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# From Green Buildings to Green Supply Chains: An Integrated Input Output Life Cycle Assessment and Optimization Framework for Carbon Footprint Reduction Policy Making

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# From Green Buildings to Green Supply Chains: An Integrated Input Output Life Cycle Assessment and Optimization Framework for Carbon Footprint Reduction Policy Making

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## Abstract

**Purpose:** This paper focuses on tracing GHG emissions across the supply chain industries associated with the U.S. residential, commercial and industrial building stock and provides optimized GHG reduction policy plans for sustainable development.

**Design/Methodology/Approach:** A two-step hierarchical approach is developed. Firstly, Economic Input Output-based Life Cycle Assessment (EIO-LCA) is utilized to quantify the GHG emissions associated with the U.S. residential, commercial and industrial building stock. Secondly, a mixed integer linear programming (MILP) based optimization framework is developed to identify the optimal GHG emissions' reduction (%) for each industry across the supply chain network of the U.S. economy.

**Findings:** The results indicated that "ready-mix concrete manufacturing", "electric power generation, transmission and distribution" and "lighting fixture manufacturing" sectors were found to be the main culprits in the GHG emissions' stock. Additionally, the majorly responsible industries in the supply chains of each building construction categories were also highlighted as the hot-spots in the supply chains with respect to the GHG emission reduction (%) requirements.

**Originality:** Although the literature is abundant with works that address quantifying environmental impacts of building structures, environmental life cycle impact-based optimization methods are scarce. This paper successfully fills this gap by integrating EIO-LCA and MILP frameworks to identify the most pollutant industries in the supply chains of building structures.

**Practical Implications:** The decision making in terms of construction-related expenses and energy use options have considerable impacts across the supply chains. Therefore, regulations and actions should be re-organized around the systematic understanding considering the principles of *"circular economy"* within the context of sustainable development.

**Key Words:**

Optimization; Carbon footprint; Green buildings; Input-output life cycle assessment; Green supply chain management

**Paper Type:** Research Paper

# 1. Introduction

## *1.1. Buildings and environmental sustainability nexus*

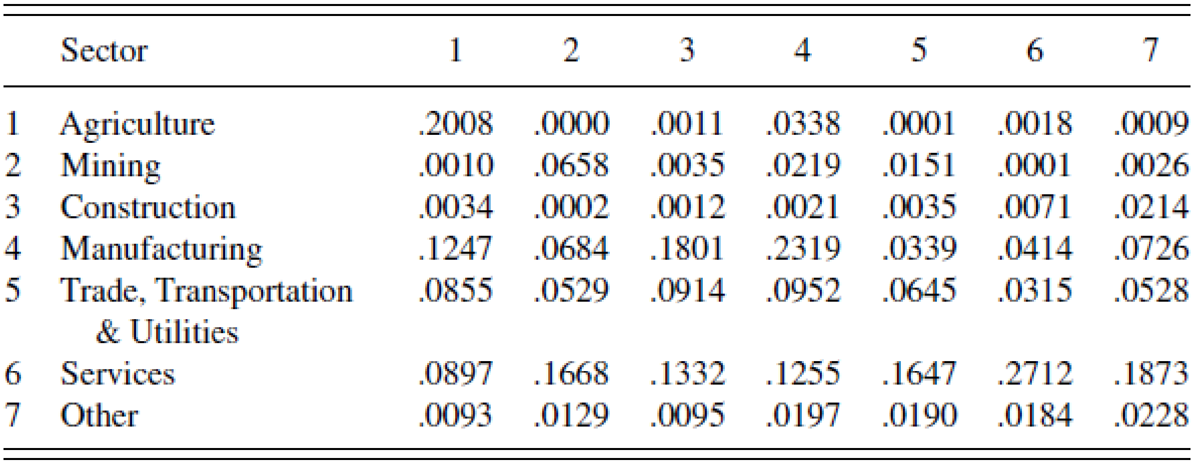
In the U.S, building stock consumes a significant amount of energy, thus resulting in GHG emissions, since most of the energy is being provided by nonrenewable sources such as coal, natural gas, etc. (Teng and Wu, 2014; Onat *et al.,* 2014). According to the U.S. Green Building Council's report, buildings account for 39% of $CO^2$ emissions in the U.S. Projections of new building is in the range of 15 million units by 2015 indicating that the building sector will continue to be a major contributor of increasing global $CO^2$ emissions (USGBC, 2005). Moreover, residential and commercial buildings in the U.S are responsible for 70% of electricity use. Therefore, research on sustainability-focused transformation of building systems is of importance for the overall sustainable development goals in the U.S.

## *1.2. Importance of supply chain-linked understanding*

Carbon footprint assessment of buildings and related climate change issues have been addressed extensively in the literature with specific focuses on building construction (Lu *et al.,* 2012; Mequignon *et. al.*, 2013; Jiang and Tovey, 2010). While majority of the literature focuses on process, material, product related assessments and improvements, works that addressed the importance of supply chains are not plenty. In fact, supply chain impact is critical component while assessing carbon footprint from raw material through the final use perspective, so called the life cycle. In a recent work related to sustainability assessment of buildings, Onat *et al.* (2014) focused on tracing scope based carbon footprint impacts of U.S. building stock considering supply chain impacts plus building construction-related impacts. The results indicated that approximately one fifth of the total GHG emissions are associated with scope 1 (onsite, in other words *direct emissions coming from building construction*), whereas, the rest of the GHG emissions' impact were attributed to the supply chain industries such as light fixture manufacturing, power generation, transportation etc.

From a macroeconomic perspective, all of industrial, transportation, construction, agriculture sectors are interrelated; each plays a critical role in a national economy, which can also have a domino effect on the overall economic and environmental performance (Ivanova *et al*., 2007). Table I illustrates a *very* broad aggregated technical coefficient (A) matrix of the U.S. economy for the year of 2003 (Miller and Blair, 2009). In Figure 1, U.S. pairwise economic transaction relationships are illustrated with 7 x 7 industry by industry matrix. For instance, for producing \$1 worth of economic goods and services in agriculture industry, \$0.2008 economic activity needs to be created within agricultural industry, similarly \$0.1247 worth of economic activity is being trigged in manufacturing industry, etc. Such a holistic, macro-level framework successfully takes into account the role of economic transactions in a national economy, which enables to trace economic impacts across the supply-chain industries. Furthermore, input-output-based life cycle assessment frameworks integrates the economic relationships with the environmental impact assessment (Egilmez *et al*., 2013), which will be explained in methods section.

**Table 1.** Example A matrix for the U.S. Economy in 2003 (Miller & Blair 2009)



| | Sector | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| 1 | Agriculture | .2008 | .0000 | .0011 | .0338 | .0001 | .0018 | .0009 |
| 2 | Mining | .0010 | .0658 | .0035 | .0219 | .0151 | .0001 | .0026 |
| 3 | Construction | .0034 | .0002 | .0012 | .0021 | .0035 | .0071 | .0214 |
| 4 | Manufacturing | .1247 | .0684 | .1801 | .2319 | .0339 | .0414 | .0726 |
| 5 | Trade, Transportation & Utilities | .0855 | .0529 | .0914 | .0952 | .0645 | .0315 | .0528 |
| 6 | Services | .0897 | .1668 | .1332 | .1255 | .1647 | .2712 | .1873 |
| 7 | Other | .0093 | .0129 | .0095 | .0197 | .0190 | .0184 | .0228 |

The U.S. economy consists of over 400 industries where each industry hypothetically has over 400 supplier industries, which contributes to the downstream supply chains (Egilmez *et al*., 2013; 2014). In this regard, studying infrastructure systems without considering upstream suppliers might have misleading results, which can lead to long term policy making failures. For instance, in a National economy level sustainability assessment study, Onat *et al.* (2014) found out that certain supply chain industries such as "Electric Power Generation, Transmission, and Distribution", "Cement Manufacturing", "Oil and Gas Extraction", "Truck Transportation", "Iron and Steel Mills and Ferroalloy Manufacturing", "Petroleum Refineries", and "Lime and Gypsum Product Manufacturing" industries accounted for over 50% contributions to the total carbon footprint associated with building construction and its supply chain impacts. Therefore, implementing input output-based life cycle assessment models is of importance to account for the supply chain-linked impacts (e.g. raw material flows in Finland by Pinero *et al*. (2015); food consumption in Australia by Reynolds *et al.* (2015); environmental risk assessment by Chen *et al.* (2014); and comparison of process versus input output-based approaches by Weinzettel *et al.* (2014). Therefore, this paper addresses optimized carbon footprint reduction strategies for the U.S. building stock with an integrated approach that consists of Economic Input Output-based Life Cycle Assessment (EIO-LCA) and Mixed Integer Linear Programming (MILP). The rest of the paper is organized as follows; in section 2, literature related to optimization and carbon footprint policy making is presented. Section 3 introduces the integrated methodology that consists of life cycle assessment and the linear programming model. The results and discussion are provided in section 4; and section 5 delineates the concluding remarks and limitations of the study along with the future research directions.

## 2. Background

### *2.1. Buildings and life cycle assessment*

Life cycle assessment (LCA) quantifies the environmental impacts of products from cradle-to-grave for various life cycle phases such as material extraction and processing, transportation, use, and end-of-life (Rebitzer *et al*., 2004; Curran, 2013). In literature, process-based LCA (P-LCA), economic input-output based LCA (EIO-LCA) and hybrid LCA (a combination of the P-LCA and EIO-LCA) are commonly used for environmental impact analysis of products or systems (Suh and Nakamura, 2007). The literature is abundant with the applications of P-LCA addressing environmental impacts of residential (Ardente *et al.,* 2011; Cuéllar-Franca and Azapagic, 2012) and commercial buildings (Junnila *et al.,* 2006; Van Ooteghem and Xu 2012). However, these works omit the impacts that are occurring in the supply chains, which is also a critical component of life cycle assessment. Therefore, use of economic input-output-based life cycle assessment (EIO-LCA) models became important and various works employed input-output methods such as (Matthews *et al*., 2008; Egilmez and Park, 2014; Onat *et al*., 2014a, b; Egilmez *et al*., 2013; Egilmez *et al*.,2014; Kucukvar *et al*., 2015; Park *et al*.,2016;). Among the applications of EIO-LCA on various problem domains, some studies focused on the U.S. construction sectors, (Hendrickson and Horvath, 2000), construction processes (Bilec *et al*., 2009; Sharrard *et al*., 2008), building retrofitting by (Cellura et al. 2013a), and residential buildings (Cellura *et al*., 2014; Heinonen *et al*., 2011; Onat *et al*., 2014b). Moreover, Kucukvar and Tatari (2013) recently developed an input-output based triple-bottom-line model to quantify the environmental, economic and social implications of seven different U.S. construction sectors including residential, commercial, industrial buildings and heavy civil infrastructures. In another recent work, Onat *el al*. (2014) integrated the triple bottom line input-output analysis into the LCA framework. The results of these investigations indicate that indirect impacts of construction work and building sectors are highly dominant compared to onsite construction and in some cases account for more than 50% of the total environmental impacts.

### *2.2. Analytical approaches for carbon reduction policy making*

An objective dimensionality reduction method presented by Čuček *et al*. (2014) was applied to different direct and total objectives including total footprints. The result shows that footprints were reduced from five to three when it applied to biomass energy supply chain. Furthermore, a study on carbon reduction strategies by Dong *et al*. (2014) using industrial symbiosis (IS) and urban symbiosis (US) by applying hybrid LCA model depicted that both symbioses offers an innovative option for carbon emission mitigation.

In another work, Fang *et al*. (2011) developed a multi-objective mixed integer linear programming formulation that takes into consideration the peak power load, energy consumption and its associated carbon footprint. Several programming formulations have been developed to analyze carbon footprint as well as managing surplus resources such as biomass and land use in a region; for example, Lam *et. al* (2010) proposed a Regional Energy Clustering (REC) algorithm for supply chain synthesis that was aimed at minimizing the system carbon footprint. Another study, Dong *et al*. (2014) addressed the carbon footprint of urban areas where they developed a Emission Sources Account (ESA) model in order to analyze and understand the nature of carbon emission in relation to human activity. Chang (2014) proposed a multi-objective programming and linkage analysis approach to identify the key $CO^2$ emission sectors and optimized production structure in order to reduce emission.

All in all, GHG emissions in regards to building industry in U.S. is critical as the U.S. economy and population will continue to grow, which will result in a significant growth in building stock. Therefore, studying the U.S. building sectors in terms of GHG emissions reduction is critical for long term sustainability policy making, which is also in parallel with the climate act plan addressed by President Obama. This paper proposes an integrated EIO-LCA and Mixed Integer Linear Programming (MILP) approach to provide optimal carbon footprint reduction policies for the residential, commercial, and industrial buildings in the U.S.

## 3. Materials and methods

An integrated approach is implemented due to the need of combining the results of LCA with the proposed optimization model. In the first phase of the integrated methodology, EIO-LCA was utilized to trace the onsite and supply-chain linked carbon footprint and economic output of residential, commercial and industrial buildings' construction and then the proposed policy programming model is used to find the most carbon emitting industries in the supply chains and assign the % carbon emission reduction policies individually for each industry. The integrated methodology is also depicted in figure 1. The steps of the methods, related formulations and data collection are given in the following sub-sections.

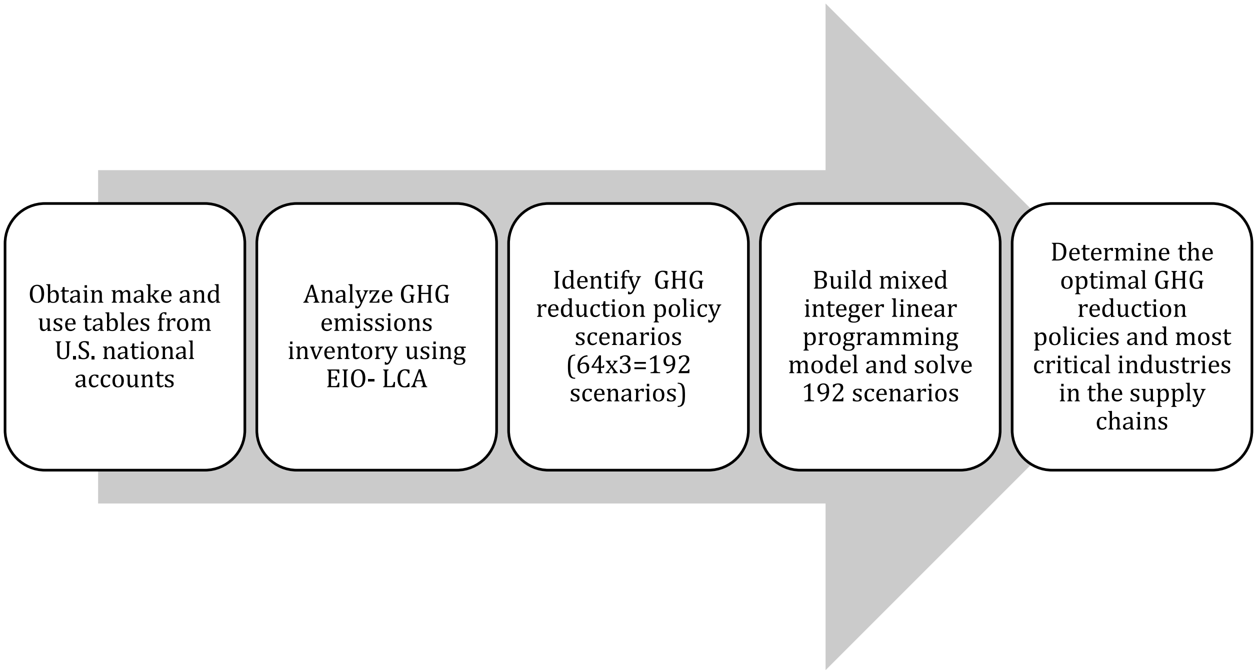


***Figure 1. Hierarchical framework of the proposed methodology 3.1. Mathematical framework of EIO-LCA***

The EIO framework is employed to analyze the environmental impacts and economic outputs of the U.S. manufacturing sectors from a holistic perspective – *a.k.a. supply chain linked perspective*. The applications of EIO analysis cover various problem domains including infrastructure systems, energy technologies, industrial sectors, international trade, and household demand (Egilmez *et al.,* 2013; Huang *et al*., 2009 ; Huppes *et al.,* 2006; Kucukvar and Tatari, 2011; Weber and Matthews, 2007; Wiedmann *et al.*, 2011). EIO-LCA methodology considers the sector-level interdependencies and represents sectoral direct requirements, which are represented by the ***A*** matrix. This matrix includes the dollar value of inputs required from other sectors to produce one dollar of output. Hence, the total output of a sector in this economic model with a final demand of ***f*** can be written as (Joshi, 2000):

$$x=[(I-A)^{-1}]f \qquad (1)$$

where ***x*** is the total industry output vector, ***I*** represents the diagonal identity matrix, and ***f*** refers to the final demand vector representing the change in a final demand of desired sector. Moreover, the bracketed term $[(\boldsymbol{I-A})^{-1}]$ represents the total requirement matrix, which is also known as the Leontief inverse (Leontief 1970). After the EIO-LCA model has been established, the total environmental impacts (direct and indirect) can be calculated by multiplying the economic output of each industrial sector by the multiplier matrix. Then, a vector of total environmental outputs can be expressed as (Hendrickson *et al.*, 2006):

$$r=E_{dir}x= E_{dir}[(I-A)^{-1}]\ f \qquad (2)$$

where ***r*** is the total environmental outputs vector which represents overall sustainability impacts per unit of final demand, and $\boldsymbol{E_{dir}}$ represents a diagonal matrix, which consists of the direct environmental impacts per dollar of output for each industrial sector. Each element of this diagonal matrix is simply calculated by dividing the total direct sectoral impact (e.g. water withdrawal, GHG emissions, energy use) with the total economic output of that sector. Also, the product of $\boldsymbol{E_{dir}}$ and the bracketed term $[(\boldsymbol{I}-\boldsymbol{A})^{-1}]$ is the multiplier matrix.

### *3.2. Mathematical framework of optimization model*

Notation:

Index:

*j: S*ector

Parameters:

$P_j$: Profit multiplier for sector *j*

$I_j$: Income multiplier for sector *j*

$T_j$: Tax multiplier for sector *j*

$M_j$: Import multiplier for sector *j*

$G_j$: GHG emissions multiplier for sector *j*

$\varepsilon$: GHG emissions reduction policy factor

Decision Variable:

$X_j$: Optimal economic output for sector *j*

Objective Function:

$$Max\ z = \sum_{J=1}^{n}(P_j * X_j) + \sum_{J=1}^{n}(I_j * X_j) + \sum_{J=1}^{n}(T_j * X_j) - \sum_{J=1}^{n}(M_j * X_j) - \sum_{J=1}^{n}(G_j * X_j) \qquad (3)$$

Subject to:

$$\sum_{J=1}^{n}(P_j * X_j) \leq Total\ Profit \qquad (4)$$

$$\sum_{J=1}^{n}(I * X_j) \leq Total\ Income \qquad (5)$$

$$\sum_{J=1}^{n}(T_j * X_j) \leq Total\,Tax \quad (6)$$

$$\sum_{J=1}^{n}(M_j * X_j) \leq Total\,Import \quad (7)$$

$$\sum_{J=1}^{n}(G_j * X_j) \leq TotalGHG * \varepsilon \quad (8)$$

$$X^{LB}{}_{\mathrm{j}} \leq \mathrm{X_j} \leq X^{UB}{}_{\mathrm{j}} \text{ for } \mathrm{j} = 1,2,\dots,\mathrm{n} \quad (9)$$

$$G^{LB}{}_{\mathrm{j}} \leq \mathrm{G_j} \leq G^{UB}{}_{\mathrm{j}} \text{ for } \mathrm{j} = 1,2,\dots,\mathrm{n} \quad (10)$$

The objective function consists of five objectives as follows:

- Maximizing total profit
- Maximizing total income
- Maximizing total tax
- Minimizing total import
- Minimizing total GHG emissions

The first four constraints (Eq. 4, 5, 6 and 7) are the allocation constraints for the indicators such as profit, income, tax and import, respectively. The fifth constraint (Eq. 9) limits the total GHG emissions allocation of sectors to the current total multiplied by the GHG emissions' reduction coefficient ($0 \leq \varepsilon \leq 1$). The last two constraints (Eq. 9 and 10) consist of the lower and upper bounds of the decision variables for optimal economic use and GHG multiplier, where the upper bound is the actual value and the lower bound is determined by the selected reduction strategy (see Table IV for 16 GHG reduction strategies).

### *3.3. Data collection and experimental setup*

Data were obtained by using EIO-LCA framework that quantifies the direct and indirect environmental and economic impacts associated with the U.S. building sectors (CMU, 2002). Three categories of buildings sector are studied, namely; residential, commercial and industrial buildings. Residential, commercial, and industrial buildings consists of 189, 177, and 137 industries in their supply chains, respectively. Table II illustrates an example for residential building construction industry. For instance, related to residential building construction industry, there are 189 sectors with different amount of economic outputs in the supply chain, which provides the residential construction industry's tangible and intangible inputs. Sector 1, abrasive product manufacturing, indicates a total of 69.6 M$ economic activity. Due to this economic activity, a total of 98 M$ economic activity occurs in the supply chain of abrasive product manufacturing.

Therefore, by multiplying the GHG emissions per M$ economic activity (so called GHG multiplier) with the economic output, an individual sector's total (onsite plus supply chain related) GHG emissions are quantified. Same logic is also applied to all remaining industries in the supply chain which will yield the total GHG emissions associated with residential buildings.

In terms of experimental setup, four main overall GHG reduction strategies are implemented, namely: 10%, 25%, 50% and 75% reduction in the total GHG emissions (onsite + supply chain industries). The MILP model simply finds the optimal reduction percentages in GHG emissions for each industry in the supply chains by either reducing the GHG multiplier, or the economic output or both. This holistic focus is assumed due to the inherent interest of studying the impact of economic output and GHG multipliers together on GHG reduction. Therefore, four reduction percentages are also used for the GHG multipliers and economic outputs individually: 10%, 25%, 50% and 75%. Therefore, for each building category, a total of 4x4x4=64 cases are experimented. Therefore, a total of 192 scenarios are run with the MILP model for all three building categories as summarized in Table 3. As mentioned before, there are three buildings category in this research where 64 scenarios for each building category so that a total of 192 scenarios analyzed as shown in Table III. Each scenario is run with the proposed MILP model. Then, the results of all scenarios were combined in order to calculate the mean and standard deviation of GHG reduction requirements (in %s). The process of obtaining the means and standard deviations were explained in the following result and discussion section.

**Table 2.** Residential building construction industry and its supply chain industries

| Building Category | ID | Sectors | Total Economic Output | Industry Economic Output | GHG Emissions (t CO2-eqv / $M) | Scenarios |
|---|---|---|---|---|---|---|
| Residential | 1 | Abrasive product manufacturing | 98 $M | 69.6 $M | 0.71 | Scenario 1,2,…16 |
| | ⋮ | ⋮ | | | | |
| | 189 | Wood windows and doors and millwork | | | | |

*See Appendix for more detailed information

**Table 3.** Overview of Experimental Setup for Residential, Commercial and Industrial Buildings

| Building Category | ID | Sectors | 10 % Overall GHG Reduction | 25 % Overall GHG Reduction | 50 % Overall GHG Reduction | 75 % Overall GHG Reduction |
|---|---|---|---|---|---|---|
| Residential Buildings | 1<br>↓<br>189 | Abrasive product manufacturing<br>↓<br>Wood windows and doors and millwork | 16 scenarios | 16 scenarios | 16 scenarios | 16 scenarios |
| Commercial Buildings | 1<br>↓<br>177 | Electric power generation, transmission, and distribution<br>↓<br>Other information services | 16 scenarios | 16 scenarios | 16 scenarios | 16 scenarios |
| Industrial Buildings | 1<br>↓<br>137 | Lighting fixture manufacturing<br>↓<br>Spectator sports | 16 scenarios | 16 scenarios | 16 scenarios | 16 scenarios |

*See Appendix for more detailed information

## 4. Results

The optimal GHG reduction (%) results of the three building categories (namely residential, commercial and industrial buildings) are presented based on the mean and standard deviation of the major responsible sectors in the supply chains for each building category. The most responsible top 20 sectors are highlighted in the results section.

### *4.1. Overall GHG reduction policy strategies*

As the final step of the analysis, the mean and standard deviation of all scenarios were obtained by taking the top 20 majorly responsible sectors in each building construction industry category. Table IV shows an example about the process of how obtain the mean and standard deviation of 10% overall GHG reduction policy results. For instance, sector 1 (ready-mix concrete manufacturing) is required to achieve the highest % reduction of GHG according to the 1st scenario, whereas cement manufacturing required to have 39% GHG reduction in its processes in scenario 16. The mean and standard deviation of the % reduction of these scenarios were then calculated (in this example, mean: 27% and std. dev.:10.3%). The same process is applied to the cases of commercial and industrial building construction industries. The results of the remaining cases are given in the following sub-sections.

**Table 4.** Obtaining the Average and Standard Deviation for 10% Overall GHG Reduction

| Building Category | ID | Scenario 1 | % Reduction | … | Scenario 16 | % Reduction | AVG | SD |
|---|---|---|---|---|---|---|---|---|
| Residential Buildings | 1 | Ready-mix concrete manufacturing | 13% | … | Cement manufacturing | 39% | 27% | 10.3% |
| | .. | .. | .. | … | .. | .. | .. | .. |
| | .. | .. | .. | … | .. | .. | .. | .. |
| | .. | .. | .. | … | .. | .. | .. | .. |
| | .. | .. | .. | … | .. | .. | .. | .. |
| | 189 | Reconstituted wood product manufacturing | .. | … | Paper mills | .. | .. | .. |

### *4.1.1. Residential building construction industry*

In this section, the results of residential buildings case are provided. The results of the top 20 sectors with the highest GHG reduction requirement are illustrated in figures 2, 3, 4 and 5 where ach represents an overall GHG reduction policy, namely 10%, 25%, 50% and 75%. Figure 2 shows the 10% overall GHG reduction and indicates that the highest contributor sector to the overall GHG is Ready-mix concrete manufacturing which requires an average of 27% reduction in its GHG emissions, which is followed by petroleum refineries with 16% reduction, electric power generation, transmission, distribution and truck transportation with the average of 13% and 8% respectively. Cement manufacturing contributes on the average of 5% higher than retail manufacturing and lime and gypsum product manufacturing. Although it was expected that plastic product manufacturing and fertilizer manufacturing would contribute a higher percentage reduced in the analysis, it only resulted in 3% and 2% reduction requirements, respectively, which are significantly lower than ready-mix concrete manufacturing. Asphalt paving mixture and block manufacturing required 1% reduction on the average, which is the same as for sawmills and wood preservation and concrete pipe, brick and block manufacturing.

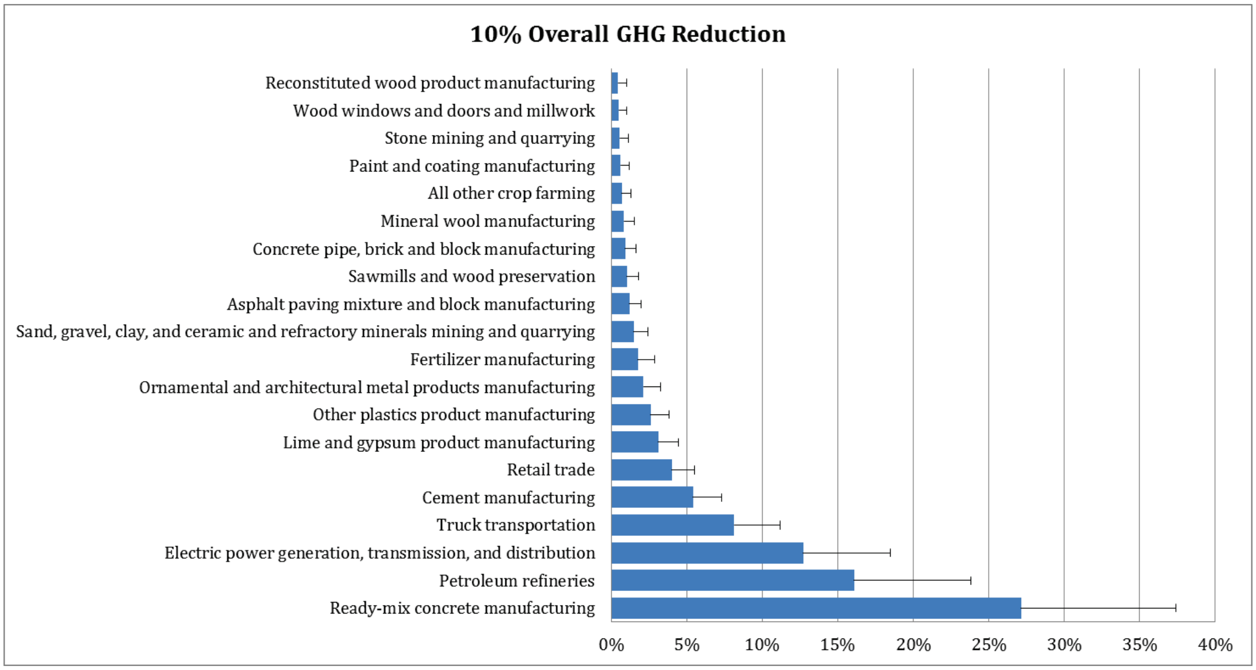


**Figure 2.** Optimal Reductions in the Supply Chains of Residential Buildings For 10% of Overall GHG Reduction

The overall GHG reduction of 25% and 50% policies' results are shown in Figure 3 and Figure 4, respectively. The resulting bar graphs indicate that the top 3 sectors are still the same as 10% overall GHG reduction which is ready-mix concrete manufacturing, petroleum refineries and electric power generation, transmission and distribution sector. Reconstituted wood product manufacturing, wood windows, doors, millwork and stone mining, quarrying sectors are found to be as the in the bottom three in the 25% overall GHG reduction.

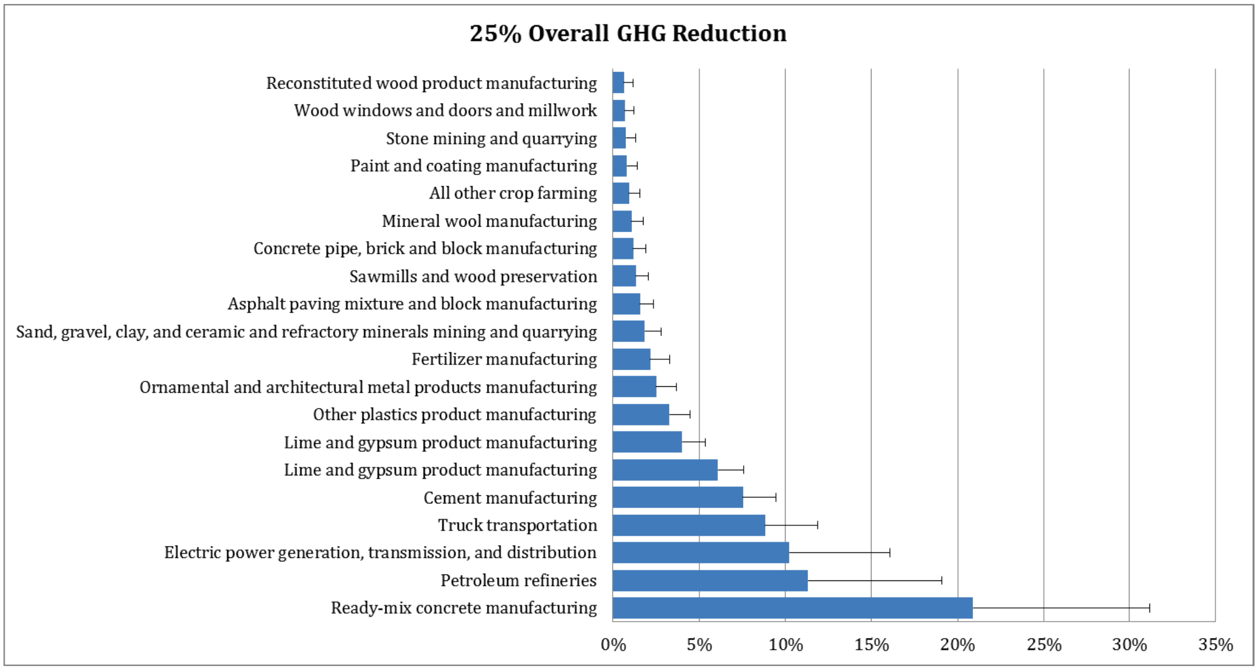


**Figure 3.** Optimal Reductions in the Supply Chains of Residential Buildings For 25% of Overall GHG Reduction

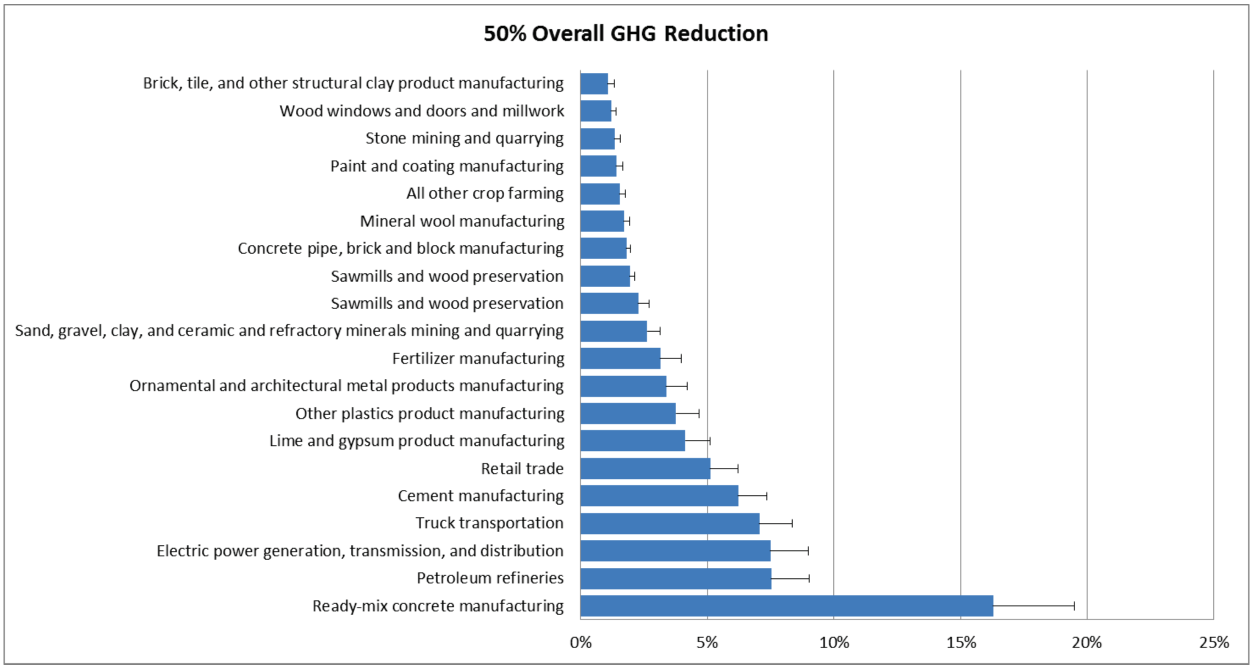


**Figure 4.** Optimal Reductions in the Supply Chains of Residential Buildings For 50% of Overall GHG Reduction

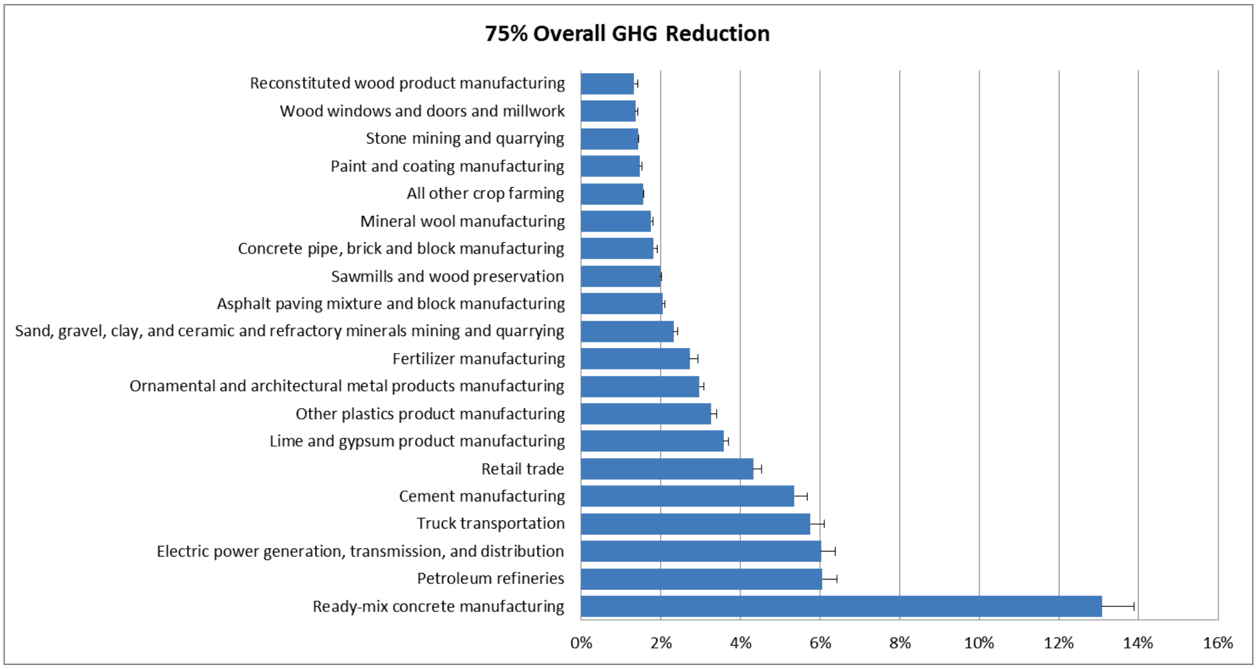


**Figure 5.** Optimal Reductions in the Supply Chains of Residential Buildings For 75% of Overall GHG Reduction

The policy of reducing the overall GHG impact by 75% indicates the same top 3 industries with percent reductions ranging between 13% and 6% (See Figure 5). The results of overall GHG reduction for commercial buildings are discussed in the next section.

### *4.1.2. Commercial building construction industry*

The results of commercial building construction industry is explained in detail in Appendix, due to space limitations.

### *4.1.3. Industrial building construction industry*

The results of commercial building construction industry is explained in detail in Appendix, due to space limitations.

## ***4.2. Detailed Results of Experiments: Case Summaries***

This section provides the highlights of the experimentation related to the three cases of U.S. building stock. Due to space limitations, this section is provided in the Appendix.

## ***4.3. Highlights of the Study***

Analyzing three buildings structures, namely residential, commercial and industrial elucidates the objectives of this paper on optimizing carbon footprint and identifying sectors in the supply chains to be responsible for GHG reduction in their individual industrial processes. Focusing on the most GHG contributing sectors or GHG sinks in buildings' supply chains is a critical way to reduce overall GHG emissions impact. All in all, "Ready-mix concrete manufacturing", "Petroleum refineries" and "Electric power generation, transmission and distribution" sectors are found to be the most affected sectors in the supply chains of the residential building infrastructures (see Figure 6 for average and standard deviation of % reduction requirements in their individual industrial activities – average and standard deviation based on the 64 scenarios' results).

As commercial buildings keep on growing, sectors that support the industry are also affected by the development. There is a need to thoroughly monitor the sectors that contribute the most GHG emissions in commercial buildings as indicated in Figure 6. "Electric power generation, transmission and distribution" sector are found to have the highest average GHG reduction of 15% while "Petroleum refineries" and "Plate work and fabricated structural product manufacturing sector" accounted for 11% and 9%, GHG reductions respectively. The "Electric power generation, transmission and distribution" sector appeared as the top responsible sector twice in both commercial and residential building structures' supply chains. This indicates that clean and renewable energy production is up-most critical for achieving sustainable climate change policy making, which is also in parallel with the President's climate act plan.

The most responsible sectors in the industrial building structures supply chains are found to be "Petroleum refineries", "lighting fixture manufacturing" and "Other purpose machinery manufacturing" as shown in Figure 6. Again, it is evident that "petroleum refineries" sector appeared to be the most affected sector in the overall GHG impact for industrial and commercial buildings. The same conditions like "Electric power generation, transmission and distribution" and "Petroleum refineries" also need to be highly monitored in term its usage in order to limit the release of GHG emissions.

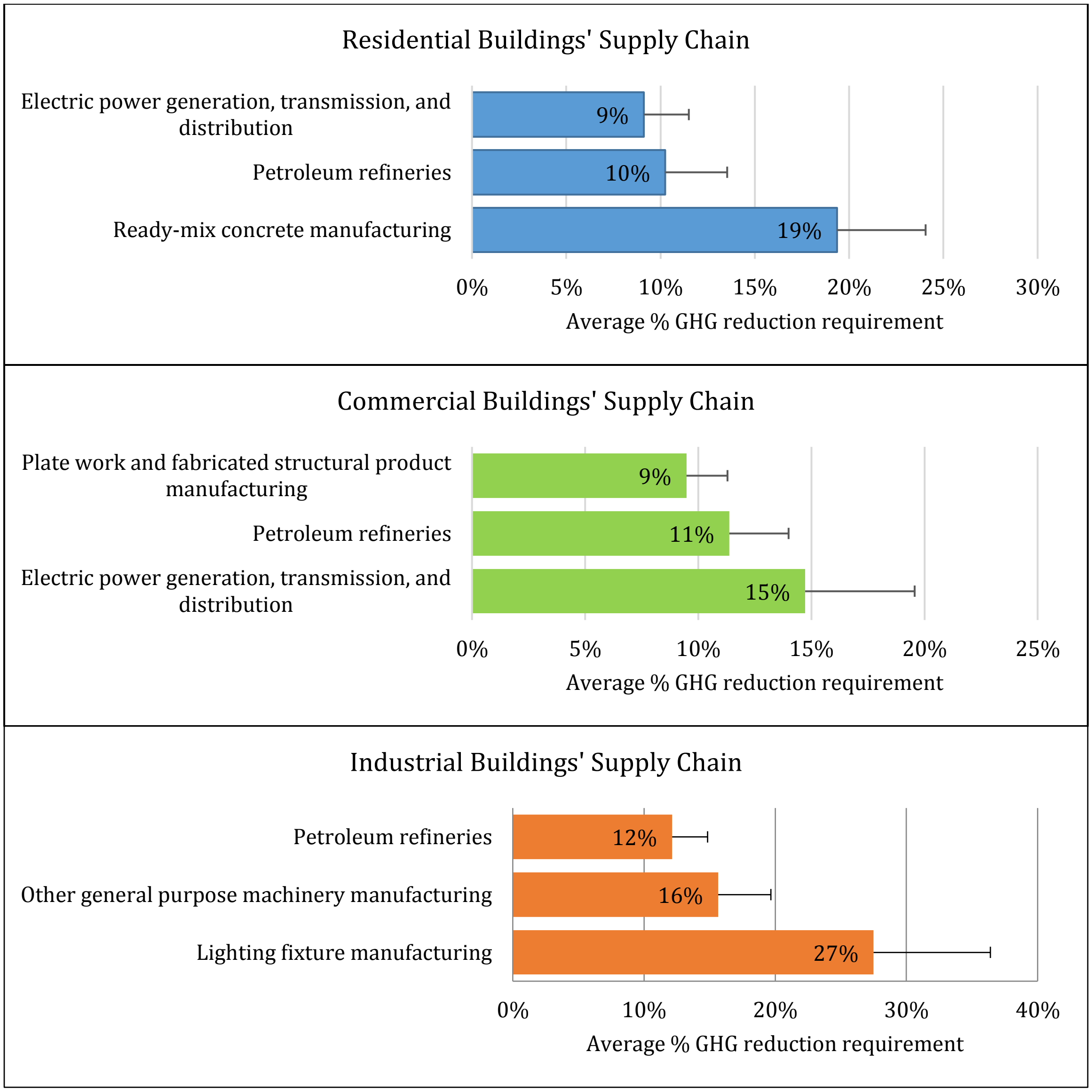


**Figure 6.** Most responsible GHG pollutant sectors in the supply chains with reduction % requirements

Combining these sectors overall, it is indicated that six sectors appeared to be very critical in terms of GHG reduction across the supply chains. Those sectors are found to be as “Electric power generation, transmission and distribution”(24%), Petroleum refineries”(23%), “Ready-mix concrete manufacturing”(19%), “Plate work and fabricated structural product manufacturing”(9%), “Lighting fixture manufacturing”(27%) and “Other general purpose machinery manufacturing”(16%) (See Figure 8). As discussed previously, the aforementioned sectors appeared repeatedly in all buildings structures and it shows that these sectors are the GHG emissions sinks in the supply chains of the building structures.

Therefore, strategies on reducing overall GHG emissions should be focused on these industries' processes as well.

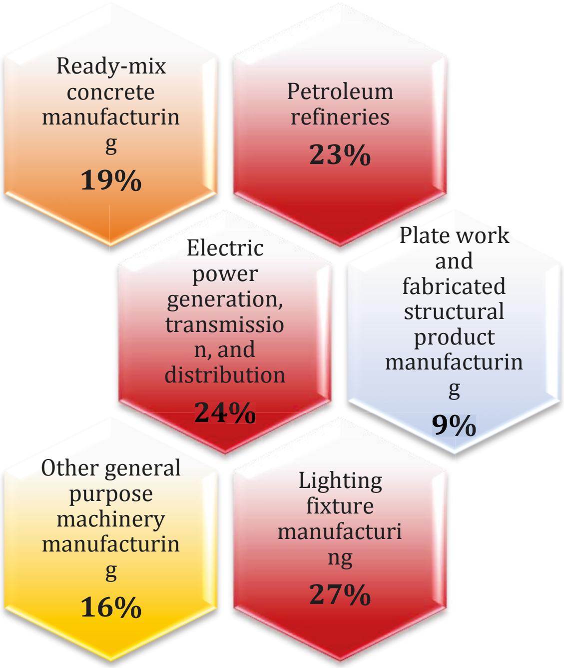


**Figure 7.** Most responsible sectors in the supply chains of building construction industries

## 5. Concluding remarks and future work

In this paper, optimized GHG reduction policy making in the supply chains of the residential, commercial, and industrial building construction industries is addressed. A MILP model is developed and used in conjunction with EIO-LCA results. A total of 192 problems were solved where 4 major overall GHG reduction strategies are studied with the three building case problems. This research primarily contributes to the body of knowledge related to GHG reduction policy making considering supply chain and onsite impacts from national economy point of view. And, the proposed integrated methodology that consists of EIO-LCA and MILP model is applicable to other problem domains such as transportation industries, manufacturing industries, final consumption categories, and food and agricultural production industries.

The results indicated that ready-mix concrete manufacturing was found to be as one of the major sector responsible for overall GHG emissions across the supply chains. In parallel with the mainstream research, power generation (electricity use) is a major driver for  GHG emissions and it was also found in this study that electric power generation, transmission and distribution was the main sector that needs high consideration in reducing overall GHG emissions from supply chain-linked sustainability assessment perspective (Egilmez *et al.,* 2013; 2014). For instance, in order to achieve 25% overall GHG reduction in commercial buildings supply chains, power generation sector has to reduce its GHG by 17% along with many other industries (Power generation was the top driver). Furthermore, the “lighting fixture manufacturing” sector was identified as one of the most responsible sectors for GHG reduction for the industrial building construction industry and its supply chains. 50% reduction policy necessitates the lighting fixture manufacturing sector to reduce its GHG impact by 19% as the top driver industry. All in all, ready-mix concrete manufacturing, electric power generation, transmission and distribution, and lighting fixture manufacturing sectors generally found to be the heaviest GHG emitter (carbon intensive) industries in the supply chains.

In terms of practical implications, input output extended LCA needs to be integrated into the building construction projects as a requirement. Most of the regions in the U.S. are now in a transition process from using fossil fuels in electricity production to the renewable alternatives. However, in most of the green building initiatives, input-output extended or hybrid LCA models are not typically used, instead process LCA methodology is preferred, which could cause up to 50% truncation errors in estimating the total life cycle impacts. The main policy-related output of this study is that petroleum refineries, power generation and lighting fixture manufacturing industries are responsible for about 23% to 27% of the total GHG impacts in the supply chains. The decision making in terms of construction-related expenses from suppliers (especially the raw materials supplied by petroleum, lighting fixture manufacturing industries and other significant pollutant industries), and type of electricity (renewable or nonrenewable) to be used needs to be regulated and evaluated by stakeholders and these impacts need to be addressed in construction project plans of commercial, industrial and residential buildings. In residential building policy making, currently building code programs are being applied and majority of coastal states in the U.S. are highly responsive to the policy making agenda. However, the coding system needs to be aligned with the region’s renewable energy production ratio. For instance, regions that need more renewable energy need to require higher level of coding in terms of energy efficiency. Additionally, raw material extraction phases need to be integrated into a similar coding system as well so that construction companies will tend to use resources that require less transportation and are more local to support local communities, socio-economic improvement in local regions.

Even though current research addresses an important paradigm shifting in policy making, several future directions still exist. First of all, manufacturing industries supply chain-linked optimized carbon footprint reduction policy making is another important topic of study left as future work. Additionally, integration of non-linear stochastic mixed integer programming models could provide results with percent ranges, which can be coupled with Monte Carlo simulation. The application area of the proposed integrated approach can be broadened by considering the global supply chains and other problem domains such as transportation, logistics, final consumption, etc.

## Appendix

The appendix file is provided via the following link:

https://drive.google.com/file/d/0B7oO7uor7BuxZVQwcE1YZFlwdmM/view?usp=sharing

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## Table captions

Table I. Example A matrix for the U.S. Economy in 2003 (Miller & Blair 2009)

Table II. Residential building construction industry and its supply chain industries

Table III. Overview of Experimental Setup for Residential, Commercial and Industrial Buildings

Table IV. Obtaining the Average and Standard Deviation for 10% Overall GHG Reduction

## Figure captions

Figure 1. Hierarchical framework of the proposed methodology

Figure 2. Optimal Reductions in the Supply Chains of Residential Buildings For 10% of Overall GHG Reduction

Figure 3. Optimal Reductions in the Supply Chains of Residential Buildings For 25% of Overall GHG Reduction

Figure 4. Optimal Reductions in the Supply Chains of Residential Buildings For 50% of Overall GHG Reduction

Figure 5. Optimal Reductions in the Supply Chains of Residential Buildings For 75% of Overall GHG Reduction

Figure 6. Most responsible GHG pollutant sectors in the supply chains with reduction % requirements

Figure 7. Most responsible sectors in the supply chains of building construction industries