Golisano Institute for Sustainability
Rochester Institute of Technology

Degree: Master of Science
Program: Sustainable Systems

Name of Candidate: Kimberly R. Bawden
Title: Hybrid Life Cycle Assessment of Low, Mid and High-Rise Multi-Family Dwellings with Development of Knowledge-Based Uncertainty Bounds

Life cycle assessment (LCA) has been used for decades to study the environmental impacts of the built environment. This study extends work in this area by completing an LCA of the cumulative energy demand (CED) and global warming potential (GWP) of low, mid and high-rise multi-family dwellings. Using a hybrid LCA, this study finds that the CED and GWP for low, mid and high-rise multi-family residences increases from 37, 39, to 42 GJ/m², and 3.6, 3.8, and 4 tCO₂eq/m² on average, respectively. As with previous studies, the operation phase dominates total life cycle energy, but with smaller share of 77% to 87%. A follow-up study examines how uncertainty in the energy intensity of materials might affect a building LCA. The exploration led to development of a knowledge-based bounding approach to mitigate uncertainty. Knowledge-based bounding maps knowledge of a product, such as country of origin or recycled content, to numerical uncertainty bounds. Gathering additional information about the product in question can shrink these bounds and, through an iterative process, reduce uncertainty until the goals of an LCA are met. Developing knowledge-based bounds for steel, this study finds that if steel type, recycled content and country of origin are all unknown, the life cycle carbon dioxide equivalent emissions of steel can vary from .7 to 5.9 kg tCO₂eq per kg of steel. In contrast, with knowledge that the steel is unalloyed, and, has a 64-100% recycled content, uncertainty bounds are reduced to .8-1.4 kg tCO₂eq/kg steel. These two bounds are applied in life cycle assessment of concrete and steel framed buildings. The 0.7 to 5.9 kg tCO₂eq emissions per kg of steel bound leads to ranges for the life cycle emissions too wide to distinguish the preferability of steel and concrete framed buildings. However, the lower bounds, 0.8-1.4 tCO₂eq/kg of steel, shows unambiguously that steel-framed buildings have lower CO₂ emissions.
Acknowledgements

I would like to express my sincere appreciation to my advisor, Dr. Eric D. Williams for his continuous insight, support and patience during my time in the Masters’ program at the Golisano Institute for Sustainability at Rochester Institute of Technology. Dr. Williams was always encouraging and supportive of my growth as a student and researcher. His insight helped to develop the research questions for this thesis, and, his guidance allowed me to advance past work in the context of life cycle assessment and highlight areas for future research.

I would like to acknowledge the valuable expertise, inputs and guidance in the context of life cycle assessment provided by Dr. Callie W. Babbitt. Further appreciation goes out to Bob Mewis, Director of Engineering at RS Means, for his valuable inputs on building construction, as well as Professor Jules Chiavaroli, for his support in gathering construction data.

Finally, I would like to recognize and thank the Civil Infrastructure Systems program at the National Science Foundation for providing the funding for this research under grant number 1031690.
Table of Contents

Abstract..........................................................................................................................III

Acknowledgements ............................................................................................................IV

List of Figures ....................................................................................................................VII

List of Tables .....................................................................................................................VIII

List of Figures in Appendices ..........................................................................................X

Chapter 1: Introduction .......................................................................................................1
  Background ......................................................................................................................1
  Research Objectives .....................................................................................................4

Chapter 2: Multi-Family Life Cycle Assessment ................................................................4
  Background and Literature Review ..............................................................................4
  Method ............................................................................................................................8
    Goal and Scope ...........................................................................................................8
    Functional Unit ..........................................................................................................8
    Reference Flow .........................................................................................................8
    System Boundary ......................................................................................................9
    Methodology .............................................................................................................9
    Impact Categories ...................................................................................................10
  Life Cycle Inventory ..................................................................................................10
    Economic Input-Output Approach .........................................................................11
    Economic-Based Approach ......................................................................................17
    Process-Sum Approach ............................................................................................20
  Results .........................................................................................................................24
    Life Cycle Impact Assessment ..............................................................................24
    Interpretation/Discussion .........................................................................................28
    Uncertainty ...............................................................................................................34

Chapter 3: Uncertainty Mitigation through Knowledge-Based Bounding..........................35
  Background and Literature Review ............................................................................35
  Framework ....................................................................................................................38
  Case Study ....................................................................................................................40
  Method ..........................................................................................................................40
    Goal and Scope ........................................................................................................40
    Functional Unit .........................................................................................................41
    Reference Flow ........................................................................................................41
    System Boundary ......................................................................................................41
    Methodology .............................................................................................................42
List of Figures

FIGURE 1. LIFE CYCLE PHASES, U.S. ENVIRONMENTAL PROTECTION AGENCY ........................................5
FIGURE 2. SYSTEM BOUNDARY FOR MULTI-FAMILY LCA ..................................................................9
FIGURE 3. CED FOR MULTI-FAMILY BUILDINGS OF DIFFERENT CONSTRUCTION AND NUMBER OF STORIES ........................................................................................................25
FIGURE 4. GWP FOR MULTI-FAMILY BUILDINGS OF DIFFERENT CONSTRUCTION AND NUMBER OF STORIES ........................................................................................................25
FIGURE 5. % CED FOR MULTI-FAMILY BUILDINGS OF DIFFERENT CONSTRUCTION AND NUMBER OF STORIES ........................................................................................................25
FIGURE 6. % GWP FOR MULTI-FAMILY BUILDINGS OF DIFFERENT CONSTRUCTION AND NUMBER OF STORIES ..........................................................................................26
FIGURE 7. % CED VERSUS LIFE SPAN OF 11-STORY MULTI-FAMILY RESIDENCE ................................27
FIGURE 8. % GWP VERSUS LIFE SPAN OF 11-STORY MULTI-FAMILY RESIDENCE ...............................28
FIGURE 9. CED VALUES FROM THE CURRENT AND PREVIOUS STUDIES FOR THE MATERIALS EXTRACTION AND PRODUCTION LIFE CYCLE PHASE .........................................................30
FIGURE 10. CED VALUES FROM THE CURRENT AND PREVIOUS STUDIES FOR THE CONSTRUCTION LIFE CYCLE PHASE ................................................................................................31
FIGURE 11. CED VALUES FROM THE CURRENT AND PREVIOUS STUDIES FOR THE OPERATION LIFE CYCLE PHASE ........................................................................................................32
FIGURE 12. FRAMEWORK FOR ITERATIVE KNOWLEDGE-BASED BOUNDING .................................38
FIGURE 13. SYSTEM BOUNDARY FOR THE CASE STUDY ON STEEL MANUFACTURING ..................42
FIGURE 14. PROCESS-SUM MODEL RESULTS FOR CRADLE TO GATE CUMULATIVE ENERGY DEMAND FOR STEEL AS A FUNCTION OF SECONDARY STEEL CONTENT, REGION AND TYPE OF STEEL (SOLID AND DASHED LINES), EIOLCA RESULTS FOR THE U.S. AND CHINA (STARS), AND PRIOR PROCESS LCA STUDIES (CIRCLES, TRIANGLES, SQUARES AND DIAMONDS) ....................49
FIGURE 15. PROCESS-SUM MODEL RESULTS FOR CRADLE TO GATE GLOBAL WARMING POTENTIAL FOR STEEL AS A FUNCTION OF SECONDARY STEEL CONTENT, REGION AND TYPE OF STEEL (SOLID AND DASHED LINES), EIOLCA RESULTS FOR THE U.S. AND CHINA (STARS), AND PRIOR PROCESS LCA STUDIES (CIRCLES, TRIANGLES, SQUARES AND DIAMONDS) ....................50
FIGURE 16. BOUNDS FROM THE THREE ITERATIONS OF KNOWLEDGE-BASED BOUNDING DEVELOPED FROM FIGURE 15 ..................................................................................................55
FIGURE 17. EFFECT OF KNOWLEDGE-BASED BOUNDS FOR STEEL ON TOTAL LIFE CYCLE GWP OF RESIDENTIAL BUILDINGS .................................................................................58
List of Tables

TABLE 1. PARAMETERS USED TO DEVELOP THE MULTI-FAMILY BILLS OF MATERIALS FOR THE EIO PORTION OF THE HYBRID LCA ................................................................. 11
TABLE 2. SAMPLE OF LINE ITEMS FROM THE BILL OF MATERIALS FOR THE 3-STORY, STUCCO ON CONCRETE BLOCK, WOOD JOISTS, MULTI-FAMILY RESIDENCE ........................................ 12
TABLE 3. VALUES FOR PPR, PPI, ENERGY AND GWP INTENSITIES FOR THE STUDY ECONOMIC SECTORS .................................................................................................................... 14
TABLE 4. EXAMPLE OF HOW A BILL OF MATERIAL LINE ITEM CONNECTS TO AN ECONOMIC SECTOR .................................................................................................................. 16
TABLE 5. GENERAL EQUATIONS USED TO DETERMINE CED AND GWP FOR THE MATERIALS EXTRACTION AND PRODUCTION LIFE CYCLE PHASE OF A MULTIFAMILY RESIDENCE .......... 16
TABLE 6. ENERGY CONSUMED IN 2002 AS A RESULT OF MULTI-FAMILY RESIDENTIAL CONSTRUCTION ................................................................................................. 19
TABLE 7. GENERAL EQUATIONS USED TO DETERMINE CED AND GWP FOR THE CONSTRUCTION LIFE CYCLE PHASE OF A MULTI-FAMILY RESIDENCE ........................................................................ 20
TABLE 8. DETAILS OF THE CALCULATIONS FOR ANNUAL CED FOR THE OPERATION LIFE CYCLE PHASE OF A MULTI-FAMILY RESIDENCE ........................................................................... 21
TABLE 9. DETAILS OF THE CALCULATIONS FOR ANNUAL GWP FOR THE OPERATION LIFE CYCLE PHASE OF A MULTI-FAMILY RESIDENCE ........................................................................... 22
TABLE 10. SUMMARY OF THE CONTRIBUTIONS TO CED AND GWP DURING THE 50 YEAR OPERATION LIFE CYCLE PHASE OF A MULTI-FAMILY RESIDENCE (FROM TABLES 8 AND 9) ........ 23
TABLE 11. GENERAL EQUATIONS USED TO DETERMINE THE CED AND GWP FOR THE TOTAL LIFE CYCLE OF A MULTI-FAMILY RESIDENCE .................................................. 23
TABLE 12. RESULTS OF THE HYBRID LCA OF MULTI-FAMILY RESIDENCES BY LIFE CYCLE PHASE ...................................................................................................................... 24
TABLE 13. COMPARING CURRENT LCA RESULTS FOR CED WITH PREVIOUS STUDIES .................................................................................................................. 29
TABLE 14. INPUT AND OUTPUT FLOWS TO PRODUCE 1KG OF PRIMARY, LOW-ALLOYED STEEL IN THE U.S., CHINA AND EUROPE ........................................................................... 44
TABLE 15. INPUT AND OUTPUT FLOWS TO PRODUCE 1KG OF PRIMARY, CHROMIUM STEEL IN THE U.S., CHINA AND EUROPE ........................................................................... 45
TABLE 16. LIFE CYCLE INVENTORY DATA SOURCES USED FOR THE EIO APPROACH .................................................................................................................. 46
TABLE 17. PURCHASE PRICE DATA FOR LOW-ALLOYED STEEL FOR U.S. AND CHINA .................................................................................................................. 46
TABLE 18. RESULTS SHOWING CED IMPACTS OF STEEL MANUFACTURING USING THE PROCESS-SUM APPROACH .................................................................................. 47
TABLE 19. RESULTS SHOWING GWP IMPACTS OF STEEL MANUFACTURING USING THE PROCESS-SUM APPROACH .................................................................................. 48
TABLE 20. RESULTS SHOWING CED AND GWP IMPACTS OF STEEL MANUFACTURING USING THE EIO APPROACH .............................................................................................. 48
TABLE 21. CED AND GWP RESULTS FOR THE EIO APPROACH AS WELL AS FROM PREVIOUS STUDIES .................................................................................................................. 51
TABLE 22. KNOWLEDGE-BASED BOUNDING ITERATIONS USED IN THIS STUDY .................................................................................................................. 54
TABLE 23. GWP AND CONTRIBUTIONS FROM STEEL IN THE ORIGINAL RESIDENTIAL BUILDING LCA STUDY (GONG ET AL. 2012 AND PERSONAL CORRESPONDANCE) ........................................................................ 56
TABLE 24. RANGES OF GWP CONTRIBUTIONS FROM STEEL IN THE RESIDENTIAL BUILDING LCA FROM THREE ITERATIONS OF KNOWLEDGE-BASED BOUNDING ........................................................................ 57
TABLE 25. TOTAL LIFE CYCLE GWP RANGES IN THE BUILDING LCA FROM THREE ITERATIONS OF KNOWLEDGE-BASED BOUNDING

<table>
<thead>
<tr>
<th>Knowledge-Based Bounding</th>
<th>1st Iteration</th>
<th>2nd Iteration</th>
<th>3rd Iteration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Page 57
List of Figures in Appendices

FIGURE A-1. ENERGY AND GWP CALCULATIONS FOR THE CONSTRUCTION LIFE CYCLE PHASE…68
Chapter 1 – Introduction

Background

The environmental impacts of urban structure have been a focus of research for many years. (Wolman 1965) first analyzes the metabolism (flows of energy, water, materials and wastes into and out of an area) of a hypothetical urban area of 1 million people. Later, (Newcombe et al. 1978) complete a comprehensive metabolic analysis of an existing city, Brussels. (Kennedy et al. 2007) complete a review of this and other urban metabolic studies completed between 1965 and 2000.

Life cycle assessment (LCA) is a tool to assess the environmental impacts of products and systems that has become an integral part in assessing the environmental impacts of urban structure. While not formally called life cycle assessments, a number of studies have compared carbon footprints of metropolitan areas; however, the findings have not been consistent. (Brown et al. 2009) compare the carbon footprints of 100 U.S. metropolitan areas and find that the urban areas have lower footprints than more rural areas. In contrast, (Lebel et al. 2007) find that in developing countries the carbon emissions are higher in urban areas perhaps due to increases in income and therefore increases in the use of services in these areas. Also, (Sovacool and Brown 2010) examine the carbon footprints of 12 global metropolitan areas and find a large variation between cities. Despite the variation, the authors suggest that urban planners can help reduce emissions in metropolitan areas through efforts such as compact urban growth, sustainable transportation, mass transit, and cleaner electricity supply (Sovacool and Brown 2010).

Other studies have used formal LCA methodologies to examine aspects of urban form. (Norman et al. 2006) use LCA to compare the life cycle energy and greenhouse gas (GHG) emissions of high and low residential density and find that low-density suburban development is more energy and GHG intensive than high-density urban development on a per capita basis. (Hillman and Ramaswami 2010) use LCA to examine ‘trans-boundary’ GHG emissions for eight cities. The authors find that GHG emissions were close to 50% higher for cross-boundary activities such as airline travel, than for in-boundary activities. Also, (Heinonen and Junnila 2011) use LCA to compare GHG emissions between rural and urban lifestyles. The authors expand on conventional LCA by including emissions produced from the consumption of leisure activities, services and travelling abroad for example (Heinonen and Junnila 2011). One notable finding is that the type of energy production, the energy efficiency of the housing, and, increased use of services can easily cancel the expected carbon-reducing influences of city density (Heinonen and Junnila 2011).

While in 2007 the United Nations reported that cities were responsible for 75% of global energy consumption and 80% of all GHG, in 2013, the United Nations Environmental Program reported that buildings alone were responsible for about 40% of global energy and resource consumption, and
approximately 1/3 of the GHG emissions (United Nations 2007, UNEP 2013). Because buildings are a fundamental aspect of urban structure, it is important to understand their associated environmental impacts. Comparative LCA has often been used to compare the environmental impacts of buildings that are similar in function but varying in size and/or materials, such as residences, offices or industrial buildings (Adalberth 1997, Gong et al. 2012, Cole and Kernan 1996, Keoleian et al. 2008). (Friija et al. 2011) also complete a comparative LCA of buildings with similar function; single-family residences of varying sizes and materials; however, the authors extend the work by constructing parametric models to describe the LCA results by the size and type of residence. Using a similar approach, this study examines the cumulative energy demand (CED) and global warming potential (GWP) of multi-family residences, revealing distinctions between low, mid and high-rise residences. Moreover, this study focuses on areas in conventional LCA such as choice of functional unit and life span that can significantly alter the results.

Life cycle assessment is an effective tool to assess the environmental impacts of products or systems, highlighting ‘hot spots’ or allowing companies to benchmark performance, for example. However, in order for LCA to be influential in decision making such as urban policy, the reliability of the results must be well understood. In LCA, this is completed through uncertainty analysis. Uncertainty analysis determines to what extent uncertainty affects the reliability of the results; it is a very important part in a decision maker’s ability to confidently draw comparative conclusions to potentially costly decisions (ISO 14044, 2006, U.S. Environmental Protection Agency, 2006). For example, California’s Low Carbon Fuel Standard Program which calls for a reduction of at least 10 percent in the carbon intensity of California’s transportation fuels by 2020, was largely based upon LCA modeling, and, has greatly challenged the transportation fuel industry (California Environmental Protection Agency Air Resources Board, 2010).

Both quantitative and qualitative approaches for uncertainty analysis in LCA are outlined in the literature including: simulations (Monte Carlo) and statistical analysis, scenario analysis, and, expert judgment (Heijungs 1996, Björklund 2002, Huijbregts 1998, Heijungs and Huijbregts 2004, Williams et al. 2009, Lloyd and Ries 2007, Finnveden et al. 2009, Huijbregts et al. 2003). On the application side, far and above most work has focused on analyzing uncertainty through statistical analysis. (Lloyd and Ries 2007) present a summary of LCA’s that applied quantitative uncertainty analysis, and stochastic modeling was used in 70% of the studies examined. Nonetheless, serious application of uncertainty analysis continues to be the exception rather than the rule in LCA practice (Björklund 2002, Heijungs and Huijbregts 2004, Finnveden et al. 2009, Blengini and Di Carlo 2010).

One major primary obstacle in statistical analysis and therefore an obstacle in uncertainty analysis is the availability of data. In contrast to analyzing uncertainty at the back end of LCA as in a statistical analysis, alternative approaches have been proposed that mitigate uncertainty as an integral part of LCA. For example, researchers have proposed combining top-down and bottom-up LCA methodologies,
referred to as a hybrid approach, in order to capitalize on the strengths while minimizing the weaknesses of each methodology thus reducing uncertainty (Bullard et al. 1978, Williams 2004, Heinonen and Junnila 2011). Iterative approaches have also been proposed in order to further reduce uncertainty (Williams et al. 2009, Olivetti et al. 2013). Bounding approaches are a subset of approaches to mitigate uncertainty as an integrated part of LCA. Also called “extreme values” and “intervals”, the idea of bounding is to identify lower and upper values for parameters and calculate results as a range rather than a point value (Heijungs 1996, Björklund 2002, Chevalier and Le Téno 1996). The main value of a bounding approach is that empirically it is much easier to characterize bounds than to characterize a detailed distribution. The disadvantage to bounds is that resulting ranges in LCA results could be too wide to draw useful conclusions. Previous applications of bounding in LCA include (Williams et al. 2002, Deng et al. 2011).

Chapter 3 of this study expands on the idea of bounding by proposing and piloting an iterative knowledge-based bounding methodology to mitigate uncertainty in LCA. Knowledge-based bounding maps knowledge of a product, such as country of origin or recycled content, to numerical uncertainty bounds. Gathering additional information about the product in question can shrink these bounds and, through an iterative process, reduce uncertainty until the goals of an LCA are met. The knowledge-based bounding approach is demonstrated in a case study of the contribution of steel manufacturing to the life cycle GWP of residences. The proposed approach provides LCA practitioners with a straightforward framework for mitigating uncertainty, meeting the goals of the LCA without adding unnecessary complexity.
Research Objectives

The scope of this research is:

Chapter 1:
• the completion of an LCA quantifying cumulative energy demand and greenhouse gases emissions for low, mid and high-rise multi-family residences,
• the construction of parametric models that describe the LCA results by type and size of multi-family residence,
• the utilization a functional unit that is more conceptually consistent with LCA principles, and,
• the examination of the impacts of different life spans on life cycle phases.

Chapter 2:
• a proposed framework to mitigate uncertainty in LCA using knowledge based bounds,
• an examination of potential sources of variability in the cumulative energy demand (CED) and global warming potential (GWP) of steel manufacturing, and,
• a demonstration of the utility of a knowledge-based bounding approach for mitigating uncertainty in a case study of the contribution of steel manufacturing to the life cycle GWP of residences.

In terms of broader impacts, this research is intended to: (1) inform policy and urban planning on the environmental impacts of multi-family dwellings, (2) provide LCA practitioners with a straightforward and practical framework for mitigating uncertainty, and (3) highlight aspects of LCA within the built environment for future research.

Chapter 2 – Multi-Family Life Cycle Assessment

Background and Literature Review

In 2013, the United Nations Environmental Program reported that buildings were responsible for about 40% of global energy and resource consumption, and approximately 1/3 of the GHG emissions (UNEP 2013). Life cycle assessment has been used for decades as a tool for examining the environmental impacts of industrial systems, including buildings; it is a “cradle to grave” approach that assesses the environmental impacts, such as the total energy consumed or GHG emissions produced, as a
result of raw material extraction through the end-of-life of an industrial product or system. Life cycle assessment provides a picture of the environmental trade-offs often made in product or process selection and can help avoid shifting problems from one phase to another (U.S. Environmental Protection Agency, 2006). The terms raw material extraction and end-of-life refer to life cycle phases of a product or system. Examples of inputs, outputs and life cycle phases of an LCA are shown in Figure 1.

![Life cycle phases diagram](image)

**Figure 1.** Life cycle phases, adapted from (U.S. Environmental Protection Agency, 2006)

In the context of building LCA, the environmental impacts associated with the following life cycle phases are typically assessed: materials extraction and production, building construction, building operation, and sometimes, renovation and deconstruction/disposal. One consistent research finding in building LCA has to do with the relative impacts from each of the life cycle phases. The operation phase consistently dominates the share of the life cycle energy, ranging from 70% to 95%, followed by the materials extraction and production phase ranging from 2% to 26% (Adalberth 1997, Cole and Kernan 1996, Gong et al. 2012, Keoleian et al. 2008, Scheuer et al. 2003).

One common approach to building LCA is to compare the environmental impacts of buildings that are similar in function but varying in size or materials. (Cole and Kernan 1996) complete an LCA comparing the total life cycle energy of three office buildings of similar size but varying in commonly used framing materials (wood, steel, concrete). The authors find that for all framing materials, the
operation life cycle phase dominates the total life cycle energy and suggest that building designs should focus on strategies that reduce operation energy (Cole and Kernan 1996). (Adalberth 1997) complete an LCA comparing the total life cycle energy three single-family, detached wood-framed residences and find that the residence with a second floor consumed the least amount of operation life cycle energy due to lower transmission losses. (Keoleian et al. 2008) compare the total life cycle energy, GHG emissions and total life cycle costs of two U.S. single-family residences; one ‘standard’ and one energy efficient. The authors find that while the energy efficient home resulted in an approximately 60% reduction in life cycle energy and emissions, the life cycle costs are higher due to the increased costs of energy efficient materials (Keoleian et al. 2008). (Gong et al. 2012) compare the total life cycle energy and GHG emissions of three multi-family residences of similar size but varying in commonly used framing materials (wood, steel, concrete). The authors find that the wood-framed residence resulted in the lowest environmental impacts while the concrete and steel-framed residences resulted in higher, yet comparable environmental impacts over the total life cycle (Gong et al. 2012).

Additional LCA work in the context of residential buildings has revealed distinctions between high and low density living, or, urban versus suburban living. (Norman et al. 2006) find that while low-density suburban development, (comparable to single-family, detached housing) is more energy and GHG intensive than high-density urban development, (comparable to multi-family housing) on a per capita basis, they find just the opposite on a per area basis. That is, on a per area basis, (Norman et al. 2006) find that low-density suburban development is less energy and GHG intensive than high-density urban development due to the larger areas of low-density, or single-family, detached residences. Other research relative to high-density, or, multi-family residences, has revealed GWP impacts for ‘standard’ apartments in Korea (Tae et al. 2011). (Tae et al. 2011) use Korean national assessment methods to examine the carbon emissions of apartment buildings and found that ‘standard’ apartment buildings consisting of 40 units, each having 86m² of area, produce 12,753 tonne-CO₂, or 3.8 tonne-CO₂/m² (Tae et al. 2011).

Previous research in the context of residential living informs urban planning. However, while (Norman et al. 2006) identify an important trend for low and high-density housing, in fact housing types are not binary. There is a continuum between “low” density (detached home) and “high” density (high rise apartment, i.e. duplexes, low-rise and medium rise) residences. As different urban forms reflect different mixes in the continuum, to better inform urban policy planning it is important to understand how the environmental impacts of multi-family residences change specifically as a function of size and type. (Friijia et al. 2011) extend previous work on residential living by constructing parametric models to describe the LCA results by size and type of single-family, detached residence. Using a similar approach, this study addresses a knowledge gap in the context of multi-family residences, revealing distinctions
between low, mid and high-rises. Moreover, this study focuses on areas in conventional LCA such as choice of functional unit and life span that can significantly alter the results.

A functional unit appropriately describes the function of the product or process being studied (U.S. Environmental Protection Agency, 2006). However, prior building LCA studies typically define a functional unit inconsistent with LCA principles. This is because the operation phase is taken to include the total energy consumed inside the building, but then the boundaries of analysis exclude supply chains associated with many of the operations. For example, while the total operation life cycle energy includes the energy consumed to do laundry, the environmental impacts associated with the production of clothes washers and dryers are not included in the usual paradigm for building LCA (Adalberth 1997, Cole and Kernan 1996, Gong et al. 2012, Keoleian et al. 2008, Scheuer et al. 2003). Taking the operation energy as all energy use within a building but only including supply chains to construct the building overstates the contribution with the operation life cycle phase and undercounts the contribution of the materials production phase. In contrast, this study defines a functional unit that is more conceptually consistent with LCA, including all of the supply chains associated with a more narrow definition of the operation phase.

Another area in the context of building LCA that changes the contribution of the operation phase impacts is the choice of life span. Building life spans used in prior LCA studies have ranged from 30 to 75 years as an assumption without empirical justification (Aden 2010, Suzuki and Oka 1998, Adalberth 1997, Cole and Kernan 1996, Keoleian et al. 2008, Scheuer et al. 2003). This study examines the relative impacts of the choice of life span and highlights the need for future work in this area.

To summarize, the research objectives for Chapter 2 include: the completion of an LCA of low, mid and high-rise multi-family dwellings; the construction of parametric models that describe the LCA results by type and size of multi-family residence; the utilization of a functional unit that is more conceptually consistent with LCA principles; and the examination of the impacts of different life spans on life cycle phases. The results of this research will inform urban policy as well as LCA practitioners in future studies of the built environment.
Method

The goal of an LCA lays out the intended application, objective, and intended audience for the study. The goal of the current study is to complete a LCA of multi-family residences, constructing parametric models that describe the results by type and size of residence. The objective of the study is to inform urban policy planning as well as LCA practitioners and researchers of recent findings. Finally, the intended audience includes urban planners and LCA practitioners and researchers.

The scope of an LCA defines the product or system being assessed, the functional unit, the boundaries and environmental impacts being reviewed as part of the assessment, methodologies, data requirements, as well as assumptions and limitations. The scope of an LCA is a very important aspect of LCA, assisting practitioners in meeting the stated goal. Aspects included in the scope of the current study are outlined below.

- Functional Unit

  The functional unit is the delivery of a controlled climate space to a multi-family residence for 50 years.

- Reference Flow

  The reference flows used to obtain the functional units are the ten different multi-family residences, including their associated HVAC systems.

- System Boundary:

  The life cycle phases included in this study are materials extraction and production, building construction and building operation for a typical multi-family residence located in Phoenix during 2002. Building maintenance/renovation and disposal are not included as part of this analysis. Figure 2 illustrates the system boundary for this LCA.
Methodology

Two approaches are generally used in practice to complete an LCA, process-sum and economic input-output (EIO). The most commonly used approach is the bottom-up, process-sum approach that physically quantifies the energy and materials flows and the resulting environmental impacts for a product or system within the system boundary. The advantage of this approach is a very detailed analysis of a specific product or system. The challenges with this approach include data availability and time or resource constraints. Moreover, a process-sum approach inevitably encounters truncation errors due to the omission of contributions outside the finite system boundary.

Alternatively, the top-down EIO approach is based on economic transactions between sectors of the economy (Leontief 1970). In contrast to using physical quantities of energy and materials flows as in the process-sum approach, EIO uses financial transactions from sectoral input-output (IO) tables to estimate the supply chain materials use and associated environmental impacts. The most detailed tables divide an economy into 400-500 sectors. As with the process-sum approach there are also advantages and disadvantages to an EIO approach. Advantages to this approach are in contrast to a process-sum approach: reduced time and resource requirements to complete, and, truncation error is removed as all supply chain activities are included as part of an EIO LCA. The disadvantage is also in contrast to process-sum. While a process-sum approach results in a very detailed analysis for a specific product or process, EIO tables aggregate many processes or products into one sector. Moreover, EIO LCA includes processes that a process-sum LCA would not, such as services, resulting in comparatively higher values.

In order to capitalize on the strengths and minimize the weaknesses of each approach, hybrid approaches have been proposed combining both methodologies (Bullard et al. 1978, Williams 2004). (Suh et al. 2004) categorizes hybrid approaches into three types: tiered, EIO-based, and integrated.
A tiered hybrid approach implies that all of the direct and downstream (construction, operation, maintenance and end-of-life) flows are detailed using a process-sum approach and the remaining upstream flows (material extraction and production) are detailed using an EIO approach (Suh et al. 2004). An EIO-based hybrid approach implies that important IO sectors are further disaggregated using a process-sum approach (Suh et al. 2004). Finally, an integrated hybrid approach implies that the process-sum data is fully incorporated into the IO model, represented in a technology matrix by physical units per unit operation time of each process (Suh et al. 2004).

The current study resembles a tiered hybrid approach in general, or, an additive approach, quantifying the materials extraction and production flows using an EIO approach, quantifying the construction flows using an economic-based approach, and finally, quantifying the flows occurring during the operation life cycle phase using a process-sum approach.

- Impact Categories

The two impact categories being assessed in this study include: CED (GJ/m²) from fossil fuels, renewables and nuclear energy sources, and climate change or GWP (tCO2eq/m²) using the 100 YR GWP from (IPCC 4th Assessment Report 2007).

**Life Cycle Inventory**

The life cycle inventory portion of an LCA involves the collection and quantification of inputs and outputs for a product or system throughout its life cycle. For this study, the inputs include energy and raw materials and the outputs include GHG emissions. Given that this is a tiered hybrid approach, three components are calculated separately and then added together to determine the total environmental impact for each category: an EIO approach is used to determine the CED and GWP for the materials extraction and production life cycle phase; an economically-based approach is used to determine the CED and GWP for the construction life cycle phases; and finally, the process-sum approach is used to determine the CED and GWP for the operation life cycle phase. Consequently, each approach requires a different data collection process.
• Economic Input-Output Approach

The EIO approach is economically based and is used to quantify the input and output flows contributed by the materials extraction and production life cycle phase. A bill of materials detailing the materials and associated costs to build each multi-family residence is required to determine the associated environmental impacts. Table 1 contains the parameters used to develop the bills of materials for the 10-multi-family residences using RSMeans On-Line software and RSMeans consulting services (Reed Construction Data Inc. 2012). The parameters were chosen based on existing multi-family residences identified in the Maricopa County Assessor’s database (Maricopa County Assessor’s Office). Table 2 contains a sample of the 300-450 material line items from each bill of material.

Table 1. Parameters used to develop the multi-family bills of materials for the EIO portion of the hybrid LCA.

<table>
<thead>
<tr>
<th>Number of Stories</th>
<th>Rise</th>
<th>Square Meters</th>
<th>Exterior Wall</th>
<th>Frame</th>
<th>Perimeter (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Low</td>
<td>2,837</td>
<td>Wood siding</td>
<td>Wood Frame</td>
<td>56</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>2,837</td>
<td>Stucco on Concrete Block</td>
<td>Wood Joists</td>
<td>56</td>
</tr>
<tr>
<td>4</td>
<td>Mid</td>
<td>6,045</td>
<td>Precast Concrete Panels</td>
<td>Steel Frame</td>
<td>74</td>
</tr>
<tr>
<td>4</td>
<td>Mid</td>
<td>6,045</td>
<td>Precast Concrete Panels</td>
<td>Reinforced Concrete Frame</td>
<td>74</td>
</tr>
<tr>
<td>7</td>
<td>Mid</td>
<td>5,580</td>
<td>Precast Concrete Panels</td>
<td>Steel Frame</td>
<td>47</td>
</tr>
<tr>
<td>7</td>
<td>Mid</td>
<td>5,580</td>
<td>Precast Concrete Panels</td>
<td>Reinforced Concrete Frame</td>
<td>47</td>
</tr>
<tr>
<td>11</td>
<td>High</td>
<td>7,510</td>
<td>Ribbed Precast Concrete</td>
<td>Steel Frame</td>
<td>37</td>
</tr>
<tr>
<td>11</td>
<td>High</td>
<td>7,510</td>
<td>Ribbed Precast Concrete</td>
<td>Reinforced Concrete Frame</td>
<td>37</td>
</tr>
<tr>
<td>21</td>
<td>High</td>
<td>20,135</td>
<td>Ribbed Precast Concrete</td>
<td>Steel Frame</td>
<td>51</td>
</tr>
<tr>
<td>21</td>
<td>High</td>
<td>20,135</td>
<td>Ribbed Precast Concrete</td>
<td>Reinforced Concrete Frame</td>
<td>51</td>
</tr>
</tbody>
</table>
Table 2. Sample of line items from the bill of materials for the 3-story, Stucco on Concrete Block, Wood Joists, multi-family residence.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Backfill, trench, 6&quot; to 12&quot; lifts, dozer backfilling, compaction with vibrating roller</td>
<td>2.66</td>
<td>E.C.Y.</td>
<td>$1.06</td>
<td>$6.08</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Excavating, trench or continuous footing, common earth, 3/8 C.Y. excavator, 1’ to 4’ deep, excludes sheeting or dewatering</td>
<td>8.02</td>
<td>B.C.Y.</td>
<td>$26.16</td>
<td>$17.82</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Excavating, trench or continuous footing, common earth, trim sides and bottom for concrete pours, excludes sheeting or dewatering</td>
<td>144.77</td>
<td>S.F.</td>
<td>$63.70</td>
<td>$4.34</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>C.I.P. concrete forms, footing, continuous wall, plywood, 4 use, includes erecting, bracing, stripping and cleaning</td>
<td>108.44</td>
<td>SFCA</td>
<td>$186.52</td>
<td>$146.40</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>C.I.P. concrete forms, footing, keyway, tapered wood, 2” x 6”, 4 use, includes erecting, bracing, stripping and cleaning</td>
<td>54.22</td>
<td>L.F.</td>
<td>$10.30</td>
<td>$20.06</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Reinforcing Steel, in place, footings, #4 to #7, A615, grade 60, incl labor for accessories, excl material for accessories</td>
<td>223.94</td>
<td>Lb.</td>
<td>$89.58</td>
<td>$49.27</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Reinforcing steel, in place, dowels, deformed, 2’ long, #4, A615, grade 60</td>
<td>108.44</td>
<td>Ea.</td>
<td>$60.73</td>
<td>$100.85</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Structural concrete, ready mix, normal weight, 3000 psi, includes local aggregate, sand, Portland cement and water, delivered, excludes all additives and treatments</td>
<td>5.37</td>
<td>C.Y.</td>
<td>$510.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Structural concrete, placing, continuous footing, shallow, direct chute, includes strike off &amp; consolidation, excludes material</td>
<td>5.37</td>
<td>C.Y.</td>
<td>$43.80</td>
<td>$2.68</td>
<td></td>
</tr>
</tbody>
</table>

**Additional Material Line Items (10-348)**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>$1,309,459</th>
<th>$540,090</th>
<th>$8,823.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1,309,459</td>
<td>$540,090</td>
<td>$8,823.</td>
</tr>
</tbody>
</table>

<sup>a</sup> Qty: quantity; Ext. Mtl.: extended material; Ext. Labor: extended labor; Ext. Eqmt.: extended equipment.
Producer costs (PC) are generally used for the EIO approach. Unfortunately, costs for each line item on a bill of materials are generally in terms of an end user’s purchasing price, including costs associated with overhead and profit (O&P). Therefore, in order to appropriately reflect producer cost, material line item costs are adjusted using producer/purchaser ratios (PPR) (U.S. Bureau of Economic Analysis). In addition, producer price indices (PPI) are used to adjust material line item costs to reflect the desired time frame of the study (U.S. Bureau of Labor Statistics). The following equation is therefore used to adjust the purchasing cost to reflect the producer cost (PC), for each line item:

\[ PC_i = (C_i)(PPR_i)(\frac{PPI_{2002_i}}{PPI_{2010_i}}), \]  

(equation 1)

where \( PC_i \) is the producer cost of the \( i^{th} \) line item on the bill of material, \( C_i \) is the extended material cost of the \( i^{th} \) line item (O&P removed) (Table 2), PPR, is the producer/purchaser ratio for the economic sector associated with the \( i^{th} \) line item (Table 3), and, \( \frac{PPI_{2002_i}}{PPI_{2010_i}} \) is the producer price index ratio associated with the economic sector for the \( i^{th} \) line item between 2002 and 2010 (Table 3).

Next, the EIO approach requires the energy and GWP intensities for the sectors from which each of the material line items is associated. Energy and GWP intensities for U.S. economic sectors are easily obtained from the Carnegie Mellon University Green Design Institute (GCU GDI 2012) input-output model. (GMU GDI 2002) is a publicly available model containing 428 U.S. industry sectors based on the North American Industry Classification System (NAICS). Table 2 details the values for PPR, PPI and Energy and GWP intensities for the sectors used in this study.
Table 3. Values for PPR, PPI, energy and GWP intensities for the study economic sectors.

<table>
<thead>
<tr>
<th>NAICS Economic Sector</th>
<th>Description</th>
<th>PPI&lt;sup&gt;ab&lt;/sup&gt; (2002/2010)</th>
<th>PPR&lt;sup&gt;ac&lt;/sup&gt;</th>
<th>Energy Intensity GJ/$&lt;sup&gt;ad&lt;/sup&gt;</th>
<th>GWP Intensity (tCO&lt;sub&gt;2&lt;/sub&gt;eq/$)&lt;sup&gt;ad&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>333415</td>
<td>Air conditioning, refrigeration, and warm air heating equipment manufacturing</td>
<td>.81</td>
<td>.56</td>
<td>8.5E-03</td>
<td>5.8E+02</td>
</tr>
<tr>
<td>33299C</td>
<td>Other fabricated metal manufacturing</td>
<td>.78</td>
<td>.61</td>
<td>1.3E-02</td>
<td>8.4E+02</td>
</tr>
<tr>
<td>33131B</td>
<td>Aluminum product manufacturing from purchased aluminum</td>
<td>.92</td>
<td>.89</td>
<td>2.4E-02</td>
<td>1.6E+03</td>
</tr>
<tr>
<td>324122</td>
<td>Asphalt shingle and coating materials manufacturing</td>
<td>.52</td>
<td>.80</td>
<td>1.6E-02</td>
<td>1.2E+03</td>
</tr>
<tr>
<td>32712A</td>
<td>Brick, Tile and Other Structural clay product Mfg.</td>
<td>.83</td>
<td>.45</td>
<td>3.1E-02</td>
<td>2.0E+03</td>
</tr>
<tr>
<td>314110</td>
<td>Carpet and rug mills</td>
<td>.78</td>
<td>.58</td>
<td>1.8E-02</td>
<td>1.2E+03</td>
</tr>
<tr>
<td>327310</td>
<td>Cement manufacturing</td>
<td>.78</td>
<td>.78</td>
<td>7.4E-02</td>
<td>1.2E+04</td>
</tr>
<tr>
<td>335920</td>
<td>Communication and energy wire and cable manufacturing</td>
<td>.62</td>
<td>.62</td>
<td>1.3E-02</td>
<td>7.6E+02</td>
</tr>
<tr>
<td>327330</td>
<td>Concrete pipe, brick, and block manufacturing</td>
<td>.81</td>
<td>.57</td>
<td>1.7E-02</td>
<td>1.9E+03</td>
</tr>
<tr>
<td>335311</td>
<td>Electric power and specialty transformer manufacturing</td>
<td>.60</td>
<td>.80</td>
<td>1.2E-02</td>
<td>8.1E+02</td>
</tr>
<tr>
<td>335120</td>
<td>Lighting fixture manufacturing</td>
<td>.88</td>
<td>.68</td>
<td>8.5E-03</td>
<td>5.6E+02</td>
</tr>
<tr>
<td>3274A0</td>
<td>Lime and gypsum product manufacturing</td>
<td>.91</td>
<td>.76</td>
<td>4.5E-02</td>
<td>5.3E+03</td>
</tr>
<tr>
<td>333920</td>
<td>Material handling equipment manufacturing</td>
<td>.81</td>
<td>.94</td>
<td>1.0E-02</td>
<td>7.5E+02</td>
</tr>
<tr>
<td>321910</td>
<td>Wood windows and doors and millwork</td>
<td>.97</td>
<td>.63</td>
<td>1.1E-02</td>
<td>6.0E+02</td>
</tr>
<tr>
<td>327993</td>
<td>Mineral wool manufacturing</td>
<td>.88</td>
<td>.95</td>
<td>2.3E-02</td>
<td>1.4E+03</td>
</tr>
<tr>
<td>335312</td>
<td>Motor and generator manufacturing</td>
<td>.77</td>
<td>.54</td>
<td>9.7E-03</td>
<td>6.6E+02</td>
</tr>
<tr>
<td>333319</td>
<td>Other commercial and service industry machinery manufacturing</td>
<td>.90</td>
<td>.72</td>
<td>7.9E-03</td>
<td>5.3E+02</td>
</tr>
<tr>
<td>335228</td>
<td>Other major household appliance manufacturing</td>
<td>.68</td>
<td>.71</td>
<td>9.9E-03</td>
<td>6.6E+02</td>
</tr>
<tr>
<td>32619A</td>
<td>Other plastics product manufacturing</td>
<td>.82</td>
<td>.58</td>
<td>1.5E-02</td>
<td>9.0E+02</td>
</tr>
<tr>
<td>325510</td>
<td>Paint and coating manufacturing</td>
<td>.70</td>
<td>.76</td>
<td>1.7E-02</td>
<td>1.1E+03</td>
</tr>
<tr>
<td>332913</td>
<td>Plumbing fixture fitting and trim manufacturing</td>
<td>.78</td>
<td>.47</td>
<td>9.3E-03</td>
<td>5.7E+02</td>
</tr>
<tr>
<td>333991</td>
<td>Power-driven handtool manufacturing</td>
<td>.97</td>
<td>.75</td>
<td>8.7E-03</td>
<td>5.8E+02</td>
</tr>
<tr>
<td>237320</td>
<td>Ready mix concrete manufacturing</td>
<td>.71</td>
<td>.69</td>
<td>2.4E-02</td>
<td>2.7E+03</td>
</tr>
<tr>
<td>212320</td>
<td>Sand, gravel, clay, and refractory mining</td>
<td>.71</td>
<td>.52</td>
<td>2.2E-02</td>
<td>1.5E+03</td>
</tr>
<tr>
<td>32121B</td>
<td>Engineered wood member and truss manufacturing</td>
<td>1.04</td>
<td>.65</td>
<td>1.4E-02</td>
<td>5.2E+02</td>
</tr>
</tbody>
</table>

<sup>a</sup> PPR: producer/purchaser ratio; PPI: producer price index; GJ/$: gigajoules per dollar; GWP: global warming potential; tCO<sub>2</sub>eq/$: tonne Carbon dioxide equivalent emissions per dollar.

<sup>b</sup> Source: U.S. Bureau of Labor Statistics

<sup>c</sup> Source: U.S Bureau of Economic Analysis

<sup>d</sup> Source: Carnegie Mellon University Green Design Institute (CMU GDI 2012)
Table 3 (cont’d). Sources and values for PPR, PPI and energy and GWP intensities for the study sectors.

<table>
<thead>
<tr>
<th>NAICS Economic Sector</th>
<th>Description</th>
<th>PPI&lt;sup&gt;b&lt;/sup&gt; (2002/2010)</th>
<th>PPR&lt;sup&gt;c/d&lt;/sup&gt;</th>
<th>Energy Intensity G/J/$&lt;sup&gt;a/d&lt;/sup&gt;</th>
<th>GWP Intensity (tCO&lt;sub&gt;2&lt;/sub&gt;eq/$)&lt;sup&gt;a/d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>32121A</td>
<td>Veneer and plywood manufacturing</td>
<td>.93</td>
<td>.83</td>
<td>1.7E-02</td>
<td>7.8E+02</td>
</tr>
<tr>
<td>337110</td>
<td>Wood kitchen cabinet and countertop manufacturing</td>
<td>.86</td>
<td>.57</td>
<td>8.6E-03</td>
<td>5.2E+02</td>
</tr>
<tr>
<td>32222A</td>
<td>Coated and laminated paper, packaging materials, and plastic films</td>
<td>.83</td>
<td>.62</td>
<td>1.9E-02</td>
<td>9.0E+02</td>
</tr>
<tr>
<td>321999</td>
<td>Miscellaneous wood product manufacturing</td>
<td>.90</td>
<td>.78</td>
<td>1.1E-02</td>
<td>6.3E+02</td>
</tr>
<tr>
<td>332996</td>
<td>Fabricated pipe and pipe fitting manufacturing</td>
<td>.57</td>
<td>.79</td>
<td>1.3E-02</td>
<td>9.4E+02</td>
</tr>
<tr>
<td>326122</td>
<td>Plastics pipe and pipe fitting manufacturing</td>
<td>.53</td>
<td>.50</td>
<td>2.4E-02</td>
<td>1.4E+03</td>
</tr>
<tr>
<td>331200</td>
<td>Iron, steel pipe and tube from purchased steel</td>
<td>.49</td>
<td>.54</td>
<td>2.5E-02</td>
<td>2.0E+03</td>
</tr>
<tr>
<td>33211A</td>
<td>All other forging, stamping and sintering</td>
<td>.75</td>
<td>.58</td>
<td>2.1E-02</td>
<td>1.5E+03</td>
</tr>
<tr>
<td>334290</td>
<td>Other communications equipment manufacturing</td>
<td>.94</td>
<td>.88</td>
<td>5.2E-03</td>
<td>3.4E+02</td>
</tr>
<tr>
<td>332800</td>
<td>Coating, engraving, heat treating and allied activities</td>
<td>.81</td>
<td>.98</td>
<td>1.7E-02</td>
<td>1.1E+03</td>
</tr>
<tr>
<td>32711A</td>
<td>Pottery, ceramics, and plumbing fixture manufacturing</td>
<td>.88</td>
<td>.75</td>
<td>1.7E-02</td>
<td>1.1E+03</td>
</tr>
<tr>
<td>334419</td>
<td>Other electronic component manufacturing</td>
<td>.89</td>
<td>.80</td>
<td>6.8E-03</td>
<td>4.5E+02</td>
</tr>
<tr>
<td>335313</td>
<td>Switchgear and switchboard apparatus manufacturing</td>
<td>.77</td>
<td>.72</td>
<td>6.4E-03</td>
<td>4.2E+02</td>
</tr>
<tr>
<td>333911</td>
<td>Pump and pumping equipment manufacturing</td>
<td>.73</td>
<td>.83</td>
<td>8.5E-03</td>
<td>5.6E+02</td>
</tr>
<tr>
<td>327215</td>
<td>Glass Product Manufacturing Made of Purchased Glass</td>
<td>.95</td>
<td>.64</td>
<td>1.6E-02</td>
<td>9.5E+02</td>
</tr>
<tr>
<td>332720</td>
<td>Turned product &amp; screw, nut &amp; bolt mfg</td>
<td>.74</td>
<td>.91</td>
<td>9.9E-03</td>
<td>7.1E+02</td>
</tr>
</tbody>
</table>

<sup>a</sup> PPR: producer/purchaser ratio; PPI: producer price index; G/J$/: gigajoules per dollar; GWP: global warming potential; tCO<sub>2</sub>eq$/: tonne Carbon dioxide equivalent emissions per dollar.

<sup>b</sup> Source: U.S. Bureau of Labor Statistics

<sup>c</sup> Source: U.S Bureau of Economic Analysis

<sup>d</sup> Source: Carnegie Mellon University Green Design Institute (CMU GDI 2012)

An example is provided in Table 4 to demonstrate the connection between the bill of material line items and economic sectors. Line item 8 from Table 2 is used in this example. Corresponding material line item cost, PPR, PPI values are easily determined from here.
Table 4. Example of how a bill of material line item connects to an economic sector.

<table>
<thead>
<tr>
<th>Line #</th>
<th>Line Item Description</th>
<th>NAICS Sector #</th>
<th>NAICS Sector Description</th>
<th>EIO Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Structural concrete, ready mix, normal weight, 3000 psi, includes local aggregate, sand, Portland cement and water, delivered, excludes all additives and treatments</td>
<td>237320</td>
<td>Ready mix concrete manufacturing</td>
<td>Ready mix concrete manufacturing</td>
</tr>
</tbody>
</table>

a NAICS: North American Industry Classification System; EIO: economic input-output; line # and line item description is obtained from Table 2.
b Source: (U.S. Census Bureau 2002)
c Source: (Carnegie Mellon University Green Design Institute)

Table 5 contains the equations used to determine the CED and GWP for the materials extraction and production life cycle phase.

Table 5. General equations used to determine CED and GWP for the materials extraction and production life cycle phase for a multi-family residence.

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>EIO Approach (^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials extraction and production life cycle phase (ME&amp;P)</td>
<td>( E_{ME&amp;P} = \sum PCE_i ) (^a,\text{b} )</td>
</tr>
<tr>
<td>CED (GJ) (^a)</td>
<td>( GWP_{ME&amp;P} = \sum PC_{GWP_i} ) (^a,\text{b} )</td>
</tr>
</tbody>
</table>

\(^a\) EIO: economic input-output; CED: cumulative energy demand; GWP: global warming potential; E: Energy; GJ: gigajoules; tCO\(_2\)eq: tonne Carbon dioxide equivalent emissions.
\(^b\) \( i \) refers to the \( i \)th line item on the bill of materials; \( PC \) refers to the producer cost of the \( i \)th line item (equation 1); \( E_i \) and \( GWP_i \) refer to the energy (GJ/$) and GWP (tCO\(_2\)eq/$) intensity, respectively, of the sector from which the \( i \)th line item has been associated with (Table 3).
• Economic-Based Approach

The economic-based approach is also monetary-based and is used to quantify the input and output flows contributed by the construction life cycle phase, or, those flows that occur as a result of the erection of the multi-family residence. For example, the use of fuels consumed during transportation, electricity production and equipment use, as well as the use of power hand tools and material handling equipment, all contribute to the input and output flows specifically occurring during the construction life cycle phase. As a result, there are three different components that contribute to the flows of the construction life cycle phase which are monetary-based, (1) contributions from the use of material handling equipment, (2) contributions from the use of power hand tools, and, (3) contributions from the construction energy consumed during the erection of the multi-family residence.

Contributions from the use of material handling equipment are calculated in a similar manner as the approach used for the items from the materials extraction and production life cycle phase, or EIO, and outlined in Table 5. The exception here is that the cost for material handling equipment used during the construction life cycle phase is not a material line item cost. Rather, the cost for material handling equipment used during the construction life cycle phase is reflected by the Total Extended Equipment Cost for a particular multi-family bill of material (Table 2). The following equation is therefore used to calculate the cost for the contribution from the use of material handling equipment:

\[ C_{MH} = EC_T, \]  
\[ \text{(equation 2)} \]

where \( C_{MH} \) is the cost contribution from the use of material handling equipment, \( EC_T \) is the total extended equipment cost (Table 2).

Equation 3 is then used to calculate the producer cost for the use of material handling equipment:

\[ PC_{MH} = (C_{MH})(PPR_{MH})(PPI_{2002MH}/PPI_{2010MH}). \]  
\[ \text{(equation 3)} \]

where \( PC_{MH} \) is the producer cost for material handling equipment, \( C_{MH} \) is the cost contribution for the use of material handling equipment (equation 2), \( PPR_{MH} \) is the producer/purchaser ratio for the material handling equipment sector (Table 3), and \( (PPI_{2002MH}/PPI_{2010MH}) \) is the producer price index ratio for the material handling equipment sector between 2002 and 2010 (Table 3).

Contributions from the use of power hand tools are also calculated in a similar manner as the approach used for the items from the materials extraction and production life cycle phase, or EIO, and
outlined in Table 5. The exception here again is in the calculation of the cost for the use of power hand tools during the construction life cycle phase. The cost contribution from the use of power hand tools is calculated by using the economic value associated with the manufacture of the tools. According to industry standards, the economic value associated with the manufacture of power hand tools is 1.5% of the total extended material cost plus 5.9% of the total extended labor cost for a particular multi-family bill of material (Table 2) (Frijia et al. 2011). The following equation is therefore used to calculate the cost for the contribution from the use of power hand tools:

\[ C_{HT} = 0.015MC_T + 0.059LC_T, \]  

(equation 4)

where \( C_{HT} \) is the cost contribution from the use of power hand tools, \( MC_T \) is the total extended material cost, and \( LC_T \) is the total extended labor cost (Table 2).

Equation 5 is then used to calculate the producer cost for the use of power hand tools:

\[ PC_{HT} = (C_{HT})(PPR_{HT})(PPI_{2002HT}/PPI_{2010HT}), \]  

(equation 5)

where \( PC_{HT} \) is the producer cost for power hand tools, \( C_{HT} \) is the cost contribution for the use of power hand tools (equation 4), \( PPR_{HT} \) is the producer/purchaser ratio for the power hand tools sector (Table 3), and \( (PPI_{2002HT}/PPI_{2010HT}) \) is the producer price index ratio for the power hand tools sector between 2002 and 2010 (Table 3).

Finally, the contribution to the input and output flows during the construction life cycle phase as a result of the construction process itself are based on the value of business done and energy purchases made in 2002 by the associated NAICS sector, 236116, New Multifamily Housing Construction (Economic Census 2002). This approach is taken in order to focus on one type of construction process relative to multi-family residences, avoiding aggregation error. According to the 2002 Economic Census, the New Multifamily Housing Construction sector reported a business value of $17 billion and spent $1.2 million in energy purchases (U.S. Census Bureau 2011). Table 6 shows that 18 PJ of energy were consumed in 2002, which is equivalent to 1.1x10^3 GJ of primary energy consumed and 1x10^-4 tCO2eq emissions produced per dollar of business done (See Appendix A-1 for details on energy and GWP calculations).
Table 6. Energy consumed in 2002 as a result of multi-family residential construction.

<table>
<thead>
<tr>
<th>Energy Type</th>
<th>Cost ($1000)</th>
<th>Unit Prices ($)</th>
<th>Energy (GJ)</th>
<th>GWP (tCO₂eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchased Electricity</td>
<td>4.3x10⁶</td>
<td>$.05/kWh</td>
<td>9.2x10⁶</td>
<td>1.2x10⁶</td>
</tr>
<tr>
<td>Natural/Manufacturing Gas</td>
<td>1.2x10⁴</td>
<td>$4.0/1000ft³</td>
<td>3.3x10⁶</td>
<td>1.7x10⁷</td>
</tr>
<tr>
<td>Gas/Diesel Fuel</td>
<td>5.9x10⁴</td>
<td>$1.4/gal</td>
<td>6.3x10⁶</td>
<td>4.4x10⁵</td>
</tr>
<tr>
<td>Total Purchases</td>
<td>1.1x10⁵</td>
<td>-</td>
<td>1.8x10⁷</td>
<td>1.8x10⁶</td>
</tr>
</tbody>
</table>

a GJ: gigajoules; tCO₂eq: tonne Carbon dioxide equivalent; $: dollars.
b Source: (U.S. Census Bureau 2002). Excludes miscellaneous fuels and lubricants of $6.5million.
c Source: (Energy Information Administration 2012) Electricity
d Source: (Energy Information Administration 2012) Natural Gas.
e Source: (Energy Information Administration 2012) Petroleum and Other Liquids.

The business value (BV) of a multi-family residence is calculated using the total extended material, labor and equipment costs from the bill of materials (Table 2), plus O&P adjusted to reflect 2002 values. According to industry standards, the O&P for material, labor and equipment are 10%, 68%, and 10%, respectively (Reed Construction Data Inc. 2012). Further, the PPI was obtained using historical construction cost indexes (Reed Construction Data Inc. 2012). The following equation is therefore used to calculate the BV for a multi-family residence:

\[ BV = (1.1MC_T + 1.68LC_T + 1.1EC_T)(.7), \]  

(equation 6)

where BV is the business value of a multi-family residence, MCₜ is the total extended material cost, LCₜ is the total extended labor cost, ECₜ is the total extended equipment cost (Table 2), and .7 is the historical cost index for construction between 2002 and 2010 (Reed Construction Data Inc. 2012). Therefore, the contribution to the input and output flows as a result of the construction process itself are calculated using the BV and the energy and GWP intensities per dollar spent, 1.1x10⁻³GJ/$ and 1x10⁻⁴tCO₂eq, respectively, calculated previously.
Table 7 details the general equations used to determine CED and GWP for the construction life cycle phase.

**Table 7. General equations used to determine CED and GWP for the construction life cycle phase of a multi-family residence**

<table>
<thead>
<tr>
<th>Economic-Based Approach</th>
<th>CED (GJ)</th>
<th>Impact Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction life cycle phase (CO)</td>
<td>( E_{CO} = PC_{HT} E_{SHT} + PC_{MH} E_{SMH} + 1.1BV^{a,b} )</td>
<td>( GWP_{CO} = PC_{HT} GWP_{SHT} + PC_{MH} GWP_{SMH} + 0.001BV^{a,b} )</td>
</tr>
</tbody>
</table>

\(^{a}\) CED: cumulative energy demand; GWP: global warming potential; E: Energy; GJ: gigajoules; tCO\(_2\)eq: tonne Carbon dioxide equivalent emissions.

\(^{b}\) PC\(_{HT}\) refers to the producer cost contribution from the use of hand tools (equation 5); E\(_{SHT}\) and GWP\(_{SHT}\) refer to the energy (GJ/S) and GWP (tCO\(_2\)eq/$) intensity, respectively, of the sector for power hand tools (Table 3); PC\(_{MH}\) refers to the producer cost contribution from the use of material handling equipment (equation 3); E\(_{SMH}\) and GWP\(_{SMH}\) refer to the energy (GJ/S) and GWP (tCO\(_2\)eq/$) intensity, respectively, of the sector for material handling equipment (Table 3); BV refers to the business value of the multi-family residence (equation 6).

- **Process-Sum Approach**

In contrast to the EIO approach, the process-sum approach is based on physical input and output flows. The process-sum approach is used in this study to quantify the input and output flows contributed by the operation life cycle phase. The reference flow for this study is the quantity of primary energy required to deliver a controlled climate to a multi-family residence for 50 years. Therefore, the input and output flows of interest are the primary energy and emissions contributed by the use of heating and cooling operations.

According to the Residential Energy Consumption Survey (RECS), the average size of a multi-family residence in the U.S. in 2005 was 81 m\(^2\) (or 872 ft\(^2\)) (Energy Information Administration 2012). In addition, the number of residences in the U.S. that consumed fuel for space heating and cooling was 15 million and 13 million, respectively (Energy Information Administration 2012). The resolution of the operation data is limited to apartments having 5 or more units only. That is, the data is not resolved to the number of floors. Therefore, contributions to CED and GWP during the operation life cycle phase will be the same for each multi-family residence, and, will be reflective of U.S. averages and not Phoenix specifically. Using physical consumption data and emissions factors from Energy Information Administration, a source conversion factor from the National Renewable Energy Laboratory, the primary energy required to deliver a controlled climate to a multi-family residence for 50 years is calculated.
Table 8 contains the details of the calculations for annual CED.

**Table 8.** Details of the calculations for annual CED for the operation life cycle phase of a multi-family residence.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Site Electricity (Billion kWh)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Source Electricity&lt;sup&gt;b&lt;/sup&gt; (Billion kWh)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>NG (MMBtu)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>FO (Million Gal)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Annual Energy (GJ)&lt;sup&gt;c,d&lt;/sup&gt;</th>
<th>Annual Energy (GJ/m²)&lt;sup&gt;c,d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Heating Consumption&lt;sup&gt;e&lt;/sup&gt;</td>
<td>14</td>
<td>41</td>
<td>2.5x10⁸</td>
<td>5.2x10⁵</td>
<td>4.9x10⁸</td>
<td>.40</td>
</tr>
<tr>
<td>Space Cooling Consumption&lt;sup&gt;f&lt;/sup&gt;</td>
<td>26</td>
<td>75</td>
<td>2.7x10⁸</td>
<td></td>
<td></td>
<td>.25</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>40</td>
<td>1.2x10⁵</td>
<td>2.5x10⁸</td>
<td>5.2x10⁵</td>
<td>7.6x10⁸</td>
<td>.65</td>
</tr>
</tbody>
</table>

<sup>a</sup> NG: natural gas, FO: fuel oil, kWh: kilowatt hour; GJ: gigajoule; GJ/m²: gigajoule per square meter; MMBtu: million British thermal units; Gal: gallon.

<sup>b</sup> Source energy reflects the amount of energy consumed during the actual production of electricity plus the energy consumed during end-use consumption. A source conversion factor of 2.894 was used here, reflective of the state of Arizona (Deru and Torcellini 2007).

<sup>c</sup> Annual Energy (GJ) is determined by converting the source electricity, NG and FO units to GJ and then adding them together. The following conversions were used.

kWh = 3.6x10⁻³GJ

MMBtu = 1.055GJ

Million Gal FO = 139,000 MMBtu = 1.47x10⁵GJ

<sup>d</sup> The total area (m²) for space heating in the U.S. in 2005 was calculated by multiplying the average size multi-family residence in 2005 (81m²) by the total number of households using fuel for space heating in 2005 (15 million). The total area (m²) for space cooling in the U.S. in 2005 was calculated by multiplying the average size multi-family residence in 2005 (81m²) by the total number of households using fuel for space cooling in 2005 (13 million). Source: Housing Unit Characteristics by Total, Heated, and Cooled Floorspace, 2005, Table HC1.1.1 (Energy Information Administration 2012).

<sup>e</sup> Source: Total Consumption for Space Heating by Major Fuels Used in 2005 (Energy Information Administration 2012).

<sup>f</sup> Source: Total Consumption for Air-Conditioning by Equipment Type in 2005 (Energy Information Administration 2012).
Using the data from Table 8 and Carbon dioxide equivalent emission factors from IPCC 4th Assessment Report 2007, the annual tCO2eq emissions are calculated and shown in Table 9 (IPCC 4th Assessment Report 2007).

**Table 9.** Details of the calculations for annual GWP for the operation life cycle phase of a multi-family residence.

<table>
<thead>
<tr>
<th>Operation</th>
<th>(Annual Primary GWP from Electricity consumption)</th>
<th>(Annual Primary GWP from NG consumption)</th>
<th>(Annual Primary GWP from FO consumption)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source Electricity(b)</td>
<td>tCO2(a,c) tCO2eq from N(_2)O(d)</td>
<td>tCO2eq from CH(_4)(d)</td>
<td>Annual GWP (tCO2eq)(a)</td>
</tr>
<tr>
<td>Space Heating Consumption(e)</td>
<td>41 (1.9 \times 10^7) 8.5 (10^4) 3 (10^3)</td>
<td>1.9 (10^7) 0.02</td>
<td></td>
</tr>
<tr>
<td>Space Cooling Consumption(f)</td>
<td>75 (3.6 \times 10^7) 1.6 (10^5) 5.8 (10^3)</td>
<td>3.6 (10^7) 0.03</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>116 (5.5 \times 10^7) 24 (10^4) 8.6 (10^5)</td>
<td>5.5 (10^7) 0.05</td>
<td></td>
</tr>
<tr>
<td>NG (MMBtu)(a)</td>
<td>tCO2(a,c) tCO2eq from N(_2)O(d)</td>
<td>tCO2eq from CH(_4)(d)</td>
<td>Annual GWP (tCO2eq)(a)</td>
</tr>
<tr>
<td>Space Heating Consumption(e)</td>
<td>2.5 (10^8) (1.3 \times 10^7) 0 0</td>
<td>1.3 (10^7) 0.01</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2.5 (10^8) (1.3 \times 10^7) 0 0</td>
<td>1.3 (10^7) 0.01</td>
<td></td>
</tr>
<tr>
<td>FO (Million Gal)(a,f)</td>
<td>tCO2(a) tCO2eq from N(_2)O(d)</td>
<td>tCO2eq from CH(_4)(d)</td>
<td>Annual GWP (tCO2eq)(a)</td>
</tr>
<tr>
<td>Space Heating Consumption(e)</td>
<td>5.2 (10^2) (5.2 \times 10^6) 0 0</td>
<td>5.2 (10^6) 4 (10^3)</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5.2 (10^2) (5.2 \times 10^6) 0 0</td>
<td>5.2 (10^6) 4 (10^3)</td>
<td></td>
</tr>
</tbody>
</table>

\(a\) NG: natural gas, FO: fuel oil, kWh: kilowatt hour; MMBtu: million British thermal units; Gal: gallon; GWP: global warming potential; tCO2eq: tonne Carbon dioxide equivalent emissions; tCO2eq/m\(^2\): tonne Carbon dioxide equivalent emissions per square meter.

\(b\) Source energy reflects the amount of energy consumed during the actual production of electricity plus the energy consumed during end-use consumption. See Table 8 for details on calculation.

\(c\) The emissions factors for electricity in Arizona are 4.8 \(10^{-3}\) tCO2/kWh, 7\(10^{-5}\) tN\(_2\)O/kWh, and 3\(10^{-9}\) tCH\(_4\)/kWh, Updated State-level Greenhouse Gas Emission Coefficients for Electricity Generation 1998-2000 (Energy Information Administration 2002).

\(d\) \(N_2O\) and \(CH_4\) have 298 and 25 times the equivalent GWP of \(CO_2\), respectively (IPCC Fourth Assessment Report). Therefore, the impacts from \(N_2O\) and \(CH_4\) are multiplied by 298 and 25, respectively, to obtain tCO2eq values.

\(e\) The weighted national average emissions factor for NG is 5.3 \(10^{-2}\) tCO2/MMBtu, Instructions for Form 1605, Appendix H, Fuel Emissions Factors (Energy Information Administration 2010).
The emission factor for home heating oil is .01 tCO₂/Gal, Instructions for Form 1605, Appendix H, Fuel Emissions Factors (Energy Information Administration 2010).

The total area (m²) for space heating in the U.S. in 2005 was calculated by multiplying the average size multi-family residence in 2005 (81m²) by the total number of households using fuel for space heating in 2005 (15.1 million). The total area (m²) for space cooling in the U.S. in 2005 was calculated by multiplying the average size multi-family residence in 2005 (81m²) by the total number of households using fuel for space cooling in 2005 (13.5 million). Source: Housing Unit Characteristics by Total, Heated, and Cooled Floorspace, 2005, Table HC1.1.1 (Energy Information Administration 2012).

Table 10 summarizes the operation life cycle phase contributions to CED and GWP.

Table 10. Summary of the contributions to CED and GWP during the 50 year operation life cycle phase of a multi-family residence (Tables 8 and 9).

<table>
<thead>
<tr>
<th>Operation</th>
<th>Annual Primary Energy (GJ/m²)</th>
<th>Total Primary Energy (50 years) (GJ/m²)</th>
<th>Annual Primary GWP (tCO₂eq/m²)</th>
<th>Total Primary GWP (50 years) (tCO₂eq/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Heating</td>
<td>.40</td>
<td>.03</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Space Cooling</td>
<td>.25</td>
<td>12</td>
<td>.03</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>.65</strong></td>
<td><strong>32</strong></td>
<td><strong>.06</strong></td>
<td><strong>3</strong></td>
</tr>
</tbody>
</table>

a GJ/m²: gigajoules per square meter; tCO₂eq/m²: tonne Carbon dioxide equivalent per square meter.

Finally, Table 11 details the general equations used to determine the total CED and GWP for the total life cycle (50 years) of a multi-family residence.

Table 11. General equations used to determine the CED and GWP for the total life cycle of a multi-family residence.

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>CED (GJ)</th>
<th>GWP (tCO₂eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (TOT) per multi-family residence</td>
<td>CEDₜₒᵗ = Eₘₑₚ + Eₖₒ + 3/²ᵃᵇ</td>
<td>GWPₜₒᵗ = GWPₘₑₚ + GWPₖₒ + 3/²ᵃᵇ</td>
</tr>
</tbody>
</table>

a CED: cumulative energy demand; GWP: global warming potential; E: energy; GJ: gigajoules; tCO₂eq: tonne Carbon dioxide equivalent emissions.

b Eₘₑₚ and GWPₘₑₚ refer to the energy (GJ) and GWP (tCO₂eq), respectively, contributed to the materials extraction and production life cycle phase (Table 5); Eₖₒ and GWPₖₒ refer to the energy (GJ) and GWP (tCO₂eq), respectively, contributed to the construction life cycle phase (Table 7).
Results

- Life Cycle Impact Assessment

Table 12 contains the results of the hybrid LCA for 10 multi-family residences. Figures 3-6 graphically illustrate the results.

Table 12. Results of the hybrid LCA of multi-family residences by life cycle phase

<table>
<thead>
<tr>
<th>Stories</th>
<th>Typea</th>
<th>m²</th>
<th>ft²</th>
<th>Material CED</th>
<th>GWP</th>
<th>Construction CED</th>
<th>GWP</th>
<th>Operation CED</th>
<th>GWP</th>
<th>Total CED</th>
<th>GWP</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>WS/W</td>
<td>2,837</td>
<td>30,500</td>
<td>4.2</td>
<td>.30</td>
<td>.75</td>
<td>.36</td>
<td>32</td>
<td>3.2</td>
<td>37</td>
<td>3.9</td>
</tr>
<tr>
<td>3</td>
<td>SCB/WJ</td>
<td>2,837</td>
<td>30,500</td>
<td>4.0</td>
<td>.30</td>
<td>.75</td>
<td>.36</td>
<td>32</td>
<td>3.2</td>
<td>37</td>
<td>3.9</td>
</tr>
<tr>
<td>4</td>
<td>PCP/RC</td>
<td>6,045</td>
<td>65,000</td>
<td>5.9</td>
<td>.50</td>
<td>1.0</td>
<td>.49</td>
<td>32</td>
<td>3.2</td>
<td>39</td>
<td>4.2</td>
</tr>
<tr>
<td>4</td>
<td>PCP/S</td>
<td>6,045</td>
<td>65,000</td>
<td>6.0</td>
<td>.50</td>
<td>1.1</td>
<td>.49</td>
<td>32</td>
<td>3.2</td>
<td>39</td>
<td>4.2</td>
</tr>
<tr>
<td>7</td>
<td>PCP/RC</td>
<td>5,580</td>
<td>60,000</td>
<td>6.2</td>
<td>.53</td>
<td>1.1</td>
<td>.50</td>
<td>32</td>
<td>3.2</td>
<td>39</td>
<td>4.2</td>
</tr>
<tr>
<td>7</td>
<td>PCP/S</td>
<td>5,580</td>
<td>60,000</td>
<td>6.3</td>
<td>.53</td>
<td>1.1</td>
<td>.51</td>
<td>32</td>
<td>3.2</td>
<td>40</td>
<td>4.2</td>
</tr>
<tr>
<td>11</td>
<td>RPC/RC</td>
<td>7,510</td>
<td>80,750</td>
<td>7.9</td>
<td>.66</td>
<td>1.5</td>
<td>.68</td>
<td>32</td>
<td>3.2</td>
<td>42</td>
<td>4.5</td>
</tr>
<tr>
<td>11</td>
<td>RPC/S</td>
<td>7,510</td>
<td>80,750</td>
<td>8.6</td>
<td>.72</td>
<td>1.6</td>
<td>.71</td>
<td>32</td>
<td>3.2</td>
<td>42</td>
<td>4.6</td>
</tr>
<tr>
<td>21</td>
<td>PCP/RC</td>
<td>20,135</td>
<td>216,500</td>
<td>7.5</td>
<td>.63</td>
<td>1.4</td>
<td>.63</td>
<td>32</td>
<td>3.2</td>
<td>41</td>
<td>4.5</td>
</tr>
<tr>
<td>21</td>
<td>PCP/S</td>
<td>20,135</td>
<td>216,500</td>
<td>8.4</td>
<td>.70</td>
<td>1.5</td>
<td>.67</td>
<td>32</td>
<td>3.2</td>
<td>42</td>
<td>4.6</td>
</tr>
</tbody>
</table>


b CED: cumulative energy demand; GJ/m²: gigajoules per square meter; tCO₂eq/m²: tonne Carbon dioxide equivalent per square meter; m²: square meter; ft²: square feet.
Figure 3. CED for Multi-family buildings of different construction and number of stories.\textsuperscript{a}

\textsuperscript{a} CED: cumulative energy demand; GJ/m\textsuperscript{2}; gigajoules square meter; WS/W: Wood siding/wood frame; SCB/WJ: Stucco on concrete block/wood joists; PCP/RC: Precast concrete panels/reinforced concrete; PCP/S: Precast concrete panels/steel; RPC/RC: Ribbed precast concrete/reinforced concrete; RPC/S: Ribbed precast concrete/steel.

Figure 4. GWP for Multi-family buildings of different construction and number of stories.\textsuperscript{a}

\textsuperscript{a} GWP: global warming potential; tCO\textsubscript{2}eq/m\textsuperscript{2}; tonne Carbon dioxide equivalent per square meter; WS/W: Wood siding/wood frame; SCB/WJ: Stucco on concrete block/wood joists; PCP/RC: Precast concrete panels/reinforced concrete; PCP/S: Precast concrete panels/steel; RPC/RC: Ribbed precast concrete/reinforced concrete; RPC/S: Ribbed precast concrete/steel.
Figure 5. % CED for Multi-family buildings of different construction and number of stories.  


Figure 6. % GWP for Multi-family buildings of different construction and number of stories.  

Using the annual contributions to CED and GWP during the operation life cycle phase (Table 10) and the impact assessment results for the materials extraction and production and construction life cycle phases (Table 12) for the 11-Story RPC/S Multi-family residence, the impacts of different life spans to total life cycle CED and GWP were examined. Figure 7 and 8 illustrate the comparative results.

**Figure 7.** % CED by Life Span of 11-Story Multi-family Residence

*CED: cumulative energy demand. The 11-Story multi-family dwelling used is the PRC/S, Ribbed precast concrete/steel type.*
**Figure 8.** % GWP versus Life Span of 11-Story Multi-family Residence

*a CED: cumulative energy demand. The 11-Story multi-family dwelling used is the PRC/S, Ribbed precast concrete/steel type.

- **Interpretation/Discussion**

  The results of the hybrid LCA for multi-family residences show that the total life cycle CED and GWP increase with the rise of the building, from 37, 39, to 42 GJ/m², and 4, 4, and 5 tCO₂eq/m² on average, respectively. Within a given rise however, such as within the mid-rise multi-family residential type, the total life cycle CED and GWP remains relatively stable despite some variability due to the different framing materials chosen. The reason behind these results can be explained by the fact that as the rise increases from low to mid to high, the general structural requirements also increase (Reed Construction Data Inc. 2012).

  In previous building LCA studies, the operation phase consistently dominates the share of the total life cycle energy, ranging from 70% to 95%, followed by the materials extraction and production phase ranging from 2% to 26% (Adalberth 1997, Cole and Kernan 1996, Gong et al. 2012, Keoleian et al. 2008, Scheuer et al. 2003). Despite the different functional unit definition in this study, the shares of the contributions to CED from the operation life cycle phase are consistent with these findings, ranging from 77% to 87%, followed by the contributions from the materials extraction and production phase ranging from 11% to 20%. The contributions to GWP during the operation life
cycle phase in this study are similar ranging from 79% to 90% of the share of total life cycle GWP, followed by the materials extraction and production phase ranging from 8%-17%.

Table 13 contains results from the current study for CED as well as results from previous studies.

**Table 13.** Comparing the current building LCA results for CED with previous studies.

<table>
<thead>
<tr>
<th>Study</th>
<th>Life Span (years)</th>
<th>Materials Extraction and Production (GJ/m²)</th>
<th>Construction (GJ/m²)</th>
<th>Operation (GJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td>50</td>
<td>Low: 4, High: 8.6</td>
<td>Low: .77, High: 1.6</td>
<td>Low: 32, High: 32</td>
</tr>
<tr>
<td>(Adalberth 1997)</td>
<td>50</td>
<td>Low: 2.6, High: 3</td>
<td>Low: .3, High: .4</td>
<td>Low: 23, High: 27</td>
</tr>
<tr>
<td>(Cole and Kernan 1996)</td>
<td>50</td>
<td>Low: 2.6, High: 3.4</td>
<td>Low: 1, High: 1.7</td>
<td>Low: 48, High: 82</td>
</tr>
<tr>
<td>(Gong et al. 2012)</td>
<td>50</td>
<td>Low: 1.7, High: 5</td>
<td>Low: .1, High: .3</td>
<td>Low: 12, High: 14</td>
</tr>
<tr>
<td>(JUNNILA et al. 2006)</td>
<td>50</td>
<td>Low: 3.4, High: 7</td>
<td>Low: 1, High: 1.2</td>
<td>Low: 46, High: 68</td>
</tr>
<tr>
<td>(Frijia et al. 2011)</td>
<td>50</td>
<td>Low: 4.2, High: 5</td>
<td>Low: 1.1, High: 1.4</td>
<td>Low: 21, High: 26</td>
</tr>
<tr>
<td>(Keoleian et al. 2008)</td>
<td>50</td>
<td>Low: 6.6 (low), 7.3 (high)</td>
<td></td>
<td>Low: 21, High: 64</td>
</tr>
</tbody>
</table>

*GJ/m²*: gigajoules per square meter.

Figures 9-11 illustrate the results for each study in table 13 for the different life cycle phases.
Figure 9. CED values from the current and previous studies for the materials extraction and production life cycle phase.

a CED: cumulative energy demand; GJ/m²: gigajoules per square meter. Each study contains a low and high value as shown on graph.
b Low value is for 3-story, wood siding/wood frame multi-family residence; high value is for 11-story, ribbed precast concrete/steel multi-family residence. Life cycle phase includes HVAC supply chain energy.
c Low value is for 2-story, wood, single-family, detached residence; high value is for 1-story, wood, single family, detached residence (Adalberth 1997).
d Low value is for 3-story, generic wood office building with no underground parking; high value is for 3-story generic steel office building with no underground parking (Cole and Kernan 1996).
e Low value is for 3-story, wood-framed, multi-family residence; high value is for 3-story, concrete-framed multi-family residence (Gong et al. 2012).
f Low value is for 4-story, steel reinforced concrete office building in Finland; high value is for 5-story, steel reinforced concrete office building in Midwest U.S. (JUNNILA et al. 2006).
g Low value is for 1-story, 326m², single-family residence; high value is for 1-story, 140m², single-family residence (Frijia et al. 2011).

Figure 9 shows relatively higher values for the current study than in previous studies. The impact of the functional unit definition may be evident here. Recall that the functional unit for the current study is the amount of energy required to deliver a controlled climate to a multi-family residence for 50 years. This study included the impacts from the supply chain for the HVAC system, consequently increasing the impacts from the materials extraction and production life cycle phase.
CED values for the Construction Life Cycle Phase

Figure 10. CED values from the current and previous studies for the construction life cycle phase.

a CED: cumulative energy demand; GJ/m²: gigajoules per square meter. All but one study contains a low and high value for the construction life cycle phase. (Cole and Kernan 2006) low and high values are equivalent for construction life cycle energy as shown on graph.

b Low value is for 3-story, wood siding/wood frame and stucco on concrete block/wood joists frame, multi-family residence; high value is for 11-story, ribbed precast concrete/steel frame multi-family residence.

c Low value is for 2-story, wood, single-family, detached residence; high value is for 1-story, wood, single family, detached residence (Adalberth 1997).

d Low value is for 3-story, generic wood office building with no underground parking; high value is for 3-story generic steel office building with no underground parking (Cole and Kernan 1996).

e Low value is for 3-story, wood-framed, multi-family residence; high value is for 3-story, concrete-framed multi-family residence (Gong et al. 2012).

f Low value is for 4-story, steel reinforced concrete office building in Finland; high value is for 5-story, steel reinforced concrete office building in Midwest U.S. (JUNNILA et al. 2006).

g Low value is for 1-story, 326m², single-family residence; high value is for 1-story, 140m², single-family residence (Frijia et al. 2011).

Figure 10 shows a large variation between studies in the construction life cycle phase. One difference between the current study and previous studies is the number of buildings assessed. The current study assesses 10 different multi-family residences, while previous studies assess 1 to 3, explaining the wider gap between the low and high CED values (Adalberth 1997, Cole and Kernan 1996, Gong et al. 2012, JUNNILA et al. 2006, Frijia et al. 2011).
Figure 11. CED values from the current and previous studies for the operation life cycle phase.

a CED: cumulative energy demand; GJ/m²: gigajoules per square meter. All but one study contains a low and high value for the operation life cycle phase. The current study only contains one value for operation life cycle energy as shown on graph.
b Single value represents operation energy for all multi-family residences in the current study.
c Low value is for 2-story, wood, single-family, detached residence; high value is for 1-story, wood, single family, detached residence (Adalberth 1997).
d Low value is for 3-story, generic office building with no underground parking located in Vancouver; high value is for 3-story generic office building with no underground parking located in Toronto (Cole and Kernan 1996).
e Low value is for 3-story, wood-framed, multi-family residence; high value is for 3-story, steel-framed multi-family residence (Gong et al. 2012).
f Low value is for 4-story, steel reinforced concrete office building in Finland; high value is for 5-story, steel reinforced concrete office building in Midwest U.S. (JUNNILA et al. 2006).
g Low value is for 1-story, 326m², single-family residence; high value is for 1-story, 140m², single-family residence (Frijia et al. 2011).
h Low value is for a 2-story, 228m², single-family, detached, energy efficient home; the high value is for a 2-story, 228m², ‘standard’ single-family, detached residence (Keoleian et al. 2008).

Figure 11 also shows large variation between studies. Recall that the functional unit defined for the current study and (Frijia et al. 2011) only includes space conditioning, or space heating and cooling. Space conditioning accounts for about 50% of the energy consumed in a residential building (Perez-Lombard et al. 2008). This could explain why the value for the current study and (Frijia et al 2011) are lower than (Cole and Kernan 1996, JUNNILA et al. 2006, Keoleian et al. 2008). However, the operation values for (Adalberth 1997, Gong et al. 2012) are also comparatively lower. This is problematic because the functional unit used in these studies includes all activities in the building. It is not clear in these particular studies if primary energy is being calculated, highlighting the importance of transparency in LCA.
The examination of the impacts of different life spans (Figures 7 and 8) show that as the life span changes, the shares of the contributions to CED and GWP from the different life cycle phases also change. While these results are intuitive, they highlight the importance of using consistent life spans between studies. As mentioned previously, the life spans used in building LCA vary from 30 to 75 years without justification as to why they were chosen (Aden 2010, Suzuki and Oka 1998, Adalberth 1997, Cole and Kernan 1996, Keoleian et al. 2008, Scheuer et al. 2003). These comparative results suggest the need for future work in the area of life span choices. Perhaps the defined life span changes as the function of the building changes.
• Uncertainty

In any LCA, there is uncertainty due to (1) unavailable, inaccurate or unrepresentative data, (2) inherent simplifications of aspects of the system being modeled, (3) the scenarios chosen to represent the system such as the choice of functional unit, and/or (4) inherent spatial and temporal variability between environments (Huijbregts 1998, Björklund 2002). This study applied a hybrid approach to complete an LCA of different size multi-family residences. Economic input-output, economically-based and process-sum approaches were used to assess different life cycle phases. First, economic input-output was used to assess the impacts during the materials extraction and production life cycle phases, ensuring the inclusion of the entire supply chain and preventing truncation errors that occur with a process-sum approach. Second, an economics-based approach was used to assess the impacts from the construction life cycle phase in order to focus on a specific process (multi-family residential construction), avoiding aggregation error. Finally, a process-sum approach was used to assess the impacts during the operation life cycle phase. This approach assessed the direct primary physical energy consumed using national data, preventing aggregation error from an EIO approach. As with any LCA study there is uncertainty, some issues are reviewed below.

One area of uncertainty involves the bills of materials (BOM’s) for each of the multi-family residences. The detailed bills of materials are cost estimates that are primarily used to assist contractors in developing quotes for the construction of buildings. While providing a detailed list of line items, the BOM’s are estimates only, resulting in parameter uncertainty due to potentially inaccurate or missing data.

Second, while the location of interest is Phoenix, Arizona, data for Phoenix is limited to construction labor costs for Phoenix, as well as to a site to source factor, and, electricity emissions factors for the state. The data used for operation energy is based on U.S. averages, and, is limited to a multi-family residence with 5 or more units, or, one data point. Thus, while the construction and materials side is resolved to different buildings in Phoenix, the operation phase is aggregated geographically and over types of buildings. Clearly it is desirable to use more specific operation energy data. A thorough search was undertaken and no appropriate data sources were found.

The objective of this study was to complete a hybrid LCA of low, mid and high-rise multi-family residences, constructing parametric models describing the results by type and size of multi-family residence. While uncertainty remains, the comparisons of the results of the current study to previous studies do not indicate any inconsistencies of concern, helping to validate the findings.
Chapter 3 - Uncertainty Mitigation through Knowledge-Based Bounding

Background and Literature Review

Uncertainty analysis has long been recognized as an important aspect of life cycle assessment (LCA). However, serious analysis of uncertainty continues to be the exception rather than the rule in LCA practice (Blengini and Di Carlo, 2010, Finnveden et al., 2009, Heijungs and Huijbregts, 2004, Björklund, 2002). This is problematic because as LCA’s become more influential in informing policy decisions, uncertainty analyses become imperative due to the large costs associated with these decisions (Lloyd and Ries, 2007). For example, California’s Low Carbon Fuel Standard Program which calls for a reduction of at least 10 percent in the carbon intensity of California's transportation fuels by 2020, was largely based upon LCA modeling, and, has greatly challenged the transportation fuel industry (California Environmental Protection Agency Air Resources Board, 2010). General aspects of uncertainty in LCA are reviewed, bounding approaches to addressing parameter uncertainty are described, and finally, an extension to bounding methodologies is proposed and piloted.

A distinction is made between theory and applications of uncertainty in LCA as the theoretical literature goes well beyond attempts to implement these ideas into practice. It is sometimes useful to distinguish between uncertainty and variability, the lines between the two often blur however, and in this manuscript we use the word uncertainty to include variability. The theory of uncertainty outlines a distinction between types and sources of uncertainty in LCA. A common taxonomy uses the three divisions of parameter, model, uncertainty due to choices (scenario), and sometimes, uncertainty due to variability (Heijungs 1996, Björklund 2002, Huijbregts 1998, Heijungs and Huijbregts 2004, Williams et al. 2009, Lloyd and Ries 2007, Finnveden et al. 2009, Huijbregts et al. 2003). A more detailed distinction between the types and potential sources is made here: (1) parameter uncertainty is uncertainty in observed or measured values; sources of parameter uncertainty include: missing, inaccurate or unrepresentative data, (2) model uncertainty occurs as a result of simplification of aspects of the system being modeled; examples of sources of model uncertainty include: aggregation of data or linear versus non-linear models, (3) choices must be made or scenarios developed in LCA, therefore uncertainty is inevitable; examples of sources of uncertainty due to choices include: choice of functional unit, system boundary or allocation procedure, (4) uncertainty due to variability occurs as a result of inherent spatial and temporal variability; sources of uncertainty due to variability include: properties of different environments, regional differences in inventories or technologies; and/or, temporal differences in inventories (Huijbregts 1998, Björklund 2002). (Heijungs and Huijbregts 2004) argue that while there are many ways to classify uncertainty, and, the utility of the classification may not be immediately apparent, distinguishing the type
of uncertainty is important in driving the particular approach chosen for analyzing, or characterizing, the uncertainty.

Characterization of uncertainty through uncertainty analysis determines to what extent different types of uncertainty (parameter, model, scenario, uncertainty due to variability) affect the reliability of the results of the LCA; it is a very important part in a decision maker’s ability to confidently draw comparative conclusions (ISO 14044, 2006, Environmental Protection Agency, 2006). Both quantitative and qualitative approaches to characterize uncertainty in LCA are outlined in the literature including simulations (Monte Carlo) and statistical analysis, scenario analysis; and expert judgment (Heijungs 1996, Björklund 2002, Huijbregts 1998, Heijungs and Huijbregts 2004, Williams et al. 2009, Lloyd and Ries 2007, Finnveden et al. 2009, Huijbregts et al. 2003). On the application side, far and above most work has focused on characterizing parameter uncertainty through statistical analysis. (Lloyd and Ries 2007) present a summary of LCA’s that applied quantitative uncertainty analysis, and stochastic modeling was used in 70% of the studies examined. (Sonnemann et al. 2003) completed a Monte Carlo analysis based on developing statistical distributions of process emissions in waste incineration. (Huijbregts et al. 2003) apply a broad framework to address multiple types of uncertainty, i.e. parameter, model, and scenario; however, the focus of characterization remains primarily on parameter through the use of Monte Carlo simulations.

In contrast to characterizing uncertainty after the life cycle inventory (LCI) process, researchers have also proposed approaches to mitigate uncertainty as an integrated part of the LCI process. First introduced by (Bullard et al. 1978), (Williams 2004) applied a hybrid framework that combined process-sum and economic input/output (EIO) approaches to mitigate model uncertainty in a desktop computer LCA. As previously discussed in Chapter 2, combining methodologies allows the practitioner to utilize the benefits from both process-sum and EIO models, while minimizing the inherent uncertainty from cut-off, or truncation error, and aggregation error, respectively (Williams 2004). Later, (Williams et al. 2009) expanded on this approach by proposing an iterative hybrid framework, arguing that explicit iteration should be included to further reduce uncertainty. (Olivetti et al. 2013) also applied an iterative approach using statistical simulation based on “structured under-specification” of parameters in a case study on metals.

Availability of data is a major primary obstacle to statistical analyses: it is often difficult to find process data for a point estimate, much less multiple data points to build a distribution. One approach to limited data is to map subjective user judgments of data quality to numerical estimates for uncertainty distributions. A popular LCA tool, Ecoinvent (PR’e Consultants 2012), uses a formula that estimates standard deviation based on the “pedigree matrix” of user judgments of data quality (Frishknect et al. 2007, Goedkoop et al, 2010). (Blengini and Di Carlo 2010) use a pedigree matrix to characterize single
measurement or estimated field data uncertainty in a residential building LCA. While this approach attempts to include uncertainty analysis as part of LCA, it is argued that it is dangerous to use such a formula without evidence as to when it reasonably matches data-based distributions. LCA analysts are tempted to substitute the difficult task of finding and grappling with multiple data sources with a simple formula with no basis in empirical reality.

Bounding approaches are a subset of approaches to mitigate parameter uncertainty as an integrated part of LCA. Also called “extreme values” and “intervals”, the idea of bounding is to identify lower and upper values for parameters and calculate results as a range rather than a point value (Heijungs 1996, Björklund 2002, Chevalier and Le Téno 1996). In the language of distributions this is equivalent to assuming rectangular distributions bounded by extreme values. The main value of a bounding approach is that empirically it is much easier to characterize bounds than to characterize a detailed distribution. The disadvantage to bounds is that resulting ranges in LCA results could be too wide to draw useful conclusions. (Morgan 2001) suggests that bounding analysis can provide insight as to where an answer might lie; eliminating the need for other more complex forms of analysis. (Johnson et al. 2011) states that using ‘most likely’ boundaries on input parameters has relatively few data requirements and requires fewer assumptions about data structure. An alternate perspective is that there is an interaction between the bounds on a result and the questions that can be answered. If your question can be answered with a given bound (is product A less impactful than product B?), the analysis can be considered done. If not, further analysis is needed to reduce bounds, returning us to the above discussion of iteration in LCA. Previous applications of bounding in LCA include (Williams et al. 2002, Deng et al. 2011, Chevalier and Le Téno 1996).

The first research objective for this chapter is to expand on previous work by proposing a framework for an iterative knowledge-based bounding approach that maps knowledge of a product to numerical uncertainty bounds. If the results of the LCA produce a range of uncertainty that is unacceptable for the study, the bounds of uncertainty are tightened by gathering additional information on the input parameter(s). The iteration process continues until the goals of the study are met. The novelty in the present study is in the use of iterations of knowledge-based bounding to achieve uncertainty goals. The suggestion is that further reduction in uncertainty should only be pursued if required by the study. This approach provides practitioners with a straightforward and practical framework for mitigating uncertainty, meeting the goals of the LCA without adding unnecessary complexity.

The second research objective for this chapter is to pilot the proposed knowledge-based bounding approach for mitigating uncertainty in a case study of the contribution of steel manufacturing to the global warming potential (GWP) of the total life cycle of residences. Potential sources of variability in steel
manufacturing are examined through LCA and the results are used to establish knowledge-based bounds, consequently demonstrating the utility of this approach to mitigate uncertainty.

**Framework**

![Diagram showing the framework for iterative knowledge-based bounding.](image)

**Figure 12.** Framework for Iterative Knowledge-Based Bounding

\*GWP: global warming potential; LCA: life cycle assessment.

\*Low: lower bound; high: upper bound; i: bounded parameter; j: parameter that is not bounded; m: physical quantity of parameter; CO₂ intensity: kilogram carbon dioxide equivalent per physical quantity of parameter.

Figure 1 illustrates the basic flow of iterative knowledge-based bounding. As with conventional LCA, process data is collected. It is during the LCI process where a parameter may be identified as a candidate for bounding. It is not suggested or recommended that all parameters are bounded. Rather, a bounded approach is most appropriate for parameters that are the largest contributors to the LCI by mass, cumulative energy demand (CED) or GWP (global warming potential) content, and/or, there exists high variability in data. This approach eliminates the requirement of choosing one value, saving time and also
allowing for variations from geographical or temporal differences for example. Once the parameters to be bounded have been identified, initial bounds (CED, GWP) need to be established. Initial knowledge-based bounds require the least amount of information. That is, very general product knowledge should be used to establish initial knowledge-based bounds. For example, if the parameter is steel, one should assume that the product could be high or low alloy, high or low secondary steel (recycled) content, and, the product could be produced anywhere. These aspects allow a large range of values (extreme high/low values) from databases and literature to be used, hence the initial knowledge-based bounds. Once initial bounds have been established, LCI_{low} and LCI_{high} for GWP for example, can be calculated using the following equations:

\[
GWP_{\text{low}} = \sum_{i=1}^{n} (m_i)(\text{CO}_2 \text{ intensity}_i)_{\text{low}} + \sum_{j=1}^{p} (m_j)(\text{CO}_2 \text{ intensity}_j) \\
GWP_{\text{high}} = \sum_{i=1}^{n} (m_i)(\text{CO}_2 \text{ intensity}_i)_{\text{high}} + \sum_{j=1}^{p} (m_j)(\text{CO}_2 \text{ intensity}_j)
\]

where GWP_{low} is the total life cycle GWP using the low bounds of the bounded parameters, likewise, GWP_{high} is the total life cycle GWP using the high bounds of the bounded parameters, i is a parameter targeted for bounding analysis, j is a parameter that is not targeted for bounding analysis (i.e. only use point estimate), n is the number of parameters targeted for bounding analysis, p is the number of parameters that are not targeted for bounding analysis, m is the physical quantity of a parameter used in the product, \text{CO}_2 \text{ intensity}_i is the GWP intensity per physical quantity of the parameters not targeted for bounding analysis, kg\text{CO}_2 \text{ intensity}_i(\text{low}) is the lower bound GWP intensity per physical quantity of the parameters targeted for bounding analysis, and kg\text{CO}_2 \text{ intensity}_i(\text{high}) is the higher bound GWP intensity per physical quantity of the parameters targeted for bounding analysis.

As shown in Figure 1, upon completion of the LCI phase, the uncertainty of the results is assessed. A bounded parameter may have a large range of uncertainty, but a small contribution in the overall assessment. Alternatively, the same bounded parameter may have a small range of uncertainty, but a large contribution to the overall assessment. If it is determined that the range of uncertainty meets the goals of the study, no further analysis is required. That is, a clear distinction can be made between decision scenarios. However, if it is determined that the uncertainty range does not reveal a clear distinction between decision scenarios, another iteration of knowledge-based bounding occurs through additional research on parameter(s). This process is repeated until the goals of the study are met.
Case Study – Steel Manufacturing

• Method

Goal and Scope

The goal is to illustrate the knowledge bounding method for a material of interest, assuming the method is promising expansion to more materials and processes is a task for future work. The motivation for choosing steel for the case study relates to its importance as a widely used material in buildings (and a variety of other products) and high variability in the energy and GWP intensities used for steel in previous LCA work, e.g. (Hammond and Jones 2008, Keoleian et al. 2008, Buchanan and Honey 1994, Zabalza Bribián et al. 2011, Scheuer et al. 2003). While the materials extraction and production life cycle make up a smaller share of the total life cycle of a building than operation energy, 2%-26% compared to 70%-95%, respectively, the choice of materials impacts the total operation energy results. For example, (Xing et al. 2008) suggest that while a steel-framed office building had less materials extraction and production life cycle energy than a comparable concrete-framed office building, the steel-framed office building had higher operation energy than the concrete-framed office building, resulting in higher total life cycle energy for the steel-framed building. With buildings consuming 40% of global energy and resources, it is important to understand the variability in commonly used construction materials, such as steel, in order to better inform policy on the environmental impacts of choices made in building design and construction (United Nations 2007).

The goal of this case study is to examine potential sources of variability in CED and GWP in steel manufacturing. Moreover, these sources of variability are subsequently utilized to demonstrate how knowledge-based bounding can reduce uncertainty as part of larger residential building LCA. The main objective is to provide guidance, process data, and, a straightforward approach to address uncertainty that can be used by both LCA practitioners and researchers in future life cycle studies.

One source of variability in the CED and GWP in steel manufacturing is in the technologies used for steel production. Two technologies dominate current steel manufacturing, the blast oxygen furnace (BOF) process and the electric arc furnace (EAF) (Fenton 2005). The BOF process reduces iron from ore, then makes steel by blasting oxygen through molten pig iron. While iron ore is the main source of iron in BOF steel, scrap can constitute up to 30% of the “charge” (American Iron and Steel Institute). In contrast, the EAF process uses an electric arc as the heat source, and scrap constitutes up to 100% of the charge (American Iron and Steel Institute). Not surprisingly, the energy requirements of the two technologies are very different. Steel produced from the BOF process
requires greater amounts of energy to produce from ore, roughly 10GJ/tonne more, than steel produced from scrap in an EAF process (Larsson 2005).

In recent years there has been little change in the energy intensity of steel making (Williams et al. 2012). China has been the world’s largest producer of steel and the industry went through rapid reductions in energy intensity starting from the late 1990’s, in recent years the national industry has approached international best standards in energy efficiency (Ibid). Thus temporal factors are excluded from this analysis.

Like potential regional differences in technology, there are also regional differences in electricity grid mixes. For example, in 2012, the U.S. used coal as a fuel for 37% of the electricity generation. In contrast, in 2011 China used primarily coal for 65% of its generation (Energy Information Administration). These differences can cause significant variability in the impacts of GWP, particularly from an EAF process which relies almost entirely on electricity. Therefore, spatial variability is being examined in this study.

Finally, types of finished steel are also being examined for potential influences to CED and GWP. Alternative types of steel such as low- or high-alloyed steel require the use of different processes. Low-alloyed steels contain small amounts of alloyed elements, less than 5% in total, and are characterized by high strength (Fenton 2005, Classen et al. 2009). In contrast, high-alloyed steels or stainless steels, contain larger amounts of alloyed elements such as chromium, at a minimum of 10%, and are characterized by high strength and resistance to abrasion (Ibid). Therefore process data for these different types of finished steels is examined.

Functional Unit:

Because steel is used in many different finished products, defining a functional unit by finished product significantly limits the utility of the results. Therefore, in order to maximize the utility of the results across the core audience, the functional unit is more generally defined. Moreover, given that two different types of steel are being examined, low- and high-alloyed, or chromium steel, two distinct functional units are required: 1 kg of finished steel (low-alloyed) and 1 kg of finished chromium steel (high-alloyed).

Reference Flow:

This study examined the potential sources of variability in the CED and GWP of steel manufacturing. That is, this study examines the impacts to CED and GWP as a result of varying specific aspects of the steel manufacturing process. The aspects being varied include: type of finished steel (either low-alloyed or chromium steel); spatial variability, which takes into account the regional
electrical grids from the U.S., Europe and China; and, the technology used to produce the steel. It is assumed in this study that the BOF process reflects primary steel, or steel that has no recycled content (no secondary content). In contrast, it is assumed that the EAF process reflects secondary steel or steel that has 100% recycled content (100% secondary content). Therefore, the reference flow used to obtain the functional unit(s) is the quantity of primary energy required to produce 1 kg of finished steel, both low-alloyed and chromium (high-alloyed) steel, produced in different regions, while varying the amounts of primary and secondary steel used.

System Boundary:

A cradle-to-to-gate analysis is completed with a specific focus on energy and climate. As a result, the study scope only includes those elementary material, energy, and emission flows that contribute to total cumulative energy and global warming intensity in the manufacture of low-alloyed steel and chromium steel (high alloy). Figure 13 contains the system boundary diagram.

![System boundary diagram for the case study on steel manufacturing.](image)

Methodology:
Two different methodologies that were discussed in detail in Chapter 2 are utilized here to complete the analysis: process-sum and economic input/output (EIO). However, in contrast to Chapter 2 which utilized the approaches in a tiered, or additive, hybrid LCA approach, this chapter utilizes each approach in parallel order to compare and contrast the results.

Impact Categories

As mentioned, the focus of this study is on energy and climate. Therefore the impact categories include: CED (MJ/kg) from fossil fuels, renewables and nuclear energy sources, and climate change or GWP (tCO2eq/kg) using the 100 YR GWP from (IPCC 4th Assessment Report 2007).

- Life Cycle Inventory

As discussed in Chapter 2, the life cycle inventory portion of an LCA involves the collection and quantification of inputs and output flows for a product or system throughout its life cycle. The inputs and outputs for this study include energy and raw materials, and, GHG emissions, respectively. Two parallel LCA approaches are being used to quantify the input and output flows: process-sum and EIO, each requiring a different data collection process.

Process-Sum Approach

A process-sum approach is a bottom-up approach based on physical input and output flows. The data points for CED and GWP for the process-sum approach comes from the Ecoinvent database (PR’e Consultants 2012). The finished steel types from the database used in this study are 1 kg of low-and un-alloyed steel, and 1 kg of chromium (18%) steel (PR’e Consultants 2012). Modifications were made to the data base to reflect the electricity grid mixes for Europe, the U.S. and China. This was not an exhaustive modification, rather only the top 5 processes with the highest impacts from electricity consumption were modified. Moreover, for each region, the amount of primary versus secondary steel used was varied in 25% increments. For example, if 1 kg of low- and un-alloyed steel contained 0% primary steel, then it must contain 100% secondary steel. Similarly, if 1 kg low- and un-alloyed steel contained 25% primary steel, then it must also contain 75% secondary steel, and so on. As a result, there are 30 different data points modeled each for CED and GWP, reflecting the variations in types of steel, regions of production, and % primary and secondary content. Tables 14 and 15 contain input and output flows for primary low- and un-alloyed and chromium steel from U.S., China and Europe.
Table 14. Input and output flows to produce 1 kg of primary, low-alloyed steel in the U.S., China and Europe.

| Inputs<sup>b</sup> | Ecovin<sup>b</sup> Ecoinvent<sup>b</sup> Ecoinvent<sup>b</sup> |
|-------------------|-------------------|-------------------|
|                   | US primary unit<sup>a</sup> | China primary unit<sup>a</sup> | Europe primary unit<sup>a</sup> |
| Coal, hard, unspecified, in ground | 1.2E+00 kg | 1.2E+00 kg | 1.1E+00 kg |
| Coal, brown, in ground | 7.3E-02 kg | 6.0E-02 kg | 1.3E-01 kg |
| Gas, natural, in ground | 1.4E-01 m³ | 1.2E-01 m³ | 1.4E-01 m³ |
| Gas, mine, off-gas, process, coal mining/m³ | 1.1E-02 m³ | 1.2E-02 m³ | 1.0E-02 m³ |
| Crude Oil | 7.5E-02 kg | 7.5E-02 kg | 7.5E-02 kg |
| Uranium, in ground | 4.7E-06 kg | 2.7E-06 kg | 5.3E-06 kg |
| Energy, solar, converted | 5.9E-04 MJ | 3.7E-04 MJ | 7.8E-04 MJ |
| Energy, potential (in hydropower reservoir), converted | 1.6E+00 MJ | 1.7E+00 MJ | 1.7E+00 MJ |
| Energy, kinetic (in wind), converted | 3.0E-02 MJ | 2.6E-02 MJ | 5.4E-02 MJ |
| Energy, gross calorific value, in biomass, primary forest | 1.9E-05 MJ | 1.8E-05 MJ | 1.9E-05 MJ |
| Energy, gross calorific value, in biomass | 2.4E-01 MJ | 2.2E-01 MJ | 2.4E-01 MJ |
| **Total CED (MJ/kg)** | **3.7E+01** | **3.6E+01** | **3.6E+01** |

<table>
<thead>
<tr>
<th>Outputs&lt;sup&gt;b&lt;/sup&gt;</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>US</td>
<td>China</td>
<td>Europe</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>2.2E+00 kg</td>
<td>2.3E+00 kg</td>
<td>2.1E+00 kg</td>
</tr>
<tr>
<td>Methane</td>
<td>7.1E-03 kg</td>
<td>9.1E-03 kg</td>
<td>6.9E-03 kg</td>
</tr>
<tr>
<td><strong>Total CO2eq (kg/kg)</strong></td>
<td><strong>2.4E+00</strong></td>
<td><strong>2.5E+00</strong></td>
<td><strong>2.3E+00</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conversions</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal, hard, unspecified, in ground</td>
<td>19.1</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Coal, brown, in ground</td>
<td>9.9</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Gas, natural, in ground</td>
<td>38.3</td>
<td>MJ/m³</td>
</tr>
<tr>
<td>Gas, mine, off-gas, process, coal mining/m³</td>
<td>39.8</td>
<td>MJ/m³</td>
</tr>
<tr>
<td>Crude Oil, in ground</td>
<td>45.8</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Uranium, in ground</td>
<td>5.6x10³</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Methane GWP&lt;sup&gt;c&lt;/sup&gt;</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> kg: kilogram; m³: cubic meter; MJ: megajoule; MJ/kg: megajoules per kilogram; MJ/m³: megajoules per cubic meter.

<sup>b</sup> Source: (PR`e Consultants 2012); Available data is for low-and un-alloyed steel.

<sup>c</sup> Source: (IPCC 4th Assessment Report 2007).
Table 15. Input and output flows to produce 1 kg of primary, chromium steel in the U.S., China and Europe.

<table>
<thead>
<tr>
<th>1 kg of Chromium Steel</th>
<th>Ecoinvent¹</th>
<th>Ecoinvent¹</th>
<th>Ecoinvent¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>US</td>
<td>China</td>
<td>Europe</td>
</tr>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal, hard, unspecified, in ground</td>
<td>1.9E+00 kg</td>
<td>2.2E+00 kg</td>
<td>1.5E+00 kg</td>
</tr>
<tr>
<td>Coal, brown, in ground</td>
<td>1.2E-01 kg</td>
<td>5.7E-02 kg</td>
<td>4.0E-01 kg</td>
</tr>
<tr>
<td>Gas, natural, in ground</td>
<td>4.7E-01 m³</td>
<td>3.8E-01 m³</td>
<td>4.6E-01 m³</td>
</tr>
<tr>
<td>Gas, mine, off-gas, process, coal mining/m³</td>
<td>1.6E-02 m³</td>
<td>2.2E-02 m³</td>
<td>1.5E-02 m³</td>
</tr>
<tr>
<td>Crude Oil</td>
<td>1.7E-01 kg</td>
<td>1.7E-01 kg</td>
<td>1.7E-01 kg</td>
</tr>
<tr>
<td>Uranium, in ground</td>
<td>1.3E-05 kg</td>
<td>3.6E-06 kg</td>
<td>1.6E-05 kg</td>
</tr>
<tr>
<td>Energy, solar, converted</td>
<td>1.4E-03 MJ</td>
<td>3.5E-01 MJ</td>
<td>2.3E-03 MJ</td>
</tr>
<tr>
<td>Energy, potential (in hydropower reservoir), converted</td>
<td>9.6E+00 MJ</td>
<td>1.0E+01 MJ</td>
<td>9.9E+00 MJ</td>
</tr>
<tr>
<td>Energy, kinetic (in wind), converted</td>
<td>4.9E-02 MJ</td>
<td>2.8E-02 MJ</td>
<td>1.6E-01 MJ</td>
</tr>
<tr>
<td>Energy, gross calorific value, in biomass, primary forest</td>
<td>6.0E-05 MJ</td>
<td>5.8E-05 MJ</td>
<td>6.1E-05 MJ</td>
</tr>
<tr>
<td>Energy, gross calorific value, in biomass</td>
<td>6.2E-01 MJ</td>
<td>5.6E-01 MJ</td>
<td>6.3E-01 MJ</td>
</tr>
<tr>
<td><strong>Total CED (MJ/kg)</strong></td>
<td>8.1E+01</td>
<td>7.9E+01</td>
<td>7.8E+01</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>4.8E+00 kg</td>
<td>5.3E+00 kg</td>
<td>4.4E+00 kg</td>
</tr>
<tr>
<td>Methane</td>
<td>1.2E-02 kg</td>
<td>2.2E-02 kg</td>
<td>1.1E-02 kg</td>
</tr>
<tr>
<td><strong>Total CO2eq (kg/kg)</strong></td>
<td>5.1E+00</td>
<td>5.8E+00</td>
<td>4.7E+00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conversions</th>
<th>value</th>
<th>unit²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal, hard, unspecified, in ground</td>
<td>19.1</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Coal, brown, in ground</td>
<td>9.9</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Gas, natural, in ground</td>
<td>38.3</td>
<td>MJ/m³</td>
</tr>
<tr>
<td>Gas, mine, off-gas, process, coal mining/m³</td>
<td>39.8</td>
<td>MJ/m³</td>
</tr>
<tr>
<td>Crude Oil</td>
<td>45.8</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Uranium, in ground</td>
<td>5.6x10⁴</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Methane</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

¹ kg: kilogram; m³: cubic meter; MJ: megajoule; MJ/kg: megajoules per kilogram; MJ/m³: megajoules per cubic meter.

² Source: (PR´e Consultants 2012)

Economic Input-Output Approach

An EIO approach is an economically-based approach using producer costing and sectoral energy intensities to determine CED and GWP. Due to data availability, the EIO approach in this study is used to examine CED and GWP for low-alloyed steel in the U.S. and China only. Table 14 contains the data needed to determine the impacts to CED and GWP from steel manufacturing using an EIO approach.

Table 16. Life cycle inventory data Sources used for the EIO approach.

<table>
<thead>
<tr>
<th>Functional Unit</th>
<th>Economic Sector</th>
<th>PPI (2002/2010)a</th>
<th>PPRa</th>
<th>MJ/$, MJ/元a</th>
<th>kgCO₂eq$/{}, kgCO₂eq$/元a</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kg low-alloyed steel from US</td>
<td>Iron and Steel Mills (331110)b</td>
<td>.49c</td>
<td>.83c</td>
<td>43.3b</td>
<td>3.7b</td>
</tr>
<tr>
<td>1 kg of low-alloyed steel from China</td>
<td>Steel Processing (56)b</td>
<td>.89d</td>
<td>.95f</td>
<td>6.2b</td>
<td>.94b</td>
</tr>
</tbody>
</table>

a PPI: producer price index; PPR: producer price index; MJ/$: megajoules/dollar (US currency); MJ/元: megajoules per yuan (China currency); kgCO₂eq$/$: kilogram CO₂equivalent per dollar; kgCO₂eq$/元: kilogram carbon dioxide equivalent per yuan.
d Source: China National Bureau of Statistics.
e Source: U.S Bureau of Economic Analysis. The wholesale sector is the purchaser.
f Source: Bank of China International.

Different forms of low-alloyed steel are examined including: hot-rolled and cold-rolled coil, structural sections and beams, and rebar (reinforced steel). Table 15 contains the purchasing prices for the different low-alloyed steels by region.

Table 17. Purchase pricing data for low-alloyed steel for U.S. and China.

<table>
<thead>
<tr>
<th>Product</th>
<th>US Price ($/kg)a</th>
<th>China Price (元/kg)b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Rolled Coil</td>
<td>$.75</td>
<td>元4.1</td>
</tr>
<tr>
<td>Cold Rolled Coil</td>
<td>$.83</td>
<td>元4.8</td>
</tr>
<tr>
<td>Rebar</td>
<td>$.76</td>
<td>元3.9</td>
</tr>
<tr>
<td>Structural Sections and Beams</td>
<td>$.85</td>
<td>元4.2</td>
</tr>
</tbody>
</table>

a $/kg: dollar per kilogram; Source: MEPS (International) Ltd.; pricing for North America (NA) for the period Oct ’11 – Nov. ’12 was used. The U.S. accounts for 70% of the steel production in NA and therefore this data was assumed to be appropriate (World Steel Association).
b 元/kg: yuan per kilogram; Source: Steelhome.com; pricing for China for the period March ’12-March ’13 was used. This data source provides current rolling average pricing only.
Using data from Tables 16 and 17, the following equations are used to calculate the CED and GWP for the low-alloyed steel for the EIO approach, similar to the EIO calculations used in Chapter 2:

\[ \text{CED}_i = (C_i)(PPI_i)(PPR_i)(E_{S,R}), \]  

(equation 9)

where CED\(_i\) is the cumulative energy demand of the \(i^{th}\) low-alloyed steel type, \(C_i\) is the cost of the \(i^{th}\) low-alloyed steel type, PPI\(_i\) is the producer price index (2002/2010) for the region the low-alloyed steel is produced in, PPR\(_r\) is the producer purchaser ratio for the region the low-alloyed steel is produced in, and \(E_{S,R}\) is the energy intensity per currency for the region the low-alloyed steel is produced in.

Similarly, equation 10 is used to calculate the GWP for the low-alloyed steel for the EIO approach:

\[ \text{GWP}_i = (C_i)(PPI_i)(PPR_i)(GWP_{S,R}), \]  

(equation 10)

where GWP\(_i\) is the global warming potential of the \(i^{th}\) low-alloyed steel type, \(C_i\) is the cost of the \(i^{th}\) low-alloyed steel type, PPI\(_i\) is the producer price index (2002/2010) for the region the low-alloyed steel is produced in, PPR\(_r\) is the producer purchaser ratio for the region the low-alloyed steel is produced in, and \(GWP_{S,R}\) is the GWP intensity per currency for the region the low-alloyed steel is produced in.

**Results**

- Life Cycle Impact Assessment

  Tables 18-20 contain the life cycle impact assessment results for steel manufacturing. Figures 14 and 15 graphically illustrate the results.

**Table 18.** Results showing CED impacts of steel manufacturing using the process-sum approach.

<table>
<thead>
<tr>
<th>% Secondary Content(^b)</th>
<th>% Primary Content(^b)</th>
<th>Low-Alloyed Steel (MJ/kg steel)(^a)</th>
<th>Chromium (Stainless) Steel (MJ/kg steel)(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Europe</td>
<td>China</td>
</tr>
<tr>
<td>0</td>
<td>100</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>25</td>
<td>75</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>75</td>
<td>25</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>

\(^a\) MJ/kg: megajoules per kilogram of steel.

\(^b\) % Secondary content: percent of recycled steel (scrap) used in production; % Primary content: percent virgin steel used in production.
Table 19. Results showing GWP impacts of steel manufacturing using the process-sum approach.

<table>
<thead>
<tr>
<th>% Secondary Content</th>
<th>% Primary Content</th>
<th>Low-Alloyed Steel (kg CO₂eq/kg steel)</th>
<th>Chromium (Stainless Steel) (kg CO₂eq/kg steel)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Europe</td>
<td>China</td>
</tr>
<tr>
<td>0</td>
<td>100</td>
<td>2.3</td>
<td>2.6</td>
</tr>
<tr>
<td>25</td>
<td>75</td>
<td>1.9</td>
<td>2.2</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>1.5</td>
<td>1.8</td>
</tr>
<tr>
<td>75</td>
<td>25</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>0.7</td>
<td>1.1</td>
</tr>
</tbody>
</table>

a kg CO₂eq/kg steel: kilogram carbon dioxide equivalent per kilogram of steel.
b % Secondary content: percent of recycled steel (scrap) used in production; % Primary content: percent virgin steel used in production.

Table 20. Results showing CED and GWP impacts of steel manufacturing using the EIO approach.

<table>
<thead>
<tr>
<th>Finished Steel Type</th>
<th>US CED (MJ/kg) a</th>
<th>US GWP (kg CO₂eq/kg) a</th>
<th>China CED (MJ/kg) a</th>
<th>China GWP (kg CO₂eq/kg) a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Rolled Coil</td>
<td>13</td>
<td>1.1</td>
<td>18</td>
<td>2.8</td>
</tr>
<tr>
<td>Cold Rolled Coil</td>
<td>15</td>
<td>1.2</td>
<td>22</td>
<td>3.3</td>
</tr>
<tr>
<td>Rebar (Reinforcing)</td>
<td>13</td>
<td>1.1</td>
<td>18</td>
<td>2.7</td>
</tr>
<tr>
<td>Structural Sections and Beams</td>
<td>15</td>
<td>1.3</td>
<td>19</td>
<td>2.9</td>
</tr>
</tbody>
</table>

a CED: cumulative energy demand; GWP: global warming potential; MJ/kg: megajoules per kilogram of steel; kg CO₂eq/kg steel: kilogram carbon dioxide equivalent per kilogram of steel.
b % Secondary content: percent of recycled steel (scrap) used in production; % Primary content: percent virgin steel used in production.

Figures 14 and 15 illustrate the results of CED and GWP versus percent secondary steel content by region and type of steel, respectively for the process-sum approach. The results for CED and GWP for the EIO approach are also included in Figures 14 and 15, respectively. Moreover, in order to examine the results in the context of the broader literature, values for CED, GWP and percent secondary steel content used in previous studies and published reports are included in the respective figures, and are detailed in Table 21.
Figure 14. Process-sum model results for cradle to gate cumulative energy demand for steel as function of secondary steel content, region and type of steel (solid and dashed lines), EIO-LCA results for the U.S. and China (stars), and prior process LCA studies (circles, triangles, squares and diamonds).

a CED: cumulative energy demand; EIO: economic input-output
b Actual values are included in Table 2.
c (Crawford, 2013)
d (Markus Engineering Services 2002)
e CED trendlines for China and Europe overlap.
f USLCI data was retrieved from (PR`e Consultants 2012)
Figure 15. Process-sum model results for cradle to gate global warming potential for steel as function of secondary steel content, region and type of steel (solid and dashed lines), EIO-LCA results for the U.S. and China (stars), and prior process LCA studies (circles, triangles, squares and diamonds).

a GWP = global warming potential; EIO: economic input output; kgCO2eq/kg steel: kilogram carbon dioxide equivalent per kilogram of steel.

b Actual values are included in Table 2.

c (Crawford, 2013)

d (Markus Engineering Services 2002)

e USLCI data was retrieved from (PR’e Consultants 2012)
Table 21. CED and GWP results for the EIO approach as well as from previous studies and reports.

<table>
<thead>
<tr>
<th>Source</th>
<th>Type of Finished Steel</th>
<th>CED (MJ/kg steel)*</th>
<th>GWP (kg CO₂ eq/kg steel)*</th>
<th>Approximate % Secondary Steel Content*</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIO approach – US (Carnegie Mellon University Green Design Institute 2013)</td>
<td>Average low-alloyed steel including: sections, reinforcing (rebar), cold-rolled, hot-rolled.</td>
<td>13 (low)</td>
<td>1.1 (low)</td>
<td>50c</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 (high)</td>
<td>1.3 (high)</td>
<td>50c</td>
</tr>
<tr>
<td>EIO approach – China (Carnegie Mellon University Green Design Institute 2013)</td>
<td>Average low-alloyed steel including: sections, reinforcing (rebar), cold-rolled, hot-rolled.</td>
<td>18</td>
<td>2.7 (low)</td>
<td>10c</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22</td>
<td>3.3 (high)</td>
<td>10c</td>
</tr>
<tr>
<td>World Steel Association)</td>
<td>Sections</td>
<td>16</td>
<td>1.2</td>
<td>85</td>
</tr>
<tr>
<td>(Crawford, 2013)</td>
<td>Tinplate</td>
<td>22</td>
<td>1.7</td>
<td>60</td>
</tr>
<tr>
<td>(A) Athena</td>
<td>Rebar, rod and light sections</td>
<td>19</td>
<td>.60</td>
<td>90</td>
</tr>
<tr>
<td>(Markus Engineering Services 2002)</td>
<td>Cold-rolled sheet</td>
<td>23</td>
<td>1.0</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Hot-rolled sheet</td>
<td>26</td>
<td>1.5</td>
<td>55</td>
</tr>
<tr>
<td>USLCI (ecoinvent database)</td>
<td>Iron and steel mix</td>
<td>10</td>
<td>.90</td>
<td>70</td>
</tr>
<tr>
<td>(PR’è Consultants 2012)</td>
<td>Hot-rolled sheet</td>
<td>26</td>
<td>2.3</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Cold-rolled sheet</td>
<td>30</td>
<td>2.6</td>
<td>30</td>
</tr>
<tr>
<td>(Hammond and Jones 2008)</td>
<td>Typical steel 42.3% RR</td>
<td>24</td>
<td>.48</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Primaryab</td>
<td>35</td>
<td>.75</td>
<td>0</td>
</tr>
<tr>
<td>(Keoleian et al. 2008)</td>
<td>Stainless†</td>
<td>16</td>
<td>1.2</td>
<td>Unknowng</td>
</tr>
<tr>
<td></td>
<td>Cold-rolled†</td>
<td>29</td>
<td>2.1</td>
<td>Unknowng</td>
</tr>
<tr>
<td></td>
<td>Extruding/galvanizing</td>
<td>37</td>
<td>3.2</td>
<td>Unknowng</td>
</tr>
<tr>
<td>(Buchanan and Honey 1994)</td>
<td>General</td>
<td>35</td>
<td>1.4</td>
<td>24d</td>
</tr>
<tr>
<td></td>
<td>Sections</td>
<td>59</td>
<td>2.0</td>
<td>24d</td>
</tr>
<tr>
<td>(Zabalza Bribián et al. 2011)</td>
<td>Reinforcing</td>
<td>24</td>
<td>1.5</td>
<td>40c</td>
</tr>
<tr>
<td>(Scheuer et al. 2003)</td>
<td>EAF technologyab</td>
<td>12</td>
<td>Unknowng</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Secondary, Hot-rolled</td>
<td>14</td>
<td>Unknowng</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Primary, Cold-rolled</td>
<td>28</td>
<td>Unknowng</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Electrogalvanized</td>
<td>31</td>
<td>Unknowng</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Stainless</td>
<td>8</td>
<td>Unknowng</td>
<td>Unknowng</td>
</tr>
</tbody>
</table>

a GWP: global warming potential; CED: cumulative energy demand; EAF: electric arc furnace; BOF: blast oxygen furnace; MJ/kg steel: megajoules per kilogram of steel; kg CO₂eq/kg steel: kilogram carbon dioxide equivalent per kilogram of steel.
b EAF technology is assumed to be comprised of 100% secondary (recycled) steel; BOF technology is assumed to be comprised of 100% primary (virgin) steel.
c Values based on the percentage of EAF and BOF technologies used in these regions in 2002 (World Steel Association).
d Values based on the percentage of EAF and BOF technologies used globally when in 1983 when study was completed (World Steel Association).
e Values based on the percentage of EAF and BOF technologies used in Europe in 2007 when study was completed (World Steel Association).
f Values do not include primary fabrication energy.
g Values were not included in previous work.
• Interpretation/Discussion

Sources of variability in CED and GWP are apparent in Figures 14 and 15, respectively. Both figures reveal a clear distinction in GWP and CED between low-alloyed and chromium steel. This distinction is due to the differing amounts of alloys in each. Recall that while low-alloyed steel contains less than 5% alloying elements in total, chromium steel (stainless steel) in contrast contains a minimum of 10.5% of the element chromium alone (Classen et al. 2009). The resulting difference between these types of steel in GWP and CED for the metallurgy step alone is > 90% (PR´e Consultants 2012).

Another commonality between the figures is the existence of an inverse relationship between the amount of secondary steel content and resulting CED and GWP values: as the amount of secondary steel content increases, CED and GWP values decrease. This result is expected because of the benefits of recycling.

Another expected result that can be observed particularly from Figure 15 is the impact of different regional electricity grid mixes on GWP. Regions that utilize greater amounts of fossil fuels such as China, have higher impacts to GWP (Energy Information Administration). In contrast, countries that utilize greater amounts of renewable resources such as Germany, who is the global leader in solar electricity production, have lower resulting impacts to GWP (Energy Information Administration). Coincidentally, these results align with the World Carbon Dioxide Emissions by Region (Energy Information Administration).

In contrast to the expected findings mentioned above, the results for the EIO approach overall are low for this coarse-grained model. The expectation is that the values for CED and GWP would be higher due to aggregation of economic sectors, however the EIO results for the U.S. are lower. Moreover, the values used in previous studies and reports are variable. All of these findings suggest that a bounding approach would be a more appropriate approach than choosing one particular value due to model, spatial, technological and product type variability.
Knowledge-Based Bounding

As previously discussed, bounding approaches are a subset of approaches proposed to mitigate parameter uncertainty as an integrated part of LCA. Also called “extreme values” and “intervals”, the idea of bounding is to identify lower and upper values for parameters and calculate results as a range rather than a point value (Heijungs 1996, Björklund 2002, Chevalier and Le Téno 1996). The main value of a bounding approach is that empirically it is much easier to characterize bounds than to characterize a detailed distribution as required by most approaches to uncertainty analysis. The novelty in the present study is in the use of iterations of knowledge-based bounding to achieve uncertainty goals. Knowledge-based bounding maps knowledge of a product, such as country of origin or recycled content, to numerical uncertainty bounds. Gathering additional information about the product in question can shrink these bounds and, through an iterative process, reduce uncertainty until the goals of an LCA are met. The suggestion is that further reduction in uncertainty should only be pursued if required by the study. This approach provides practitioners with a straightforward and practical framework for mitigating uncertainty, meeting the goals of the LCA without adding unnecessary complexity.

In the previous case study, potential sources of variability in steel manufacturing were examined through LCA in order to provide a basis for demonstrating the proposed framework for knowledge-based bounding (Figure 12). In this section, the utility of the approach is demonstrated by (1) establishing knowledge-based bounds using the LCA results related to the GWP impacts of steel manufacturing (Table 19) and then, (2) using these established bounds along with previous work on comparative multi-family LCA results to demonstrate the utility of the proposed knowledge-based bounding framework (Gong et al. 2012). First, three iterations of knowledge-based bounding are developed and outlined in Table 22.
Table 22. Knowledge-based bounding iterations used in this study.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Product Knowledge</td>
<td>An LCA practitioner may not be an expert in steel manufacturing, i.e. processes used, material composition, finished products, different regions of production or applications. Therefore, the first iteration requires only general knowledge of steel manufacturing, requiring minimal research about the product itself, processes used, or specific region of production. As a result, the bounds of uncertainty are at the extreme, $0.70 - 5.9$ kgCO$_2$eq/kg steel (Table 19).(^a)</td>
</tr>
<tr>
<td>Finished Product Knowledge</td>
<td>Through additional research, it has been determined that the steel is being used in a construction application and is low-alloy. The region of production remains unknown. As a result of this iteration, the bounds of uncertainty are tightened to indicate low-alloyed steel from the U.S. China or Europe, $0.70 - 2.6$ kgCO$_2$eq/kg steel (Table 19).(^a,b)</td>
</tr>
<tr>
<td>Percent Secondary Steel content Knowledge</td>
<td>Through additional research is has been determined that Nucor Corporation, located in the U.S. is supplying the steel. Nucor’s bar, sheet, beam and plate products have a percent secondary steel content between 64% and 99.9%. As a result of this iteration, the bounds of uncertainty are further tightened to indicate a range of recycled content of (64% - 100%) from the U.S., or $0.8 - 1.4$ kgCO$_2$eq/kg steel.(^a,c)</td>
</tr>
</tbody>
</table>

\(^a\) kg CO$_2$eq/lg steel: kilogram carbon dioxide equivalent per kilogram of steel.

\(^b\) Source: (Classen et al. 2009, Reed Construction Data 2012)

\(^c\) Source: (Nucor 2013); upper bound value was determined using the regression line for U.S. (max): $y = (-.4)x + 2.8$. Lower bound is from Table 19.
Figure 16 illustrates the established iterations for the knowledge-based bounding approach outlined in Table 22.

![Graph showing GWP vs % Secondary Steel Content](image)

**Figure 16.** Bounds from the three iterations of knowledge-based bounding developed from Figure 15.

- **a** GWP: global warming potential; kgCO2eq/kg steel: kilogram carbon dioxide equivalent per kilogram of steel.
- **b** General Product Knowledge: steel type, % secondary steel content and region of production unknown; Finished Product Knowledge: steel type known, % secondary steel content and region of production unknown; % Secondary Steel Content Knowledge: steel type, % secondary steel content known and region of production known.

Previous work is now used to demonstrate the impacts of these three iterations of knowledge-based bounding on uncertainty (Gong et al. 2012). In the previous study, an LCA is completed to examine the GWP of different residential building construction types including concrete-framed construction (CFC) and steel-framed construction (SFC) (Gong et al. 2012). In order to accurately examine the utility of the proposed approach, the contributions to GWP from steel in the original study are removed and replaced by the three bounded ranges established in current study. Table 23 details the contributions from the original study.
Table 23. GWP and contributions from steel in the original residential building LCA study (Gong et al. 2012 and personal correspondence).

<table>
<thead>
<tr>
<th>Construction Type</th>
<th>Quantity (tonne)</th>
<th>GWP (kg CO2eq/kg steel)</th>
<th>Contribution to life cycle GWP from steel in original study (kg CO2eq)</th>
<th>Total Life Cycle GWP in original study without steel (kg CO2eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC</td>
<td>282</td>
<td>2.2</td>
<td>6.2x10⁵</td>
<td>4.3x10⁶</td>
</tr>
<tr>
<td>SFC</td>
<td>459</td>
<td>2.2</td>
<td>1x10⁶</td>
<td>2.8x10⁶</td>
</tr>
</tbody>
</table>

*GWP: global warming potential; kgCO₂/kg steel: kilogram carbon dioxide equivalent per kilogram of steel; kgCO₂eq: kilogram carbon dioxide equivalent.

Using equations 7 and 8 detailed initially in the knowledge-based bounding framework but shown here again, and, the bounding values identified in Table 22, the GWP for the three different iterations are calculated. Table 24 details the contributions from the current study:

\[
\text{GWP}_{\text{low}} = \sum_{i=1}^{n} (m_i)(\text{CO}_2\text{intensity}_{i(\text{low})}) + \sum_{j=1}^{p} (m_j)(\text{CO}_2\text{intensity}_{j}) \quad \text{(equation 7)}
\]

\[
\text{GWP}_{\text{high}} = \sum_{i=1}^{n} (m_i)(\text{CO}_2\text{intensity}_{i(\text{high})}) + \sum_{j=1}^{p} (m_j)(\text{CO}_2\text{intensity}_{j}) \quad \text{(equation 8)}
\]

where GWP_{low} is the total life cycle GWP using the low bounds of the bounded parameters, likewise, GWP_{high} is the total life cycle GWP using the high bounds of the bounded parameters, i is a parameter targeted for bounding analysis, j is a parameter that is not targeted for bounding analysis (i.e. only use point estimate), n is the number of parameters targeted for bounding analysis, p is the number of parameters that are not targeted for bounding analysis, m is the physical quantity of a parameter used in the product, CO₂ intensity_i is the GWP intensity per physical quantity of the parameters targeted for bounding analysis, kgCO₂ intensity_i(low) is the lower bound GWP intensity per physical quantity of the parameters targeted for bounding analysis, and CO₂ intensity_i(high) is the higher bound GWP intensity per physical quantity of the parameters targeted for bounding analysis.
Table 24. Ranges of GWP contributions from steel in the residential building LCA from three iterations of knowledge-based bounding.

<table>
<thead>
<tr>
<th>Construction Type</th>
<th>Quantity (tonne)</th>
<th>GWP General Product Knowledge (kg CO2eq)(^a)</th>
<th>GWP Finished Product Knowledge (kg CO2eq)(^a)</th>
<th>GWP % Secondary Content Knowledge (kg CO2eq)(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Using lower bound(^b)</td>
<td>Using Upper bound(^b)</td>
<td>Using lower bound(^b)</td>
</tr>
<tr>
<td>CFC</td>
<td>282</td>
<td>2x10^6</td>
<td>1.7x10^6</td>
<td>2x10^5</td>
</tr>
<tr>
<td>SFC</td>
<td>459</td>
<td>3.2x10^5</td>
<td>2.7x10^6</td>
<td>3.2x10^5</td>
</tr>
</tbody>
</table>

\(^a\) GWP: global warming potential; kgCO2eq: kilogram carbon dioxide equivalent. General Product Knowledge: steel type, % secondary steel content and region of production unknown; Finished Product Knowledge: steel type known, % secondary steel content and region of production unknown; % Secondary Steel Content Knowledge: steel type, % secondary steel content and region of production known.

\(^b\) Previously established bounds from Table 22 and Figure 16 in terms of kgCO\(_2\)eq/kg of steel, or kilogram carbon dioxide per kilogram of steel.

Finally, Table 25 details the total life cycle GWP ranges in the residential building LCA from three iterations of knowledge-based bounding. Figure 17 illustrates these ranges of uncertainty for the different construction types by iteration.

Table 25. Total Life Cycle GWP ranges in the residential building LCA from three iterations of knowledge-based bounding.

<table>
<thead>
<tr>
<th>Construction Type</th>
<th>GWP General Product Knowledge (kg CO2eq)(^a)</th>
<th>GWP Finished Product Knowledge (kg CO2eq)(^a)</th>
<th>GWP % Secondary Content Knowledge (kg CO2eq)(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Using lower bound(^b)</td>
<td>Using Upper bound(^b)</td>
<td>Using lower bound(^b)</td>
</tr>
<tr>
<td>CFC</td>
<td>.7</td>
<td>5.9</td>
<td>.7</td>
</tr>
<tr>
<td>SFC</td>
<td>3.1x10^6</td>
<td>5.5x10^6</td>
<td>3.1x10^6</td>
</tr>
</tbody>
</table>

\(^a\) GWP: global warming potential; kgCO2eq: kilogram carbon dioxide equivalent. General Product Knowledge: steel type, % secondary steel content and region of production unknown; Finished Product Knowledge: steel type known, % secondary steel content and region of production unknown; % Secondary Steel Content Knowledge: steel type, % secondary steel content and region of production known.

\(^b\) Previously established bounds from Table 22 and Figure 16 in terms of kgCO\(_2\)eq/kg of steel, or kilogram carbon dioxide per kilogram of steel.
Figure 17. Effect of knowledge-based bounds for steel on total life cycle GWP of residential buildings.

a GWP: global warming potential; kgCO2eq: kilogram carbon dioxide equivalent; CFC: concrete-framed construction; SFC: steel-framed construction. General Product Knowledge: steel type, % secondary steel content and region of production unknown; Finished Product Knowledge: steel type known, % secondary steel content and region of production unknown; % Secondary Steel Content Knowledge: steel type, % secondary steel content and region of production known.

b Previously established bounds from Table 22 and Figure 16 in terms of kgCO2eq/kg of steel, or kilogram carbon dioxide per kilogram of steel.

Figure 17 reveals an overlap in the uncertainty bounds between SFC and CFC in the first iteration (General Product Knowledge), suggesting the need for further reduction. It is during the second iteration of knowledge mapping (Finished Product Knowledge) where a clear distinction can be made in the total life cycle GWP between the construction types. This distinction eliminates the need to further reduce uncertainty. That is, the third iteration that focused on % secondary steel content was not necessary for this particular study. Moreover, despite the consistently larger contribution to GWP from steel in the SFC construction type (Table 24), the overall impacts to GWP in the CFC remain higher.
Uncertainty

While the focus of this study is a straightforward approach for addressing uncertainty in LCA, uncertainty nonetheless remains. This study used one source, ecoinvent (PR’e Consultants 2012), to examine variability in steel manufacturing which relies heavily on data from Europe to establish electricity grid mixes, for example (Dones et al, 2007). Therefore, additional sources were examined in order to put the results in context with the broader literature and reports. While variable, these data points were found to generally fall within the bounds identified during the second iteration of knowledge mapping (Finished Product Knowledge), further highlighting the appropriateness of using a bounding approach for this particular material rather than a one value approach.

Another area of uncertainty is introduced as part of the regional electricity grid mixes. The impacts to GWP and CED from different electricity grid mixes was completed by modifying the default European grid mix in SimaPro (PR’e Consultants 2012) to reflect the region of interest. This was not an exhaustive modification. Only the top 3-5 highest CED and GWP contributing processes were modified to reflect the region of interest. This approach was assumed to reveal contrast between regions by focusing on the highest contributors without being excessively time consuming and adding relatively minimal value to the study. As a result, the overall impacts to GWP in particular from electricity grid mix, will be higher in both the US and China. Furthermore, the type of coal used in both the US and China, primarily bituminous and anthracite, respectively, contain higher amounts of carbon as compared to the coal used in Europe, primarily lignite (Energy Information Administration). Higher amounts of carbon content result in higher emissions of greenhouse gases (GHG) (Energy Information Administration). This distinction is not fully represented in the results. Consequently, the overall impacts to GWP in general will be higher in both the US and China. This is because coal is not only used for electricity generation, but also as an energy source for manufacturing processes such as providing a heat source for the BOF.

Nevertheless, this study has demonstrated a practical and straightforward approach for mitigating uncertainty in LCA. The importance of an LCA in the development of policy is to increase a decision maker’s ability to confidently draw comparative conclusions. A knowledge-based bounding approach accomplishes this objective without adding unnecessary complexity and time to a study.
Chapter 4 - Conclusion

Life cycle of multi-family residences

This study has contributed to the body of research on the built environment by completing an LCA of different size multi-family dwellings in Chapter 2. Using a hybrid LCA methodology, this study has found that the CED and GWP for low, mid and high-rise multi-family residences increases from 37, 39, to 42 GJ/m$^2$, and 4, 4, to 5 tCO2eq/m$^2$ on average, respectively, indicating a direct relationship between energy and emissions to size of multi-family dwelling. If operation energy remains relatively constant between building rise, CED and GHG emissions increase with building rise. This result is in contrast to the theoretical expectation that as building rise increases, CED and GHG emissions would decrease on a normalized basis, as a result of decreasing exposed surface areas. However, this expectation has not been proven in practice. In fact, results from a recent empirical study in Vancouver, BC find that as multi-family residential rise increases, so does operation energy on a normalized basis (RDH Building Engineering Ltd., 2012). These findings were attributed to the increased amenities, such as an indoor pool, found at more luxurious high-rise residential buildings (RDH Building Engineering Ltd., 2012). These results also align with previous work suggesting that increased consumption of leisure activities and services can cancel the expected carbon-reducing influences of city density (Heinonen and Junnila 2011).

More work is needed to compare the life cycle energy use of single and different multi-family residences on a per dwelling or per resident basis, instead of per area basis. (Norman et al. 2006) and this study find increasing per area energy use with “size” of building. (Norman et al. 2006) assert smaller energy per capita and per dwelling for high-rise housing based on much smaller living area for high rise versus detached single family homes. It is important to note however that there could be large socioeconomic differences between apartment and detached house dwellers and a meaningful comparison needs to control for such differences. This is a task for future work.

Functional units and LCA practice for buildings

The use of a functional unit that is more conceptually consistent with LCA principles has not contrasted with previous results. The operation life cycle phase continues to dominate with consistently greater than 75% of the share. However, if additional supply chains, such as the supply chains of washers and dryers, were included as part of the materials extraction and production phase, the share of this phase would continue to increase, consequently decreasing the share of the operation life cycle phase.
Intuitively, the focus is traditionally on reducing impacts during the operation life cycle phase. However, there may be hidden, greater impacts from missing supply chains that have not been revealed. Future building LCA should consider choosing functional units that are more conceptually consistent with LCA principles in order to more accurately reflect total life cycle impacts.

Life span and LCA practice for buildings

Finally, the results in Chapter 2 have highlighted the effects of the choice of life span on overall results. The shorter the life span of the multi-family dwelling, the lower the impacts of the operation life cycle phase, thus increasing the share of the construction and materials life cycle phases. Building life spans used in prior LCA studies have ranged from 30 to 50 years as an assumption without empirical justification (Aden 2010, Suzuki and Oka 1998, Adalberth 1997, Cole and Kernan 1996, Keoleian et al. 2008). Future empirical work is needed to determine if the life span of a building changes according to its function providing justification, and ensuring consistency to choice of lifespan in future LCA studies. It is important that the impacts from each life cycle are appropriately reflected so that efforts to reduce environmental loads can be prioritized accordingly during the design phase. Moreover, it is important that building LCA studies are consistent so that proper comparisons can be made.

Uncertainty and LCA practice

Further contribution of this study is provided to the LCA community by proposing and demonstrating a straightforward and practical approach for mitigating uncertainty in Chapter 3. Using the proposed knowledge-based bounding methodology to mitigate uncertainty, this study found that if steel type, recycled content and country of origin are all unknown, the life cycle Carbon dioxide equivalent emissions of steel can vary from 0.7-5.9 kg CO$_2$eq/kg steel. In contrast, with knowledge that the steel is un-alloyed, and has 64-100% recycled content, uncertainty bounds are reduced to 0.8-1.4 kg CO$_2$eq/kg steel, producing a clear distinction between decision scenarios. The knowledge-based bounding approach proposed in this study is a straightforward approach to mitigate uncertainty in LCA. Future work could examine the potential to integrate bounding into LCA software, perhaps adding ranges of values at higher, general process levels. An LCA practitioner may be an expert in LCA tools, but not in all the products and processes they analyze, e.g. what types of steel are used in different applications such as construction. Adding ranges of values allows a practitioner to have a starting point with which to work from if needed by the study objectives. From a policy perspective, this approach increases a decision maker’s ability to confidently draw comparative conclusions allowing LCA to become more influential in policy making.
Overall, this study has contributed to research on the built environment, urban form and LCA. The results of Chapter 2 help to inform policy on the built environment and urban structure while also highlighting important issues that need further study. The contribution from Chapter 3 is a straightforward, practical framework for practitioners and researchers from the LCA community to mitigate uncertainty, meeting the goals of the study without adding unnecessary complexity. Future work should expand on these findings in order to better inform policy makers on the impacts of urban form.
References


Bank of China International (2012) *Steel Industry Outlook*, Figure 70, Net Profit Margin and ROE Trends, p35.


http://www.eia.gov/countries/cab.cfm?fips=CH


http://www.eia.gov/electricity/data.cfm#sales


http://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states#tab2


http://www.eia.gov/emeu/mecs/mecs94/ei/elec.html


http://www.eia.gov/countries/country-data.cfm?fips=GM


http://www.eia.gov/dnav/ng/hist/n3035us3m.htm


http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=emm_epm0_pte_nus_dpg&f=a


Larsson, M. (2005) 'Process integration in the steel industry: possibilities to analyse energy use and environmental impacts for an integrated steel mill'.


http://mcassessor.maricopa.gov/


Reed Construction Data Inc. (2012) RS MeansOn-line and consulting services.


http://www.unep.org/sbci/AboutSBCI/Background.asp

http://www.bea.gov/industry/io_benchmark.htm

http://www.bls.gov/ppi/.

http://www.census.gov/econ/census02/guide/INDRPT23.HTM

http://www.census.gov/cgi-bin/sssd/naics/naicsrch?chart=2002


Appendix A - Multi-Family LCA Supporting Information

**Energy Calculations for Construction Energy**

**Electricity:**

\[ \left(4.3 \times 10^7\right)^a \times \left[\text{kWh}/\$0.05\right]^b \times \left[2.894\right]^c \times \left[3,412 \text{ Btu/kWh}\right] \times \left[1.055 \times 10^{-6} \text{ GJ/Btu}\right] = 9.2 \times 10^6 \text{ GJ} \]

\( ^a \) (U.S. Census Bureau 2002)

\( ^b \) (Energy Information Administration, 2012) Electricity

\( ^c \) Source energy reflects the amount of energy consumed during the actual production of electricity plus the energy consumed during end-use consumption. A source conversion factor of 2.894 was used here, reflective of the state of Arizona (Deru and Torcellini 2007).

**Natural Gas:**

\[ \left(1.2 \times 10^7\right)^a \times \left[1000 \text{ ft}^3/\$4.0\right]^b \times \left[1,020,000 \text{ Btu/1000 ft}^3\right] \times \left[1.055 \times 10^{-6} \text{ GJ/Btu}\right] = 3.3 \times 10^6 \text{ GJ} \]

\( ^a \) (U.S. Census Bureau 2002)

\( ^b \) (Energy Information Administration 2012) Natural Gas

**Gas/Diesel Fuel:**

\[ \left(5.9 \times 10^7\right)^a \times \left[\text{gal}/\$1.4\right]^b \times \left[139,000 \text{ Btu/gal}\right] \times \left[1.055 \times 10^{-6} \text{ GJ/Btu}\right] = 6.3 \times 10^6 \text{ GJ} \]

\( ^a \) (U.S. Census Bureau 2002)

\( ^b \) (Energy Information Administration 2012) Petroleum and other Liquids

**GWP Calculations for Construction Energy**

**Electricity:**

\[ \left(4.3 \times 10^7\right)^a \times \left[\text{kWh}/\$0.05\right]^b \times \left[2.894\right]^c \times \left[(0.000476 \text{ tCO}_2/\text{kWh}) + 298(7 \times 10^{-9} \text{ tN}_2\text{O}/\text{kWh}) + 25(3 \times 10^{-9} \text{ tCH}_4/\text{kWh})\right]^d = 1.2 \times 10^6 \text{ tCO}_2 \text{ eq} \]

\( ^a \) (U.S. Census Bureau 2002)

\( ^b \) (Energy Information Administration, 2012) Electricity

\( ^c \) Source energy reflects the amount of energy consumed during the actual production of electricity plus the energy consumed during end-use consumption. A source conversion factor of 2.894 was used here, reflective of the state of Arizona (Deru and Torcellini 2007).

\( ^d \) (Energy Information Administration 2002), (IPCC Fourth Assessment Report 2007)

**Natural Gas:**

\[ \left(1.2 \times 10^7\right)^a \times \left[1000 \text{ ft}^3/\$4.0\right]^b \times \left[5.5 \times 10^{-5} \text{ tCO}_2/\text{ft}^3\right]^c = 1.7 \times 10^5 \text{ tCO}_2 \text{ eq} \]

\( ^a \) (U.S. Census Bureau 2002)

\( ^b \) (Energy Information Administration, 2012) Natural Gas


**Gas/Diesel Fuel:** divide into highway and non-highway

Off highway: \[ \left(1.2 \times 10^7\right)^a \times \left[\text{gal}/\$1.39\right]^b \times \left[(0.01015 \text{ tCO}_2/\text{gal}) + 298(2.6 \times 10^{-7} \text{ tN}_2\text{O}/\text{gal}) + 25(5.8 \times 10^{-7} \text{ tCH}_4/\text{gal})\right]^c = 8.8 \times 10^4 \text{ tCO}_2 \text{ eq}. \]
On-highway: \[ (4.8 \times 10^7) \times \frac{\text{gal}}{\$1.39} \times \left( \left( 0.01015 \frac{\text{tCO}_2}{\text{gal}} \right) + 298 \left( 2.78 \times 10^{-8} \frac{\text{tN}_2\text{O}}{\text{gal}} \right) + 25 \left( 2.96 \times 10^{-7} \frac{\text{tCH}_4}{\text{gal}} \right) \right) = 3.5 \times 10^5 \text{ tCO}_2 \text{ eq.} \]

\(^a\) (U.S. Census Bureau 2002)

\(^b\) (Energy Information Administration 2012) Petroleum and Other Liquids

\(^c\) (Energy Information Administration 2010), (IPCC Fourth Assessment Report 2007)

**Figure A-1.** Energy and GWP calculations for the Construction Life Cycle Phase