2013

Life Cycle Sustainability Assessment Framework For The U.S. Built Environment

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STARS Citation

Kucukvar, Murat, "Life Cycle Sustainability Assessment Framework For The U.S. Built Environment" (2013). *Electronic Theses and Dissertations, 2004-2019*. 2868.
https://stars.library.ucf.edu/etd/2868

LIFE CYCLE SUSTAINABILITY ASSESSMENT FRAMEWORK FOR THE U.S. BUILT ENVIRONMENT

by

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A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Civil, Environmental and Construction Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Fall Term
2013

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ABSTRACT

The overall goals of this dissertation are to investigate the sustainability of the built environment, holistically, by assessing its Triple Bottom Line (TBL): environmental, economic, and social impacts, as well as propose cost-effective, socially acceptable, and environmentally benign policies using several decision support models. This research is anticipated to transform life cycle assessment (LCA) of the built environment by using a TBL framework, integrated with economic input-output analysis, simulation, and multi-criteria optimization tools. The major objectives of the outlined research are to (1) build a system-based TBL sustainability assessment framework for the sustainable built environment, by (a) advancing a national TBL-LCA model which is not available for the United States of America; (b) extending the integrated sustainability framework through environmental, economic, and social sustainability indicators; and (2) develop a system-based analysis toolbox for sustainable decisions including Monte Carlo simulation and multi-criteria compromise programming.

When analyzing the total sustainability impacts by each U.S. construction sector, “Residential Permanent Single and Multi-Family Structures" and "Other Non-residential Structures" are found to have the highest environmental, economic, and social impacts compared to other construction sectors. The analysis results also show that indirect suppliers of construction sectors have the largest sustainability impacts compared to on-site activities. For example, for all U.S. construction sectors, on-site construction processes are found to be responsible for less than 5 % of total water consumption, whereas about 95

% of total water use can be attributed to indirect suppliers. In addition, Scope 3 emissions are responsible for the highest carbon emissions compared to Scope 1 and 2. Therefore, using narrowly defined system boundaries by ignoring supply chain-related impacts can result in underestimation of TBL sustainability impacts of the U.S. construction industry.

Residential buildings have higher shares in the most of the sustainability impact categories compared to other construction sectors. Analysis results revealed that construction phase, electricity use, and commuting played important role in much of the sustainability impact categories. Natural gas and electricity consumption accounted for 72% and 78% of the total energy consumed in the U.S. residential buildings. Also, the electricity use was the most dominant component of the environmental impacts with more than 50% of greenhouse gases emitted and energy used through all life stages. Furthermore, electricity generation was responsible for 60% of the total water withdrawal of residential buildings, which was even greater than the direct water consumption in residential buildings. In addition, construction phase had the largest share in income category with 60% of the total income generated through residential building's life cycle. Residential construction sector and its supply chain were responsible for 36% of the import, 40% of the gross operating surplus, and 50% of the gross domestic product. The most sensitive parameters were construction activities and its multiplier in most the sustainability impact categories.

In addition, several emerging pavement types are analyzed using a hybrid TBL-LCA framework. Warm-mix Asphalts (WMAs) did not perform better in terms of environmental impacts compared to Hot-mix Asphalt (HMA). Asphamin® WMA was found to have the highest environmental and socio-economic impacts compared to other pavement types. Material extractions and processing phase had the highest contribution to all environmental impact indicators that shows the importance of cleaner production strategies for pavement materials. Based on stochastic compromise programming results, in a balanced weighting situation, Sasobit® WMA had the highest percentage of allocation (61%), while only socio-economic aspects matter, Asphamin® WMA had the largest share (57%) among the WMA and HMA mixtures. The optimization results also supported the significance of an increased WMA use in the United States for sustainable pavement construction.

Consequently, the outcomes of this dissertation will advance the state of the art in built environment sustainability research by investigating novel efficient methodologies capable of offering optimized policy recommendations by taking the TBL impacts of supply chain into account. It is expected that the results of this research would facilitate better sustainability decisions in the adoption of system-based TBL thinking in the construction field.

Dedicated to my family and friends

ACKNOWLEDGMENTS

First and foremost, I would like to offer my special thanks to my advisor, Dr. Omer Tatari. I was so fortunate to have him as my Ph.D. advisor. He has been an extraordinary mentor helping me improve professionally and personally. Without his support and guidance, it would not be possible to complete this dissertation.

I am also so grateful to Dr. Amr Oloufa, Dr. Amir Behzadan, Dr. Jennifer Pazour, and Dr. Haitham Al-Deek for their significant support during my research and for serving as a committee member of my dissertation. They have provided me with helpful guidance throughout my research and encouraged me to perform better in an every stage of this comprehensive research.

Lastly, I would like to thank my mother and father for their incredible contribution and encouragement during my Ph.D. work. I am fortunate to have a family that always believes in my success and gives me the opportunity to extend my horizon. Finally, special thanks to Dr. Gokhan Egilmez, Mehdi Noori, and Nuri C. Onat for their supports to make this research possible.

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CHAPTER 1. INTRODUCTION

1.1. Background

In 1983, sustainable development was coined as a future vision for as an environmentally friendly, economically feasible, and socially acceptable growth pattern in the Brundtland Commission. Sustainable development was first defined as "*the development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED 1987). To be able to manage the technological advancements towards the goal of sustainable development, it is crucial to evaluate the Triple Bottom Line (TBL) sustainability impacts of construction activities so that economically viable, environmentally sound, and socially responsible policies can be achieved towards realizing the objectives of sustainable development.

Today, many government agencies have given substantial importance to sustainability and resource conservation, and therefore environmental analyses of the built environment activities have become a subject of considerable interest globally (Tatari and Kucukvar 2011a; Tatari an Kucukvar 2011b). The construction industry consists primarily of establishments related to constructing, renovating, and demolishing buildings and other engineering structures. The construction industry includes contractors in commercial, residential, highway, heavy industrial and municipal utility construction (U.S. EPA 2009). In the United States, the construction sectors accounted for $611 billion, or 4.4 % of the gross domestic product more than many industries, including information, arts and entertainment, utilities, agriculture, and mining (BEA 2010).

In addition to economic impacts, construction sectors are among the main contributors to the depletion of natural capital, and a significant source of environmental pollution such as air, water, and soil, solid waste generation, land use, toxic wastes, health hazards, and global climate change. Moreover, in the United States, 80 % of all resources by mass are employed in construction, renovation, and retrofit of buildings and infrastructure systems (Gradel and Allenby 2009). The built environment also account for approximately 30 % of the raw materials and 25 % of the water used annually in the U.S. In addition, construction projects annually generate 164,000 million tons of waste and demolition debris, which accounts for about 30 % of the content in landfills (NRC 2009).

1.2. Life Cycle Assessment (LCA)

1.2.1. Process-based LCA

In LCA literature, four approaches have been used in the majority of the studies: Process-based LCA (P-LCA), Economic Input-Output LCA (EIO-LCA), Ecologically-based LCA, hybrid LCA, and Triple Bottom Line LCA (TBL-LCA) (see Fig.1). P-LCA is a well-established decision-making tool that aims to quantify the environmental impacts of a product or a process from cradle to grave including material extraction and processing, transportation, use, and end-of-life phases (Finnveden et al. 2009). It primarily consists of goal and scope definition, life-cycle inventory analysis, life-cycle impact assessment, and interpretation (Gradel and Allenby, 2009).

LCA models have been successfully utilized in several studies from various industrial sectors. Several researchers also utilized LCA to assess the environmental impact individual products or processes from cradle to grave, including milk production (Cederberg and Mattsson 2000), semi-conductors (Krishnan et al. 2008), photovoltaic technologies (Fthenakis et al. 2008), wind turbines (Martínez et al. 2009), pavement designs (Tatari et al. 2012), and electricity production (Kucukvar and Tatari 2011). For a more comprehensive review with classification of LCA models and future direction of LCA research, see Finnveden et al. (2009) and Guinee et al. (2011).

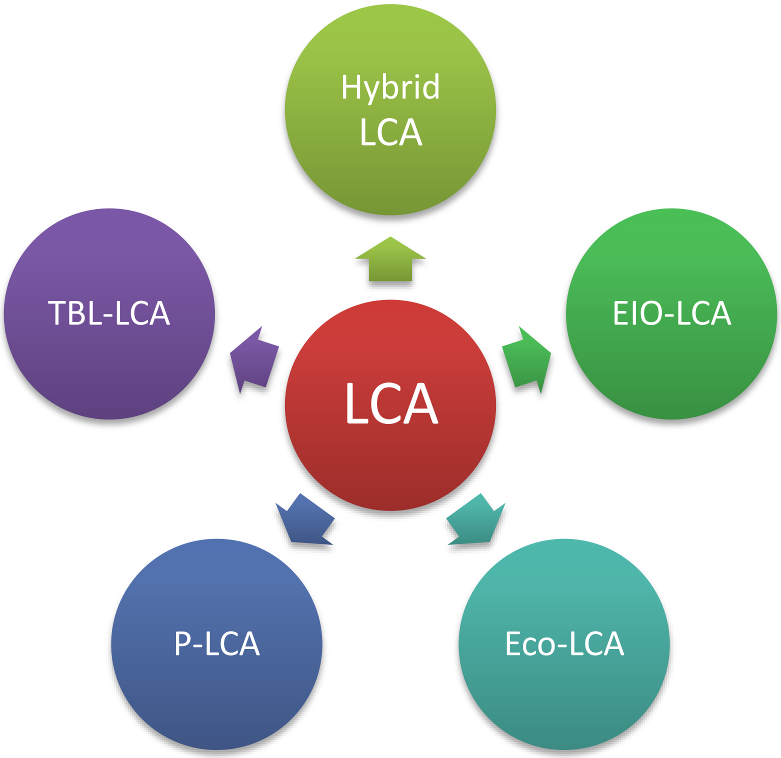


Figure 1. LCA models

1.2.2. Economic Input-Output based LCA

Among the LCA methodologies, P-LCA analyzes the life cycle environmental impacts of some construction materials; however it is not able to consider the indirect impacts of construction sectors including non-residential heavy civil infrastructure systems. In P-LCA, due to the narrowly defined boundaries, some important environmental impacts in the extended supply chains might be overlooked since it is not possible to include all upstream suppliers for impact assessment using the P-LCA (Facanha and Horvath 2007). Additionally, P-LCA enables very detailed analysis, but can be very expensive, time-consuming, and inappropriate (Guinée et al., 2011).

To overcome these problems, EIO-LCA models initiated as robust methods in early 2000s (Guinée et al., 2011). The EIO analysis is a well-known model, which was theorized and developed by Wassily Leontief in 1970s, based on his earlier works in the late 1930s, for which he received the Nobel Prize (Leontief 1970). The EIO analysis is a top-down technique, which considers financial flows and interdependencies between sectors that form the economic structure of a country (Suh et al. 2004). The EIO-LCA has been utilized extensively to analyze the environmental impact of the construction industry. EIO analysis is commonly used to expand the system boundary of process life cycle inventories and thus analyses the supply chain wide resource requirements and environmental impacts of products or systems (Hendrickson et al. 2005; Joshi 2000; Lenzen et al. 2003).

In the literature, EIO methodology has been used to analyze a wide range of policy issues in environmental, economic and social areas, and several researchers utilized the EIO model for analyzing the sustainability impacts of infrastructures, energy technologies, sectors, international trade, and household demand (Egilmez et al. 2013c; Huang et al. 2009a; Huppes et al. 2006; Lenzen et al. 2012; Kucukvar and Tatari 2011; Kucukvar and Tatari 2012; Weber and Matthews 2007; Wiedmann et al. 2011).

In addition, EIO methodology has been utilized to analyze the sustainability impacts of infrastructure projects and buildings by using the EIO-LCA tool. Several applications of the EIO analysis are found in the literature for the environmental analysis of buildings and other engineering structures. Hendrickson and Horvath (2000) estimated the major commodity and service inputs, resource requirements, environmental emissions and wastes for four major U.S. construction sectors, including highway, bridge, and other horizontal construction, industrial facilities and commercial and office buildings, residential one-unit buildings, and other constructions such as towers, water, sewer and irrigation systems, railroads, etc. They quantified all direct plus indirect material, energy, and service inputs for these construction sectors using the EIO-LCA model. In addition, Ochoa et al. (2002) estimated the total resource, fossil energy, greenhouse gas emissions (GHG), hazardous waste generation, and toxic releases into air for the construction, use, and demolition phases of the U.S. residential buildings by using the EIO-LCA model, which considered the interaction among 480 sectors in the United States.

Junnila and Horvath (2003) analyzed the life cycle energy use and atmospheric emissions of newly constructed European and U.S. office buildings from materials production through construction, use, and maintenance to end-of-life treatment using the P-LCA and EIO-LCA methodologies. In another study, Bilec et al. (2005) developed a LCA model combining both the P-LCA and EIO-LCA methodologies to quantify the atmospheric emissions related to construction of a precast concrete parking garage. Sharrad (2007) constructed an input-output based LCA methodology to estimate the environmental impacts of construction processes, comprehensively.

On the other hand, the Eco-LCA model, developed by the Center of Resilience at the Ohio State University, emerged as a tool which is capable of analyzing the role of the ecological goods and services used by the industrial sectors (OSU 2013). This model utilizes the same input-output tables used by the EIO-LCA. A first detailed Eco-LCA study of construction industry was conducted by Tatari and Kucukvar (2012) where natural resource consumption and atmospheric emissions of the 13 the U.S. construction sectors were analyzed. The researchers analyzed the direct and indirect role of ecological resource consumption using several indicators such as mass, energy, and ecological exergy. Also, the researchers holistically evaluated these construction sectors by using several key sustainability assessment metrics, such as resource intensity, efficiency ratio, renewability ratio, and loading ratio.

1.2.3. Hybrid LCA

As mentioned earlier, P-LCA and EIO-LCA are mainly used in the environmental analysis of products or processes. In the P-LCA, every process that is included from the supply chain of the product analyzed needs to be properly inventoried. As the system boundary becomes broader, the life cycle results' analysis becomes more complicated. However, with narrowly defined systems boundaries, some important environmental impacts in the full production chain can be overlooked. The EIO-LCA model combines environmental data with the economic input-output matrix of the U.S. economy to form a comprehensive system boundary.

On the other hand, current EIO-LCA methodology does not allow for specific product comparisons which make process assessments difficult. In order to take advantage of both the P-LCA and EIO-LCA models and provide a more accurate and holistic LCA methodology, hybrid LCA models were developed (Suh et al. 2004). The combination of the EIO-LCA and P-LCA enabled the researchers to analyze specific processes with details while considering the entire supply chain, simultaneously (Acquaye et al., 2011). Furthermore, the hybrid LCA is useful for minimizing the aggregation and uncertainty related errors commonly encountered when both the P-LCA and EIO-LCA are used independently.

1.2.4. Triple Bottom Line LCA

While former EIO-based LCA models can only quantify environmental burdens, the TBL - based LCA model is capable to quantify not only environmental loads, but also social and economic impacts. This can be achieved by using an integrated approach which merges economic and social indicators of the sustainability into EIO framework as an addition to environment. TBL concept focuses on the three main pillars of sustainability such as environment, economy, and society (Wiedmann et al. 2009; Wiedmann and Lenzen 2006). With the increasing concerns related to integration of social and economic dimensions of the sustainability into LCA, a traditional LCA approach has been transformed into a new concept, which is called as *Life Cycle Sustainability Assessment* (LCSA). This concept was suggested by Kloepffer (2008) and *Life Cycle Cost* (LCC) and *Social Life Cycle Assessment* (SLCA) methods were integrated into the LCA framework in order to evaluate economic and social dimensions (Finkbeiner et al. 2010; Traverso et al. 2012; Zamagni et al. 2012).

In the literature, Foran et al. (2005a) developed a first comprehensive EIO based TBL model of the industrial sectors of an entire economy for the Australia. This model has been named as *Balancing Act* that integrates the EIO tables with environmental, economic, and social metrics for 135 sectors. Researchers from the University of Sydney established the foundation of the EIO model for the *Balancing Act* study and created a TBL software tool for the Australia, United Kingdom, and Japan economies (Foran et al. 2005b; Wiedmann et al. 2009). However, TBL model of the U.S. economy was also developed in order to quantify the TBL implications of the U.S. construction industry (Kucukvar and Tatari 2013), food manufacturing sectors (Egilmez et al. 2013a; Egilmez et al. 2013b), warm-mix asphalts (Kucukvar et al. 2013a), residential and commercial buildings (Onat et al. 2013a), wind power turbines (Noori et al. 2013), intelligent transportation (Ercan et al. 2013) and U.S. manufacturing industry (Kucukvar et al. 2013b).

In addition to TBL-based EIO tools, the World Input Output Database (WIOD) established a strong foundation for a multi-regional input-output (MRIO) framework by presenting supply and use tables for 40 countries, covering around 85% of the world economy. This project was supported by the EU's 7th Framework Program that presents the derivation of international trade and transport margins together with detailed supply and use tables at the world level. Together with extensive satellite accounts including environmental and socio-economic indicators, these database can provide the necessary input to several types of EIO models that can be used to evaluate trade-offs between socio-economic and environmental objectives (Streicher and Stehrer 2012). Furthermore, the Global Trade Analysis Project (GTAP) also produces an extensive database of trade-linked input-output tables for the world economy, which involves about 57 sectors and 87 regions in the world (Hertwich and Peters 2009). Although GTAP is an extremely important tool for the modeling of the role of international trade in goods and services, environmental extensions are still limited to some energy and carbon indicators (Tukker et al. 2009).

1.3. Problem Statement

The aforementioned LCA studies have been extensively used to analyze the environmental impacts of buildings, energy systems, and other civil infrastructures from a system-wide perspective. The same EIO methodology would also be expanded to estimate the environmental, as well as the economic and social impacts, termed as the TBL, of the built environment, a current gap that will aid in broader analysis results that could help in more effective policies. In parallel with the current trend in LCSA, this research envisions a comprehensive LCSA framework which includes the social, economic, and environmental impacts from a broader perspective: direct (on-site) and indirect (supply chain) burdens. Due to the broader scope of analysis, EIO analysis is utilized in order to provide a holistic framework to trace the impacts across the supply chains in addition to direct impacts related to asphalt production processes. On the other hand, since recent trends also emphasize the inclusion of three pillars of sustainability as economy, society and the environment, the proposed sustainability scope perfectly fits to the needs of such a comprehensive sustainability assessment understanding. Therefore, this dissertation aims to address this important research problem by using several sustainability metrics augmented with U.S. EIO tables to reach better insights regarding the sustainability performance of the nation's civil infrastructures and buildings.

1.4. Research Objectives

In order to advance the TBL sustainability performance analysis of the built environment, it is necessary to consider all direct and indirect impacts of buildings and infrastructures using various decision making models to provide more robust decision-making framework for the sustainable built environment. Hence, the following research questions are addressed to analyze environmental, economic and social implications of the sustainable construction by using integration of several robust decision making tools (See Fig. 2):

1. How can we integrate the U.S. supply and use tables with a range of social, economic, and environmental metrics to holistically assess the U.S. built environment to achieve sustainable construction goals?
2. What are direct plus indirect economic impacts of buildings and civil infrastructures in terms of gross operating surplus, gross domestic product, and imports?
3. What are the direct plus social indirect impacts of buildings and civil infrastructure projects in terms of employment, income, tax, and work-related injuries?
4. What are the direct and indirect implications of the U.S. built environmental in terms of carbon, energy, water, waste, and land footprints?
5. How can we integrate multi-criteria decision making & optimization framework for sustainable built environment to have environmentally sound, economically viable, and socially acceptable infrastructure solutions?
6. What is the sensitivity of different input parameters such as energy consumption or material utilization on selected TBL sustainability indicators?

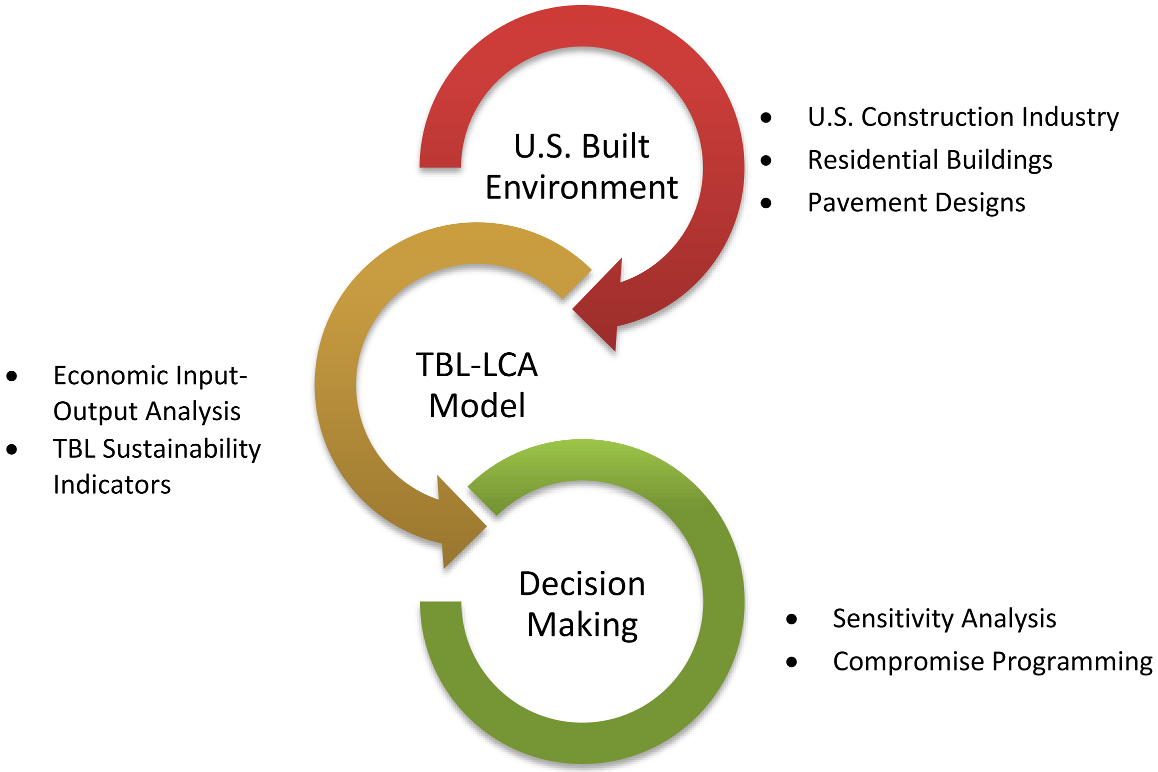


Figure 2. Research framework

This research aims to provide answers to all of the questions mentioned above, from which the following objective are postulated:

a) Develop a national EIO-based TBL-LCA model,

b) Build an integrated sustainability framework by exploring sustainability indicators within the developed TBL-LCA model,

c) Analyze the TBL sustainability interventions of the U.S. construction sectors, including residential and non-residential structures, such as commercial, industrial, and residential buildings, and heavy civil infrastructures,

d) Develop a hybrid TBL-LCA model in order to quantify cradle to grave life cycle sustainability impacts of the U.S. residential buildings using 16 macro-level sustainability indicators,

e) Construct a hybrid TBL-LCA model to quantify the sustainability impacts of pavements such as conventional hot-mix asphalt (HMA and warm-mix asphalt (WMA) mixtures including Asphamin® WMA, Evotherm™ WMA, and Sasobit® WMA,

f) Advance a stochastic multi-criteria optimization and simulation models for decision making of sustainable civil infrastructures.

By answering these questions, the research aims to bring a better understanding of environmental, economic and social interventions of civil infrastructures. It is expected that the results of this research would facilitate better sustainability decisions in the adoption of system-based TBL thinking in the construction field.

1.5. Dissertation Outline

This dissertation is structured into six chapters. *Chapter 1* presents general information about the U.S. built environment, and its sustainability impacts. It will also involve problem statement, research objectives, and organization of the dissertation. In addition, this section will include a review of LCA models (P-LCA, EIO-LCA, and hybrid LCA) as well as input-output based TBL sustainability accounting and its applications in building and civil infrastructures systems.

Chapter 2 aims to present a newly proposed industry-by-industry TBL-LCA model, including its mathematical framework. Also, data sources of the model and several important reference reports are presented in this section. TBL sustainability indicators (environmental, economic and social) of developed EIO model are also described with details and corresponding data sources are presented. Finally, a statistical analysis tool has been used to validate the developed TBL-LCA model.

Chapter 3 includes the applications of proposed TBL-LCA model for the U.S. construction industry. TBL sustainability analysis of the U.S. construction sectors including Non-residential Commercial and Health Care Structures” (NR-CHCS), “Non-residential Manufacturing Structures” (NR-MS), “Other Non-residential Structures” (NR-OTR), “Residential Permanent Single and Multi-Family Structures” (R-PSMFS), “Other Residential Structures” (R-OTR), “Non-Residential Maintenance and Repair” (NR-MR) and “Residential Maintenance and Repair” (R-MR) is presented.

Chapter 4 aims to identify and outline the TBL hotspots of the U.S. residential buildings through their life cycle phases including building construction, operation and disposal, and supply chain of these life cycle phases. To realize this goal, a hybrid TBL-oriented EIO model is utilized for assessing building sustainability. Also, *Monte-Carlo Simulation and Sensitivity Analysis* will be integrated into this analysis to identify the most critical impact variables.

Chapter 5 aims to build a hybrid TBL-oriented EIO model for evaluating the environmental as well as socio-economic impacts of pavements constructed with different types of WMA mixtures and compare them to a conventional HMA design. The types of WMA technologies analyzed in this chapter involve: Asphamin® WMA, Evotherm™ WMA, and Sasobit® WMA. The life phases of materials extraction and processing, transportation of pavement materials and ready-mixtures, asphalt mixing process and construction of pavements have been included within the scope.

Chapter 6 will summarize the findings of the research and present their significance for the U.S. built environment. Limitations of the research and conclusions based on the results are investigated and discussed. Ultimately, the future recommendations are pointed out.

CHAPTER 2. METHODOLOGY

2.1. Mathematical Framework of the Triple-Bottom-Line Input-Output Model

In this dissertation, EIO-based sustainability accounting approach has been developed to analyze the sustainability of the construction from a holistic perspective. To realize this goal, the supply and use tables published by the U.S. Bureau of Economic Analysis (BEA 2002), as part of the International System of National Accounts, are merged with a range of environmental, economic, and social sustainability metrics to develop a comprehensive sustainability assessment framework for the U.S. construction industry. The commodity-industry format is utilized since the basic input–output model presents the financial flows between industrial sectors without distinguishing between primary and secondary products. However, using commodity-industry format, it is possible to account for the fact that an industry can produce more than one commodity, such as secondary products and by-products (Wachsmann et al. 2009). Especially, the Eurostat manual provides a comprehensive and detailed discussion on the use of this format in the EIO models (Eurostat 2008).

In this approach, the Use matrix, which is usually denoted as U, provides information on the consumption of commodities by industries or by final demand categories, such as households, government, investment or export. As an element of U, u_{ij} denotes the value of commodity purchase of commodity i by industry j and x_j represents the total output of industry j, including imports. Therefore, b_{ij} is the amount of commodity i required for producing one-dollar output of industry j. By using the total industrial output of industry j, the technical coefficient matrix B can be written as (Miller and Blair 2009):

$$B= [b_{ij}] = \left[\frac{u_{ij}}{x_j}\right] \tag{1}$$

In addition to the Use matrix, the Make matrix, which is usually denoted as called as V, provides detailed information on production of commodities by industries. In the make table, each row represents the production of commodities by different industries. As an element of the Make matrix, v_{ji} is the value of the output of commodity i by industry j and q_i represents the total output of commodity i. Hence, d_{ji} represents the fraction of total commodity i output which is produced by industries both as main product as well as by-product. Using the total output of commodity i, the industry-based technology coefficient matrix D can be written as (Miller and Blair 2009):

$$D= [d_{ji}] = \left[\frac{v_{ji}}{q_i}\right] \tag{2}$$

After defining B and D matrices, an industry-by-industry input-output model can be formulated as follows (Miller and Blair 2009):

$$x= [(I-DB)^{-1}]\, f \tag{3}$$

where *x* represents the total industry output vector, I refers to the identity matrix, and f is the total final demand vector for industries. In addition, B is the input requirements for products per unit of output of an industry matrix, and D is sometimes called as market-share matrix. Also, the term $[(I\text{-}DB)^{-1}]$ represents the total requirement matrix, which is also known as the Leontief inverse and DB is the direct requirement matrix, which is represented by A matrix in the Leontief input-output model (Leontief 1970). For more detailed information on transformation of the supply and use tables into a symmetric industry-by-industry model, please see the reference reports prepared by the Eurostat and United Nations (Eurostat 2008; UN 1999).

After an industry-by-industry input-output framework has been established, total sustainability impacts (direct and indirect) can easily be calculated by multiplying the final demand of a sector with the multiplier matrix. Then, a vector of total sustainability impacts can be formulated as follows:

$$r=E_{dir}x= E_{dir}\ [(I\text{-}DB)^{-1}]\ f \tag{4}$$

where r denotes the total impacts vector that represents overall sustainability impacts per unit of final demand, and E_{dir} represents a diagonal matrix, which consists of the direct environmental, economic, or social impact values 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 consumption, carbon emissions, income) with total economic output of that sector. In addition, the product of E_{dir} and the bracketed term $[(I\text{-}DB)^{-1}]$ represents the multiplier matrix.

2.1.1. Power Series Approximation

Using a power series expansion of the Leontief inverse, it is also possible to account for the impacts of direct and indirect suppliers on environmental, economic, and social impact categories. Eq.5 presents the mathematical framework of the power series approximation of the Leontief inverse that is applied in this research (Hendrickson et al. 2005):

$$x= [(\underbrace{I}_{L1} + (\underbrace{DB}_{L2}) + \underbrace{(DB)^2+ (DB)^3 +(DB)^4\cdots\cdots}_{\text{L3 and higher}})] f \tag{5}$$

Using this power series approximation, the results are presented in three different layers to account for the contribution of high order suppliers to each sustainability indicator. In this analysis, Layer 1 (L1) represents each construction sector itself, which is contributing with on-site activities through direct use of energy or water, as well as direct economic and social impacts. Layer 2 (L2) accounts for contributions from all direct suppliers to U.S. constructions sectors. Finally, Layer 3 (L3) and higher represents the suppliers of the suppliers and other high order suppliers in the U.S. economy (see Fig. 3).

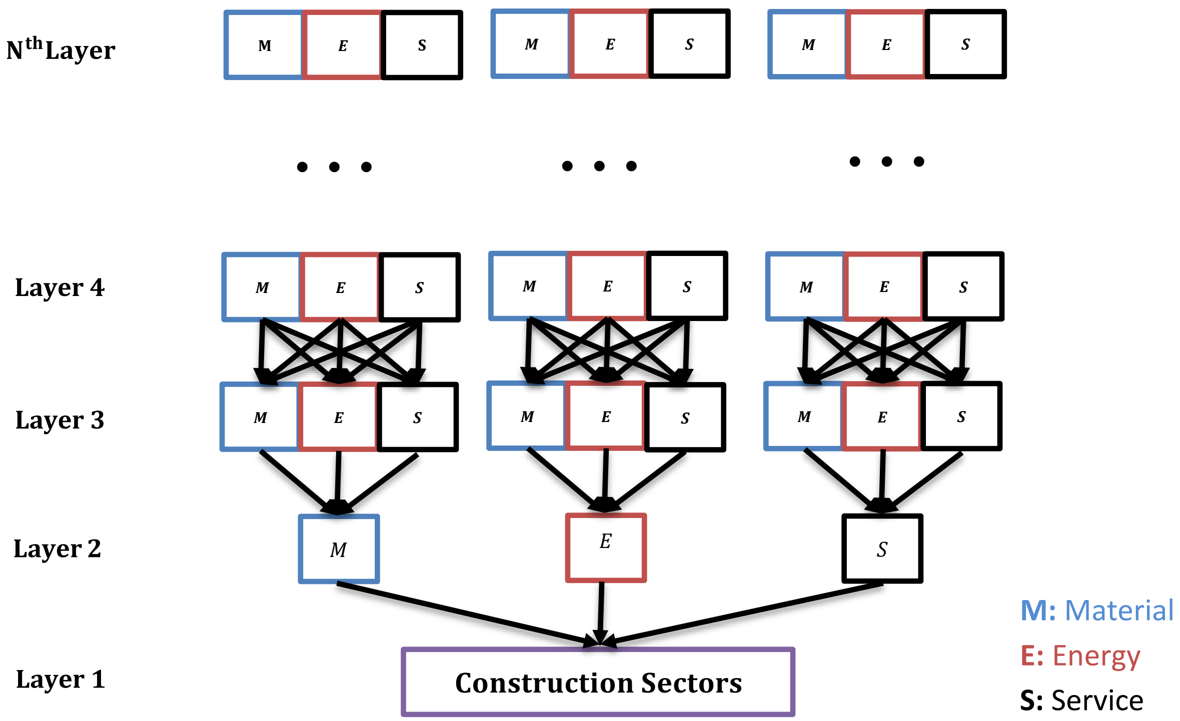


Figure 3. Representation of layers in the supply chain

2.2. Economic, Social, and Environmental Sustainability Indicators

The EIO analysis is utilized to build a comprehensive sustainability assessment framework of the U.S. economy using numerous environmental, economic, and social indicators (see Fig. 4). These sustainability indicators are considered as multipliers, and will be then used to analyze sustainability of construction sectors, residential buildings and pavement designs. After determining these sustainability assessment metrics, the direct and indirect sustainability impacts of the U.S built environment are quantified from a triple bottom line perspective.

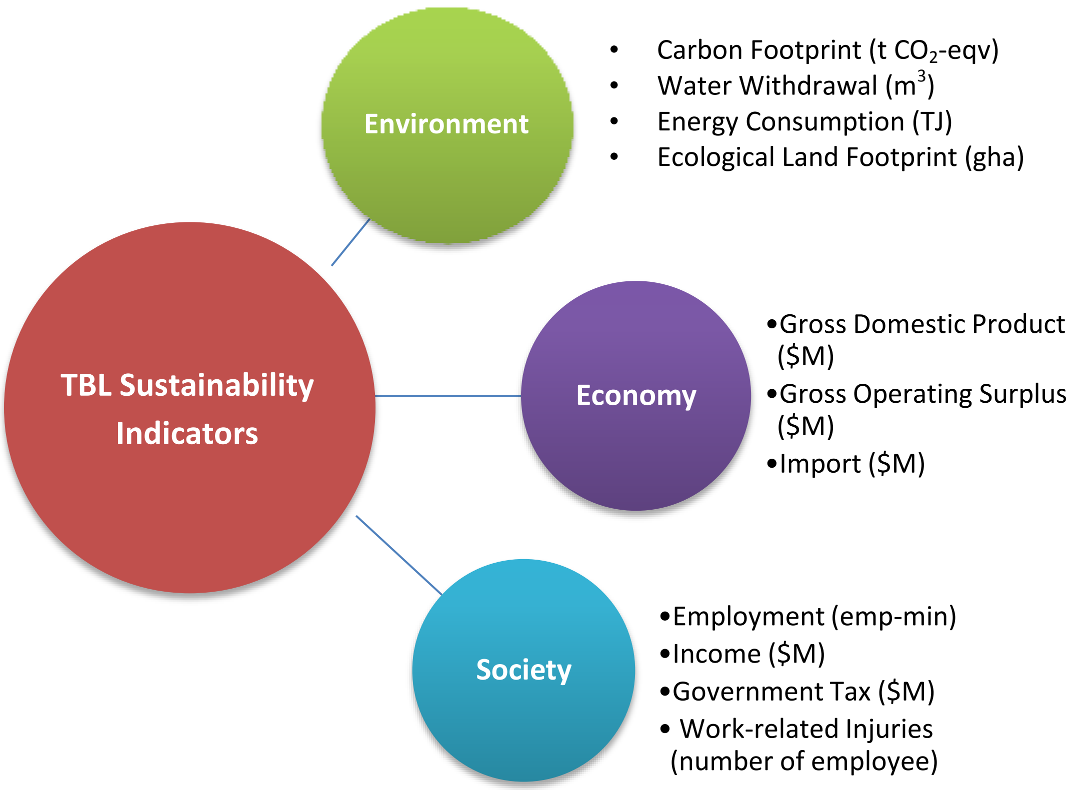


Figure 4. TBL sustainability indicators

2.2.1. Economic Indicators

Firstly, gross operating surplus, contribution to gross domestic product, and import are selected as key economic indicators, and are presented in terms of millions of dollars ($M). The values of these economic indicators are obtained from the U.S. input-output tables (BEA 2002). Although it was not used for a sustainability analysis of construction sectors, these indicators were merged with the EIO analysis before to provide a macro-level sustainability accounting framework (Foran 2005b; Wiedmann and Lenzen 2009). These economic indicators of sustainability are defined as follows:

Gross Operating Surplus (GOS): is obtained as a residual for most industries after subtracting total intermediate inputs, compensation of employees and taxes from total industry output (Eurostat 2008). GOS is a positive economic indicator since it represents the capital available to sectors, which allow them to repay their creditors, to pay taxes, and to finance their investments.

Gross Domestic Product (GDP): is used as another useful economic indicator. GDP represents the market value of goods and services produced within the country in a given period of time. GDP is a positive economic indicator that monitors the health of a nation's economy and includes compensation of employees, GOS and net taxes on production and imports (Lenzen 2002). This positive economic indicator is the direct and indirect contribution of one sector to GDP.

Imports: represent the value of goods and services purchased from foreign countries to produce domestic commodities by industries (Wiedmann et al. 2009) Imports can be considered as a negative indicator due to the fact that an excess of imports means an increase in the current deficit through the flow of money out of the country. This economic indicator accounts for the direct and indirect contribution of one sector to foreign purchases.

2.2.2. Social Indicators

Social indicators of sustainability are also critical since they are considered an integral part of the LCSA framework that analyzes environmental, economic, and social dimensions of sustainable development (Guinee et al. 2011; Klöpffer 2008; Zamagni 2012).

In this research, three social indicators such as income ($M), taxes ($M), and work-related injuries (number of employee) are selected as prominent social indicators and obtained from federally available public data sources. These social sustainability indicators are defined as follows:

Income: is considered an important social indicator since it contributes to the social welfare of households and represents the compensation of employees, including wages and salaries (Wiedmann et al. 2009). The income generated by each industrial sector is obtained from the U.S. input-output tables (BEA 2002).

Tax: is chosen in this model as a positive sustainability indicator since collected taxes will be used for supporting the national health and education systems, public transportation, highways, and other civil infrastructures (Forran 2005). Taxes are referred to as government revenue, which includes the taxes on production and imports. The data source for taxes generated by each sector is the U.S. input-output tables (BEA 2002).

Work-related Injuries: The U.S. construction industry accounts for the largest share of work-related injuries and illnesses, and results in loses in wage and productivity of households (Waehrer 2007). Hence, injury is a critical indicator of social sustainability that has a significant impact on the quality of life. This negative indicator represents the total number of non-fatal injuries at industrial facilities. The data including the number of total work place injuries is gathered from the U.S. Bureau of Labor Statistics (BLS) to investigate the contributions of the U.S. construction sectors to work-related injuries (BLS 2002). The BLS provides a publicly available data, which presents the rate of non-fatal injuries per 100 equivalent full-time employees. To calculate the total number of direct injuries for each U.S. sector, the total number of full-time employee is then multiplied with corresponding incidence rates per 100 full-time workers.

2.2.3. Environmental Indicators

The United Nations Environment Program (UNEP) has recently released emerging environmental concerns and ranked water scarcity, global climate change, and energy resource depletion among the most important emerging issues related to the global environment (UNEP 2012). With the aim of analyzing the direct and indirect contribution of the U.S. built environment to the aforementioned major themes of the global environment, water, carbon and energy footprint categories have been presented in our analysis. The diagonal environmental impact matrixes including the value of these environmental indicators per $M output of each industrial sector is obtained from the EIO-LCA model, which was developed by the Green Design Institute at Carnegie Mellon University (CMU 2002). These environmental footprint categories were used in conjunction with the EIO analysis for sector-level life cycle impact assessment (Blackhurst 2010; Matthews et al. 2008; Williams 2004).

Several ecological footprint types, such as fishery, grazing, forestry, cropland, and CO_2 uptake land are also analyzed for each construction sector. The ecological footprint is defined as a measure of how much area of biologically productive land and water an individual, population or activity requires to produce all the resources it consumes and to absorb the waste (Wackernagel 2009). In this analysis, ecological footprint indicators are also considered as a part of the environmental dimension of the sustainability, and these indicators have already been used as a measure of environmental sustainability in previous input-output studies (Lenzen and Murray 2001; McDonald and Patterson 2004; Wiedmann et al. 2009). The global hectare values associated with fishery, grazing, forestry, cropland, and CO_2 uptake land are obtained from the GFN, and allocated to 426 U.S. sectors based on their resource consumption and CO_2 emissions (GFN 2010a). The aforementioned environmental indicators are briefly explained as follows:

Water Footprint: is a measure of direct and indirect water used by each industrial sector. The EIO-LCA model uses the United States Geological Survey (USGS) data to estimate direct water withdrawals for each consumption category such as power generation, irrigation, industrial, livestock and aquaculture, mining, public supply, and domestic water use. Some of these USGS categories are then allocated to different industrial sectors that are in the U.S. economic input-output table (Blackhurst et al. 2010). All water footprint results are presented in terms of cubic meter (m^3).

Carbon Footprint: is a measure of the total amount of carbon dioxide, nitrogen oxides, and methane emissions from fossil fuel combustion. In this analysis, carbon footprint calculations are based on different scopes which are set by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) in which all possible indirect emissions from a construction sector are considered (WRI&WBCSD 2004). Scope 1 includes direct GHG emissions from a construction sector, including on-site emissions from natural gas, oil, and diesel combustion. Scope 2 GHG emissions account for indirect emissions from the generation of electricity used by each construction sector (Wood and Dey 2009). Finally, Scope 3 emissions are all indirect emissions (not included in Scope 2) that occur in the value chain of the construction sectors, including all upstream emissions. All scope-based carbon footprint results are presented in terms of metric tons of CO_2 equivalents (t CO_2-eqv).

Energy Footprint: The energy footprint of each sector is calculated by summing the energy content of different fossil fuels and electricity from non-fossil sources. The consumption values of major fuels by industrial sectors are obtained from the using the U.S. input-output tables (Joshi 2000). The quantities of fuel consumption are based on the average producer price of individual fuels and are presented in terms of tera-joules (TJ).

Cropland Footprint: represents the most bio-productive of all the land use types and includes areas used to produce food and fiber for human consumption, feed for livestock, crops, and rubber (GFN 2010b). The National Footprint Accounts calculate the cropland footprint according to the production quantities of 164 different crop categories. The total ecological footprint of cropland use (1.08 gha per capita) is allocated to the U.S. agricultural sectors completely.

Grazing Land Footprint: is calculated by comparing the amount of livestock feed available in a country with the amount of feed required for the livestock produced in that year, with the remainder of feed demand assumed to come from grazing land (GFN 2010b). The total ecological footprint of grazing use (0.14 gha per capita) is allocated to the U.S. agricultural sectors.

Forest Land Footprint: is calculated based on the amount of lumber, pulp, timber products, and fuel wood consumed by a country on a yearly basis (GFN 2010b). The total ecological footprint of forest use (1.03 gha per capita) is allocated to the U.S. forestry nurseries, forest products, and timber tracks sector.

Fishery Land Footprint: The fishery land footprint, in other words, fishing grounds footprint is calculated using estimates of the maximum sustainable catch for a variety of fish species. The calculation is based on the estimated primary production required to support the fish caught (GFN 2010b). Assigned completely to the U.S. fishing sector is the total ecological footprint of fishing ground (0.10 gha per capita).

Carbon Dioxide (CO_2) Uptake Land Footprint: is calculated as the amount of forestland required to absorb given carbon emissions (GFN 2010b). Carbon Dioxide (CO_2) emissions, generated primarily from the fossil fuel combustion, account for the largest portion of nation's ecological footprint. The total CO_2 emissions related to fuel consumption of industrial sectors, transportation, households and government are obtained from the U.S. Energy Information Administration (EIA 2010). Then, the total ecological footprint for CO_2 uptake (4.79 gha per capita) is allocated to the U.S. sectors based on their CO_2 emissions.

2.3. Model Validation

Initially, industry-by-industry TBL-LCA model is compared with the EIO-LCA model, which has been accessed over a million times by researchers, LCA practitioners, and business users (CMU 2002; Hendrickson et al. 2005).

To compare both models, total energy consumption (direct plus indirect) of seven construction sectors are compared based on per $M economic output. As mentioned earlier, first layer represents direct impacts whereas higher layers account for the impacts of all higher order suppliers. Fig. 5 presents the direct and indirect energy consumption of each construction sector. Additionally, the descriptive statistics of the data are provided in Table 1.

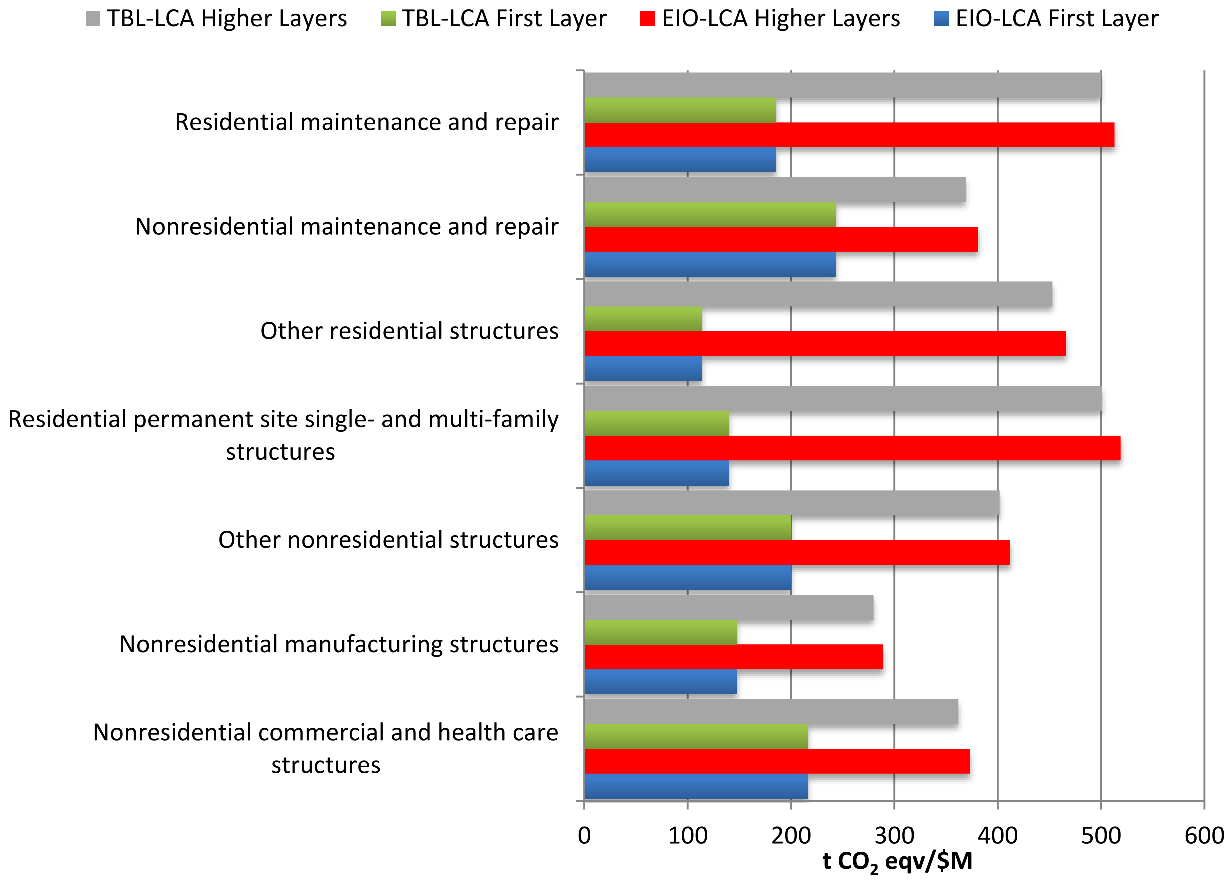


Figure 5. Comparison of models based on carbon emissions located in first and higher layers per $M economic output

Prior to statistical analysis to compare both the EIO-LCA and TBL-LCA, normality and homogeneity of variances tests were conducted for all data since Analysis of Variance (ANOVA), which is a parametric statistical method, requires data to be normal with homogenous variance (Johnson and Wichern 2007). The results of normality and homogeneity variance tests are shown in Table 2 and 3. According to test results, all of the data obtained from the EIO-LCA and TBL-LCA satisfied both assumptions made by the ANOVA (all p values are greater than 0.05). Therefore, the use of ANOVA is justified.

Table 1. Descriptive statistics

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum	Between-Component Variance
						Lower Bound	Upper Bound			
EIO-LCA		7	599.85	82.55	31.20	523.50	676.21	437	698	
TBL-LCA		7	587.57	80.75	30.52	512.88	662.25	428	685	
Total		14	593.71	78.71	21.03	548.26	639.16	428	698	
Model	Fixed Effects			81.66	21.82	546.16	641.26			
	Random Effects				21.82[a]	316.3996[a]	871.02[a]			-877.20408

Table 2. Normality test results

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
VAR00001	.262	7	.158	.897	7	**.312**
VAR00002	.257	7	.181	.897	7	**.314**

Table 3. Test of homogeneity of variances

Levene Statistic	df1	df2	Sig.
.001	1	12	**.971**

After completing normality check, ANOVA is used to compare the results of both models. To determine if both LCA models statistically present different results, the following hypotheses (H_o, H_1) are tested.

$$H_o: \mu_i = \mu \qquad \text{all } i = 1, 2 \tag{6}$$

$$H_1: \mu_i \neq \mu \qquad \text{all } i = 1, 2 \tag{7}$$

where μ_i is the population mean for model *i*. Then, IBM's SPSS software package is used to conduct the ANOVA test (SPSS 2012). With a significance level, α=0.05, the null hypothesis is accepted since ANOVA's significance value was greater than 0.05 (see Table 4).

Table 4. ANOVA test results

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	528.286	1	528.286	.079	**.783**
Within Groups	80024.571	12	6668.714		
Total	80552.857	13			

CHAPTER 3. SUSTAINABILITY ASSESSMENT OF THE U.S. CONSTRUCTION INDUSTRY

3.1. General Remarks

Due to the fact that the built environment has significant impacts on the environment, it is necessary for the construction industry stakeholders to address the issues related to sustainable construction. Today, many construction companies have given a substantial importance to sustainability and resource conservation, and therefore the environmental LCA of construction activities have become a subject of considerable interest globally (Sharrad et al. 2008).

LCA-based decision support tools have also been developed for analyzing the environmental implications of buildings and building materials both in the Europe and United States (Haapio and Viitaniemi 2008). To give a few examples, ENVEST was developed in UK to quantify the environmental impacts of buildings considering materials utilized in construction and maintenance (Tatari and Kucukvar 2011). In addition to that, the Building Environmental Assessment Tool (BEAT), which was developed by the Danish Building and Urban Research Institute, provides a LCA-based inventory and database for the LCA of building products, as well (Folsberg and Malborgh 2004). ATHENA, which estimates the life cycle environmental impacts of construction materials and building systems, was developed by the Athena Sustainability Institute in North America as a decision support tool for buildings (Seo and Hwang 2001). The U.S. National Institute of Standards and Technology (NIST) has also developed Buildings for Environmental and

Economic Software (BEES) to select environmental and economically balanced building materials for commercial and residential buildings (Lippiat 2007). The National Renewable Energy Laboratory (NREL) Life Cycle Inventory database which was developed by the Athena Institute and NREL provides some data on building material production and transportation; however it does not provide any information regarding construction processes (NREL 2012).

3.2. Motivation and Organization of the Chapter

The previous LCA tools have successfully analyzed the environmental impacts of buildings and other civil infrastructures from a system-wide perspective. In addition to the environment, sustainable construction should also include the economic and social aspects. Hence, the EIO methodology could be expanded to estimate the environmental, as well as the economic and social impacts of different U.S. construction sectors. The current research aims to fill this important research gap, and account for the total sustainability impacts of the construction industry, including its supply chain.

The rest of the chapter is structured as follows. First, the U.S. construction sectors and corresponding economic outputs are presented Second, sustainability indicators such as environmental (water, energy, carbon and ecological land footprint), economic (GOS, GDP, and import) and social (income, tax, and work-related injuries) are used for TBL sustainability analysis. Finally, sustainability impacts of the U.S. construction industry including residential and non-residential construction sectors have been presented with details.

3.3. Construction Sectors and Sustainability Assessment

The economic output values of each U.S. construction sector were obtained from the U.S. Department of Commerce Input-Output Tables (BEA 2002). Table 5 lists seven different construction sectors along with their acronyms and industry outputs. Among the U.S. construction sector, “Non-residential Commercial and Health Care Structures” (NR-CHCS) consists primarily of different structures such as office building, educational building, airport building, industrial warehouse, hospital, hotel, etc. “Non-residential Manufacturing Structures” (NR-MS) includes manufacturing plants such as cement, aluminum, chemical, incinerator, etc and “Other Non-residential Structures” (NR-OTR) compromises of heavy civil infrastructures including highway, bridge, dams, water, sewer, petroleum, gas, power, and communication lines. In addition, residential construction sectors include the “Residential Permanent Single and Multi-Family Structures” (R-PSMFS), and “Other Residential Structures” (R-OTR), and maintenance and repair works are represented by the sectors of “Non-Residential Maintenance and Repair” (NR-MR) and “Residential Maintenance and Repair” (R-MR), respectively.

The developed TBL-LCA was used to identify the sustainability impacts of previously mentioned construction sectors. The results are presented using two different metrics, such as “*multiplier”* and “*total impact”*. First, multiplier incorporates direct plus indirect sustainability effects (e.g.: water footprint, income, tax) per $M output of each construction sector. Second, total impact is the product of multiplier and total economic output of construction sector for each sustainability indicator.

Table 5. U.S. construction sectors and total economic outputs ($M)

Sector Acronym	**Description**	**Total Industry Output ($M)**
NR-CHCS	Non-residential Commercial and Health Care Structures	129,239
NR-MS	Non-residential Manufacturing Structures	23,465
NR-OTR	Other Non-residential Structures	292,328
R-PSMFS	Residential Permanent Site single and Multi-Family Structures	304,950
R-OTR	Other Residential Structures	133,483
NR-MR	Non-residential Maintenance and Repair	101,516
R-MR	Residential Maintenance and Repair	47,379

3.4. Economic Impacts

3.4.1 GOS

When looked more closely at GOS multiplier, which is defined as total GOS per $M economic output, R-MR shows the highest values compared to others. This result also indicates that residential maintenance and repair work requires more capital outlay than new construction. In addition, residential construction sectors are found to have higher GOS multiplier than non-residential construction sectors. R-MR sector is then followed by R-OTR and R-PSFMS in terms of GOS multiplier. The on-site construction activities contribute highly on total GOS multipliers for these residential sectors, as well. For non-residential sectors, indirect suppliers, including L2, L3 and higher are responsible for over 60 % of total GOS (see Fig. 6a). For total GOS, R-PSFMS and NR-OTR show the highest values in comparison with other construction sectors (see Fig. 6b).

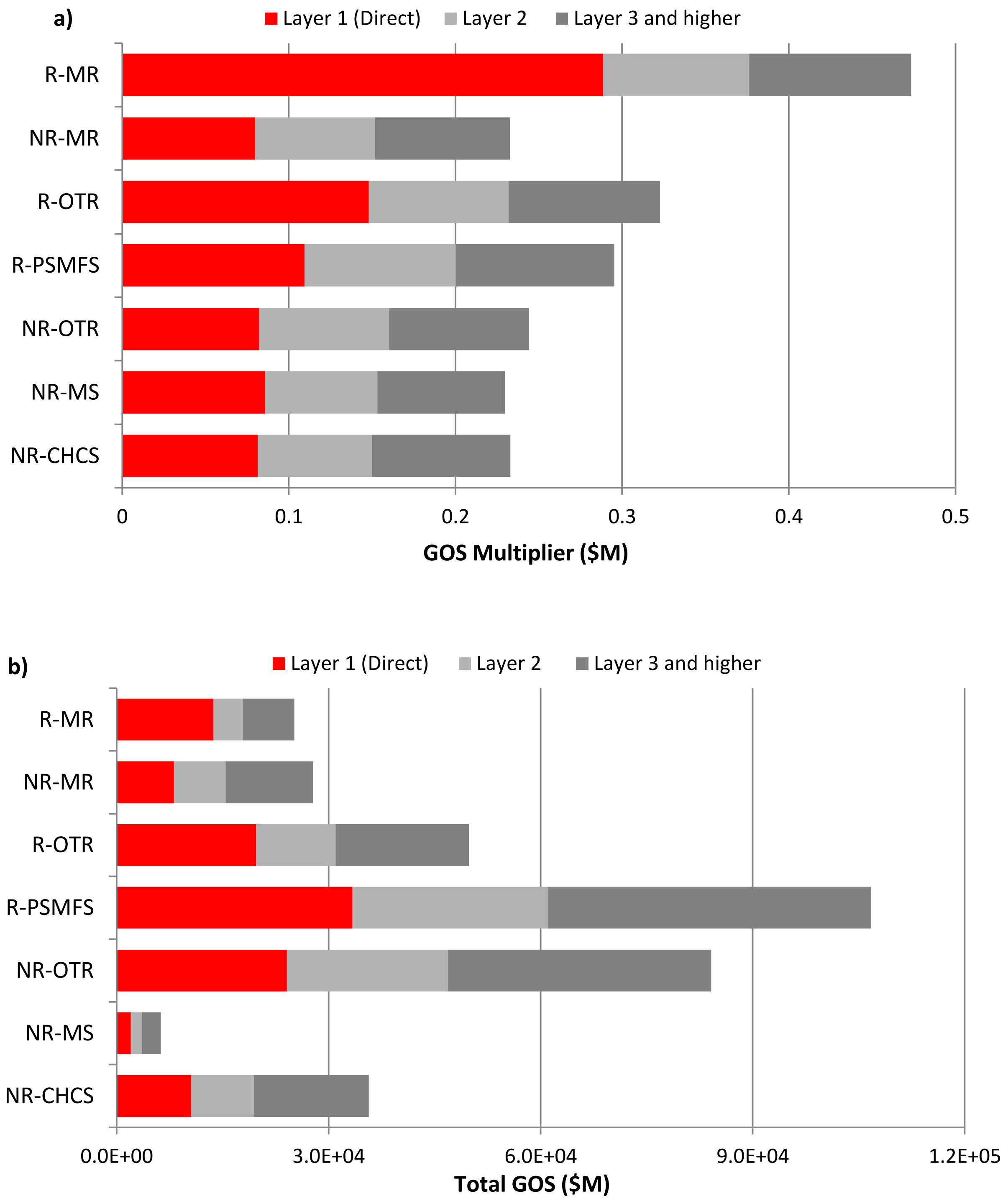


Figure 6. Economic impacts (a) GOS multiplier ($M) (b) Total GOS ($M)

3.4.2. GDP

In addition to GOS, the direct and indirect contribution of each construction sector to GDP is also investigated. The analysis results reveal that GDP multiplier is the same for all construction sectors. This is because this multiplier represents the dual of the input-output equation which simply gives the unit price. The contribution of on-site construction activities (represented by L1) to GDP has the higher percentage values for non-residential sectors compared to residential ones. On the other hand, the indirect suppliers are responsible for approximately 60 % of total GDP generated by per $M output of U.S. residential sectors (see Fig. 7a). In parallel with total economic outputs, R-PSFMS and NR-OTR represent the construction sectors with the highest contribution to GDP (see Fig. 7b).

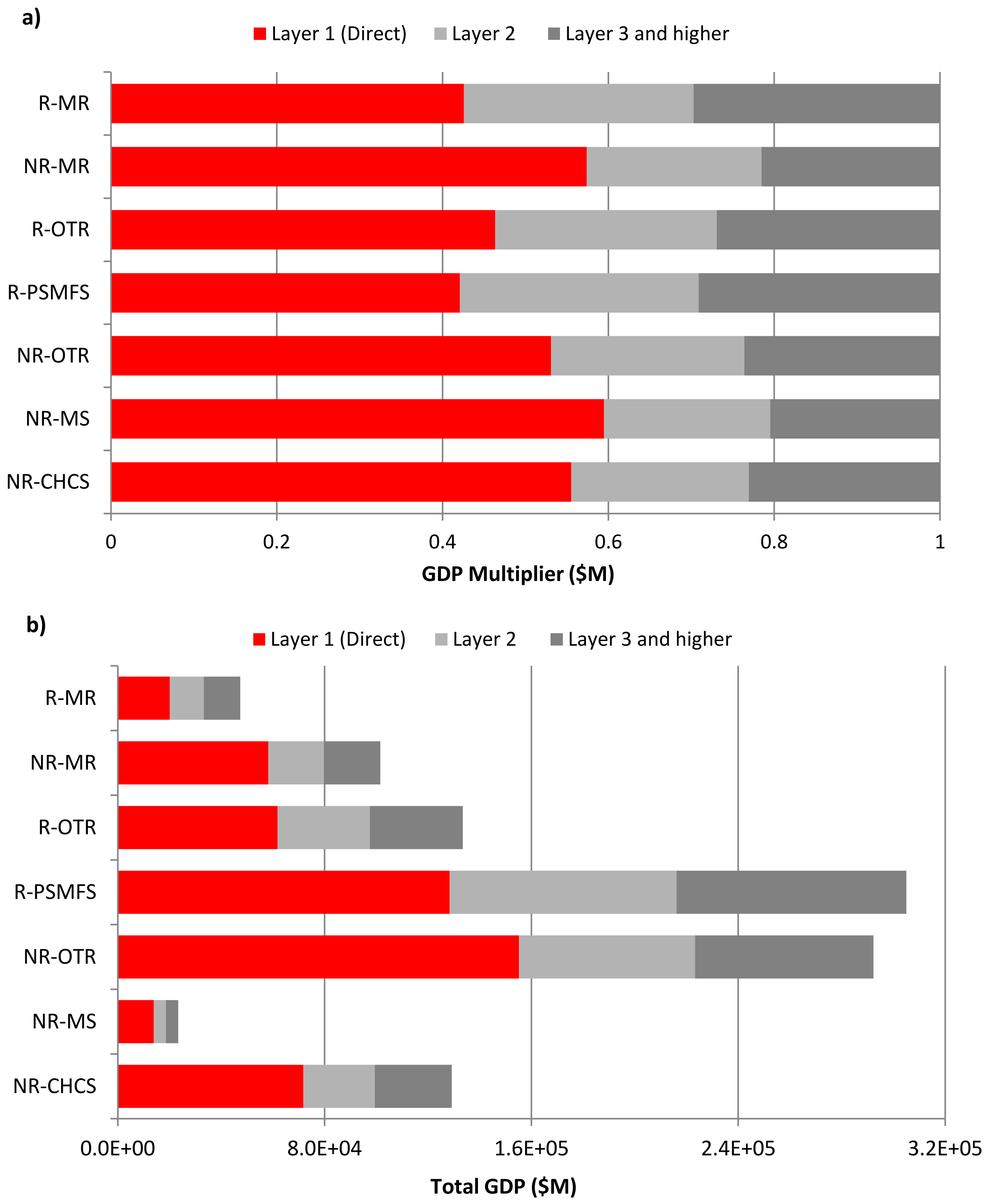


Figure 7. Economic impacts (a) GDP multiplier (b) Total GDP ($M)

3.4.3. Import

The import analysis results show that NR-MS has the highest import multiplier in comparison with other construction sectors. L2 suppliers of this sector are responsible for more than 60 % of total imports (see Fig. 8a). This sector is followed by R-PSFMS and R-MR, respectively. For the remaining construction sectors, L2 suppliers contributed to approximately 40 % of total import, and the rest is found in the higher order suppliers. On the other hand, there is no direct import related to construction sectors. For total import generated by each sector, R-PSMFS and NR-OTR show the highest values in comparison with others sectors (see Fig. 8b).

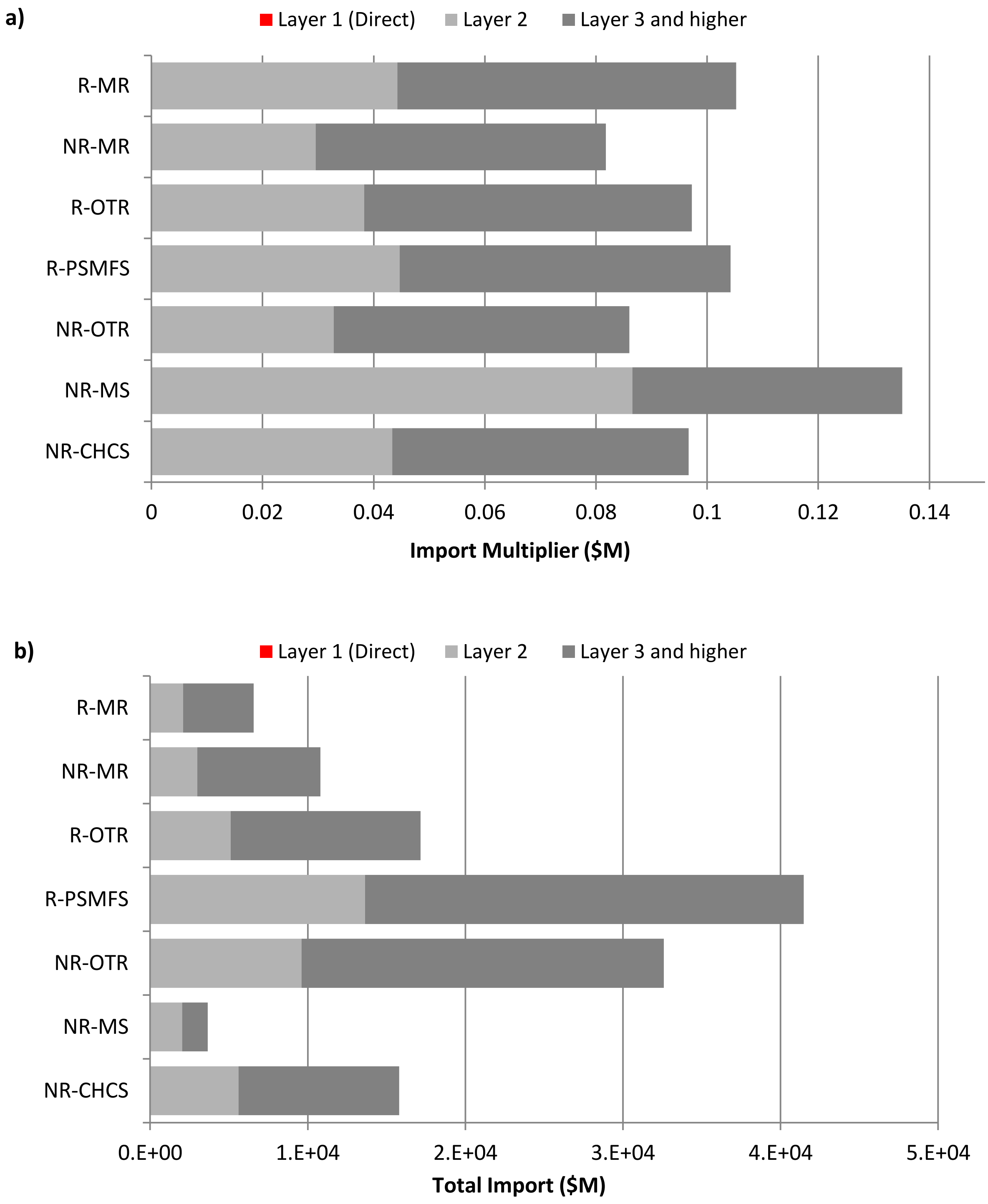


Figure 8. Economic impacts (a) Import multiplier ($M) (b) Total import ($M)

A further analysis is also conducted to gain valuable insights regarding the imports of metallic and non-metallic minerals since construction is the largest consumer of these raw materials in U.S. by weight (Horvath 2004). In the U.S. supply and use tables, the metallic and non-metallic minerals, which are highly utilized in construction, are represented by the sectors of "Iron Ore Mining" (IO-M), "Copper, Nickel, Lead and Zinc Mining" (CNLZ-M), "Stone Mining and Quarrying" (S-MQ), "Sand, Gravel, Clay and Ceramic and Refractory Minerals Mining and Quarrying" (SGCCR-MQ), and "Other Non-metallic Mineral Mining and Quarrying" (ONMM-MQ), respectively.

Fig. 9a presents total economic output (TEO) (excluding imports), as well as overall imports related to direct and indirect consumption of metallic and non-metallic minerals based on per $M output of each construction sector. Analysis results indicate that imported minerals have the lowest economic share, and the highest percentage of minerals consumed by construction sectors is produced domestically. To illustrate, for NR-CHCS and NR-MS, TEO (excluding imports) related to production of these raw materials are found to be over 80%, and the rest is imported from other countries. Among the construction sectors, residential constructions have the highest import of mineral products, whereas non-residential constructions which show the highest TEO are found to have the minimum total import of metallic and non-metallic minerals. In addition, NR-CHCS show more imports of metallic minerals, such as iron or copper than other construction sectors, whereas the highest share of total imports are attributed to non-metallic minerals consumption for residential buildings, as shown in Fig 9b.

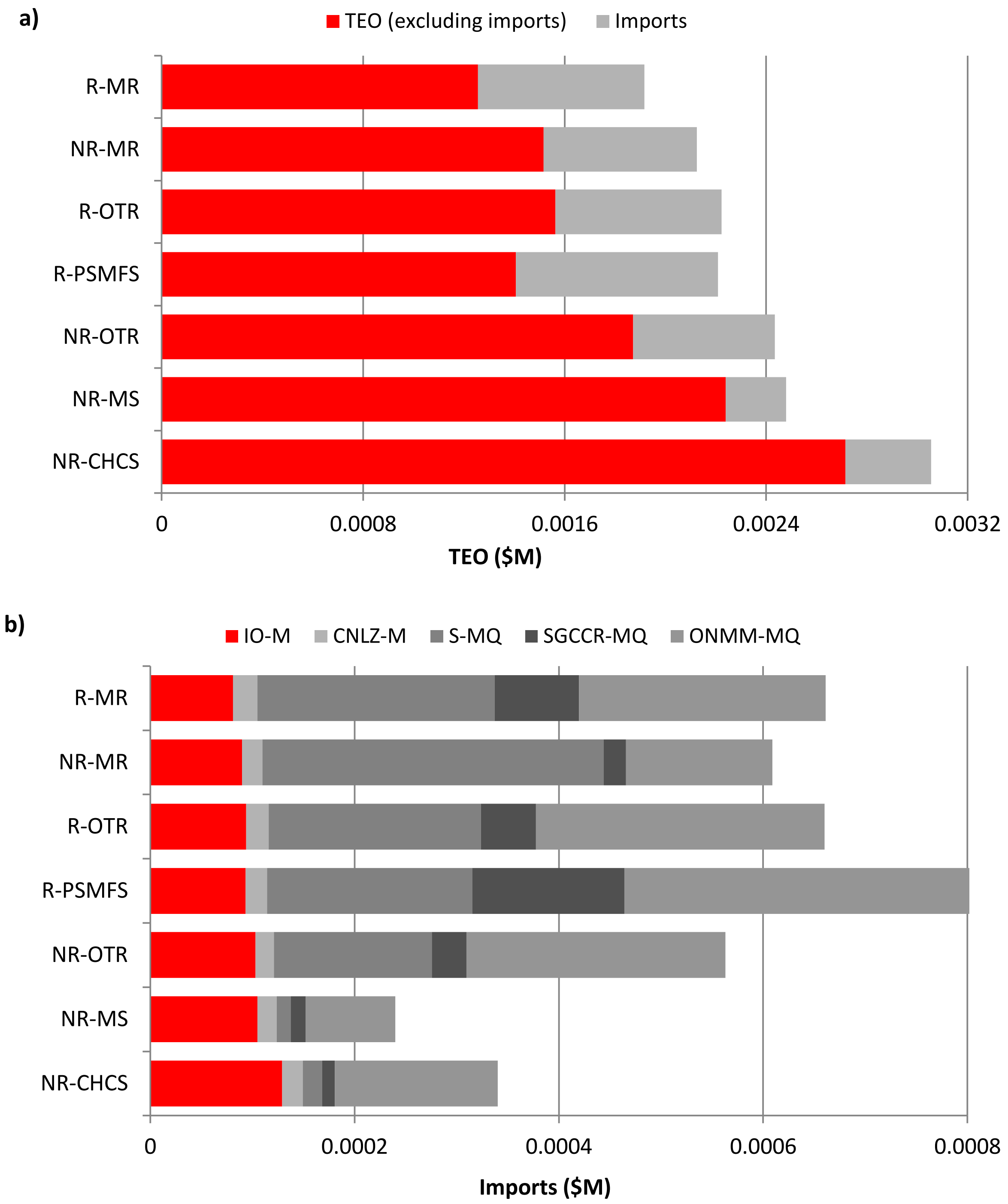


Figure 9. Economic analysis of metallic and non-metallic mineral consumption based on per $M output of construction sectors (a) TEO ($M) (b) Imports ($M)

3.5. Social Impacts

3.5.1. Income

Presented in this section are the income results. Based on research findings, R-PSMFS and NR-OTR have the highest value of income multiplier compared to other construction sectors (see Fig. 10a). In general, non-residential construction sectors have higher income multiplier than residential sectors. Two non-residential construction sectors, such as NR-MS and NR-MR have the largest income multiplier in comparison with other sectors. Additionally, for all non-residential U.S. construction sectors, approximately 60 % of total income is generated directly, which is represented by L1.

On the contrary, direct employment impacts are found to be less than 50 % of total income for U.S. residential sectors. Among the upstream suppliers, service sectors, including “Retail Trade”, “Wholesale Trade”, “Management of Companies and Enterprises”, “Employment services”, and “Architectural, Engineering and Related Services” provide the highest contributions to total income generated by each residential sector. When analyzing the total income generated by each construction sector, R-PSMFS and NR-OTR show the highest values in comparison with others (see Fig. 10b).

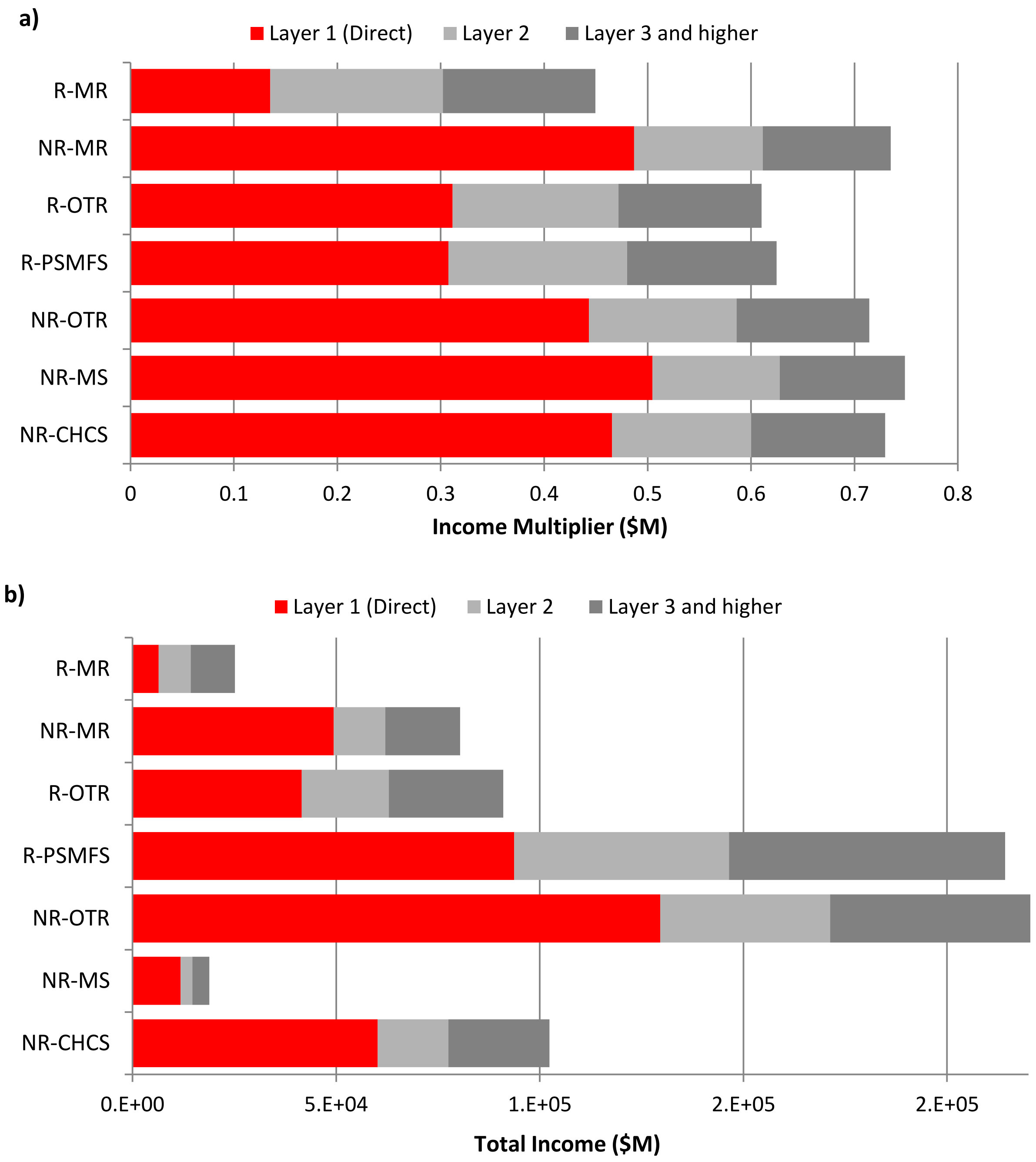


Figure 10. Social impacts (a) Income multiplier ($M) (b) Total income ($M)

3.5.2. Tax

Direct and indirect tax generated by each sector is also investigated, and the results are presented in Fig. 11a. L2 and L3 suppliers represent 80 % of total government tax generated from each construction sector. In other words, the U.S. construction sectors generate more tax indirectly than they do directly. The results also reveal that residential construction sectors generate a higher amount of total tax per $M of their economic output in comparison with non-residential sectors, including NR-MS, NR-OTR and NR-MR.

For the residential sectors, over 90 % of total tax is generated by indirect suppliers, which are located in L2, L3 and higher layers. Among these suppliers, "Retail and Wholesale Trade", "Real Estate", "Electric Power Generation", "Oil and Gas Extraction", "Telecommunications", and "Truck Transportation" are responsible for around 80 % of indirect tax generated in the value chain of residential sectors. When looked more closely at total government tax generated by each sector, NR-OTR and R-PSMFS represent the sectors with the highest total tax generation (see Fig. 11b).

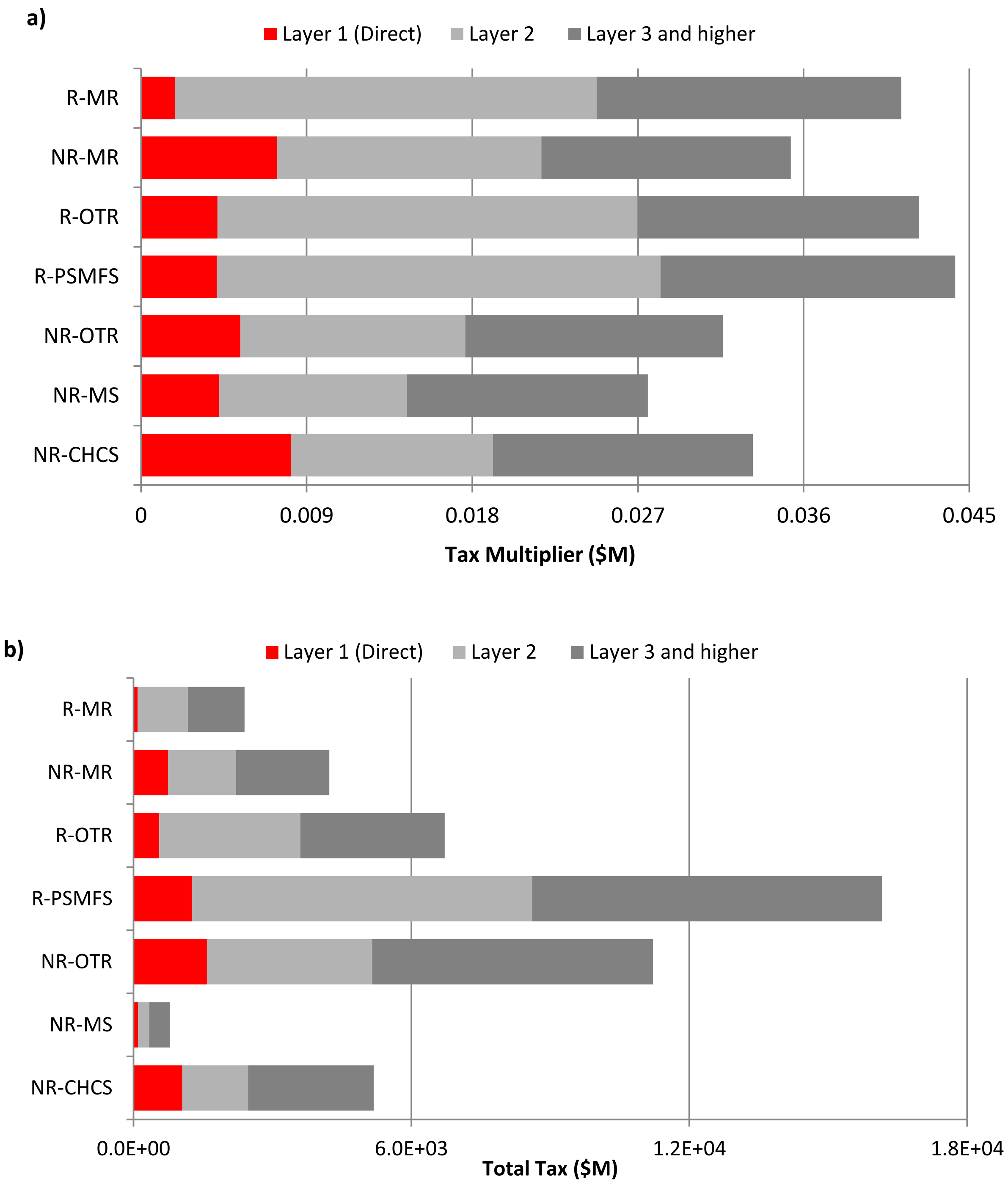


Figure 11. Social impacts (a) Tax multiplier ($M) (b) Total tax ($M)

3.5.3. Work-related Injuries

In addition to income and tax, the direct and indirect contribution of each construction sector to work-related injuries is also investigated. The analysis results indicate that injury multiplier of each sector is found to be similar for non-residential construction sectors. The contribution of on-site construction activities (represented by L1) to injuries has the higher percentage values for non-residential sectors compared to all residential construction sectors. For NR-CHCS, NR-MS, and NR-MR, the on-site activities are responsible for over 60 % of total work-related non-fatal injuries (see Fig. 12a). On the contrary, it was found that residential sector have more injuries indirectly than they do directly. In addition, non-residential construction sectors are found to have higher injury multiplier in comparison with residential sectors.

From the analysis results, it is apparent that R-PSFMS and NR-OTR represent the construction sectors with the highest total work-injuries among the U.S. constriction sectors (see Fig. 12b). It is should also be noted that income and injury multipliers show a similar trend and sectors with high income multiplier also have the highest total work-related injuries per $M economic output.

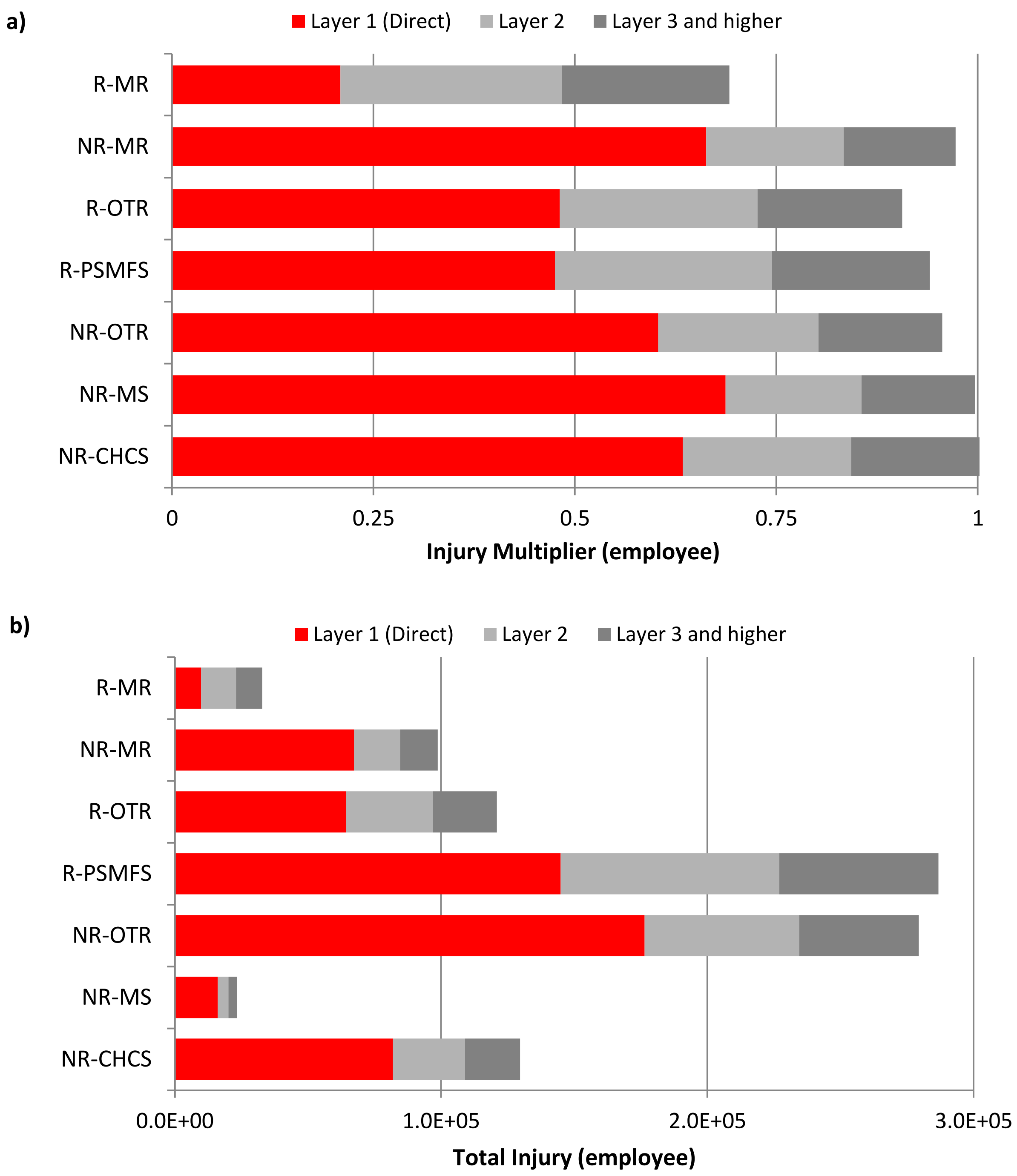


Figure 12. Social impacts (a) Injury multiplier (employee) (b) Total injury (employee)

3.6. Environmental Impacts

3.6.1. Energy Footprint Analysis

Presented in this section are the total energy footprint results. Initially calculated were the energy multipliers of different construction sectors. Among the construction sectors, R-MR had the highest energy multiplier compared to other sectors. Following this sector was the R-PSMFS and NR-MR, respectively (see Fig. 13a). The analysis results also show that less than 40 % of total energy footprint can be attributed to direct or on-site construction activities (represented by L1) for all construction sectors. To give an example, for R-MR, about one third of total energy consumption is found to be in L1, whereas two thirds (63 %) of total energy utilization can be attributed to indirect suppliers of this sector, which are located in L2, L3 and higher layers of the supply chain. For R-OTR, about 25 % of total energy consumption can be attributed to on-site construction processes, whereas 75 % of total energy use is found to be in higher order suppliers. For this reason, it is should be note that although energy efficiency of on-site construction activities are important for residential and non-residential sectors, supply-chain based energy consumption still has a dominant impact on overall energy footprint. Based on total energy consumption results, R-PSMFS and NR-OTR sectors show the largest energy footprint values compared to other construction sectors (see Fig. 13b).

Analysis results also show that the U.S. sectors, including “Electric Power Generation, Transmission, and Distribution”, “Cement Manufacturing”, “Truck transportation”, “Petroleum refineries”, “Iron and Steel Mills and Ferro Alloy Manufacturing”, and “Oil and Gas Extraction” have the highest contributions to total energy footprint of U.S. construction industry, and should be considered for more effective energy footprint reduction strategies. For example, the U.S. Green Building Council (USGBC) developed a green building rating system, namely Leadership in Energy and Environmental Design (LEED, 2009). In materials and resources category of this rating system, the use of regionally produced building materials and products receives credit toward LEED certification. The findings of energy footprint analysis also support this credit strategy in order to minimize transportation distance of construction materials since truck transportation is among the top three supply sectors which have the highest share on total energy footprints. Table 6 and 7 also present the direct and indirect energy consumption of R-PSMFS and NR-OTR with major contributing supply chain sectors.

Table 6. Direct plus indirect energy consumption of R-PSMFS per $M economic output

U.S. Economic Sectors	**Energy (TJ)**	**% Contr.**
Residential permanent site single- and multi-family structures	2.26	25.35
Electric power generation, transmission, and distribution	1.52	17.03
Cement manufacturing	0.49	5.47
Truck transportation	0.44	4.92
Petroleum refineries	0.38	4.23
Iron and steel mills and ferroalloy manufacturing	0.35	3.94
Oil and gas extraction	0.19	2.18
Other basic organic chemical manufacturing	0.16	1.88
Sawmills and wood preservation	0.14	1.55
Plastics material and resin manufacturing	0.13	1.42
Paperboard Mills	0.12	1.40
Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying	0.12	1.33
Reconstituted wood product manufacturing	0.11	1.24
Steel product manufacturing from purchased steel	0.10	1.17
All Other Sectors	**2.40**	**26.87**

Table 7. Direct plus indirect energy consumption of NR-OTR per $M economic output

U.S. Economic Sectors	**Energy (TJ)**	**% Contr.**
Other nonresidential structures	3.16	37.88
Electric power generation, transmission, and distribution	1.19	14.25
Petroleum refineries	0.48	5.80
Iron and steel mills and ferroalloy manufacturing	0.39	4.66
Cement manufacturing	0.35	4.15
Truck transportation	0.26	3.10
Oil and gas extraction	0.23	2.77
Other basic organic chemical manufacturing	0.11	1.37
Steel product manufacturing from purchased steel	0.11	1.36
Paperboard Mills	0.11	1.26
Pipeline transportation	0.08	0.94
Plastics material and resin manufacturing	0.08	0.92
Natural gas distribution	0.07	0.79
Air transportation	0.06	0.75
Sawmills and wood preservation	0.06	0.72
Stone mining and quarrying	0.06	0.67
Paper mills	0.05	0.63
Architectural, engineering, and related services	0.05	0.62
Rail transportation	0.05	0.62
Fertilizer manufacturing	0.05	0.55
Brick, tile, and other structural clay product manufacturing	0.04	0.53
Lime and gypsum product manufacturing	0.04	0.52
All other Sectors	**1.21**	**14.62**

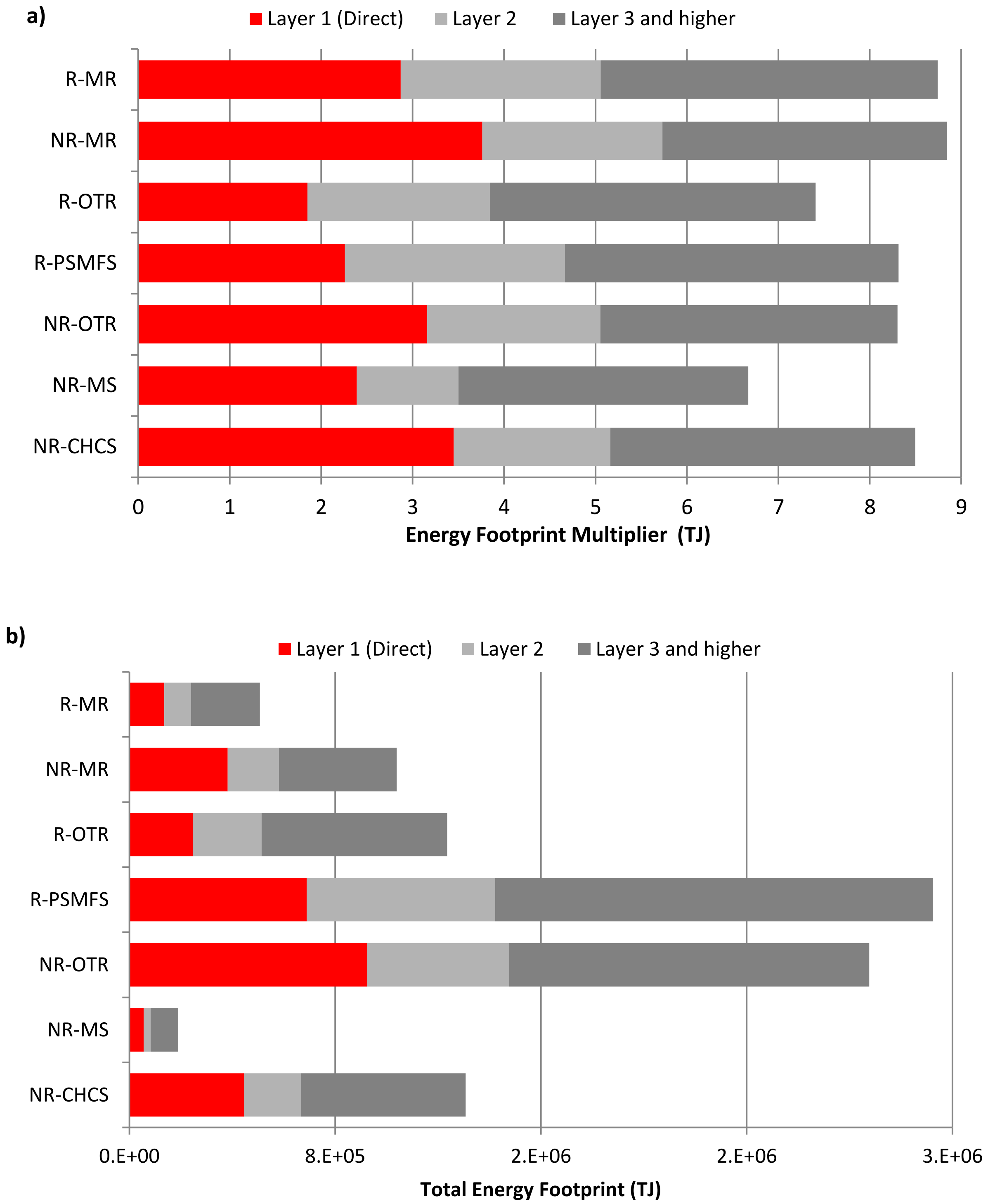


Figure 13. Environmental impacts (a) Energy footprint multiplier (TJ) (b) Total energy footprint (TJ)

3.6.2. Water Footprint Analysis

Fig. 14a also presents the total water multipliers of each construction sector. First, R-MR and R-PSMFS are found to have the highest total water footprint per $M economic output. Among the construction sectors, residential constructions consume higher amounts of water than non-residential construction sectors based on per $M economic activity. In addition, for all construction sectors, on-site construction processes are found to be responsible for less than 5 % of total water consumption, whereas about 95 % of total water use can be attributed to indirect suppliers, which are located in L2, L3 and higher layers. Hence, it is important to note that construction sector uses more on-site than they do off-site. Based on total water footprint results, R-PSMFS and NR-OTR represent the construction sectors with the highest total water consumption amounts (see Fig. 14b).

When analyzing the supply chain of these two construction sectors were more closely, sectors such as, “Electric Power Generation, Transmission, and Distribution”, “Paint and Coating Manufacturing”, “Grain farming”, and” Stone Mining and Quarrying” are found to be responsible for nearly 80 % of total supply chain related water consumption. Especially, direct suppliers (represented by L2) of residential construction sectors are found to be responsible for nearly 40% of water footprint, and the largest portion of this water consumption is attributed to electric power utilization. Therefore, any improvement in electricity consumption through increased energy efficiency or use of non-fossil renewable energy sources might have a considerable impact on minimizing the indirect water consumption. Table 8 and 9 show the direct and indirect water consumption of R-PSMFS and NR-OTR with major contributing supply chain sectors.

Table 8. Direct plus indirect water consumption of R-PSMFS per $M economic output

U.S. Economic Sectors	**Water Use (kgal)**	**% Cont.**
Electric power generation, transmission, and distribution	3528.30	46.22
Paint and coating manufacturing	1118.92	14.66
Grain farming	787.82	10.32
Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying	575.41	7.54
Stone mining and quarrying	422.56	5.54
All other crop farming	211.75	2.77
Cotton farming	159.82	2.09
Residential permanent site single- and multi-family structures	118.00	1.55
Paperboard Mills	97.89	1.28
Other basic organic chemical manufacturing	50.56	0.66
Iron and steel mills and ferroalloy manufacturing	44.13	0.58
Adhesive manufacturing	42.12	0.55
Synthetic dye and pigment manufacturing	32.49	0.43
Fertilizer manufacturing	26.75	0.35
Greenhouse, nursery, and floriculture production	20.13	0.26
Fruit farming	17.83	0.23
All other basic inorganic chemical manufacturing	16.56	0.22
Petroleum refineries	14.79	0.19
Retail trade	13.69	0.18
Gold, silver, and other metal ore mining	13.38	0.18
Sugarcane and sugar beet farming	13.09	0.17
Paper mills	13.07	0.17
Wood kitchen cabinet and countertop manufacturing	12.82	0.17
Iron ore mining	12.34	0.17
All Other Sectors	**268.88**	**3.52**

Table 9. Direct plus indirect water consumption of NR-OTR per $M economic output

U.S. Economic Sectors	**Water (kgal)**	**% Cont.**
Electric power generation, transmission, and distribution	2762.35	53.32
Paint and coating manufacturing	550.62	10.63
Grain farming	468.40	9.04
Stone mining and quarrying	325.15	6.28
Other nonresidential structures	216	4.17
Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying	130.18	2.51
All other crop farming	118.70	2.29
Paperboard Mills	82.96	1.6
Cotton farming	79.54	1.54
Iron and steel mills and ferroalloy manufacturing	48.77	0.94
Other basic organic chemical manufacturing	34.59	0.67
Adhesive manufacturing	20.21	0.39
Petroleum refineries	18.97	0.37
Synthetic dye and pigment manufacturing	18.53	0.36
Fertilizer manufacturing	15.77	0.30
Industrial gas manufacturing	14.51	0.28
Iron ore mining	13.60	0.26
All other basic inorganic chemical manufacturing	12.19	0.24
Gold, silver, and other metal ore mining	11.60	0.22
All Other Sectors	**237.36**	**4.58**

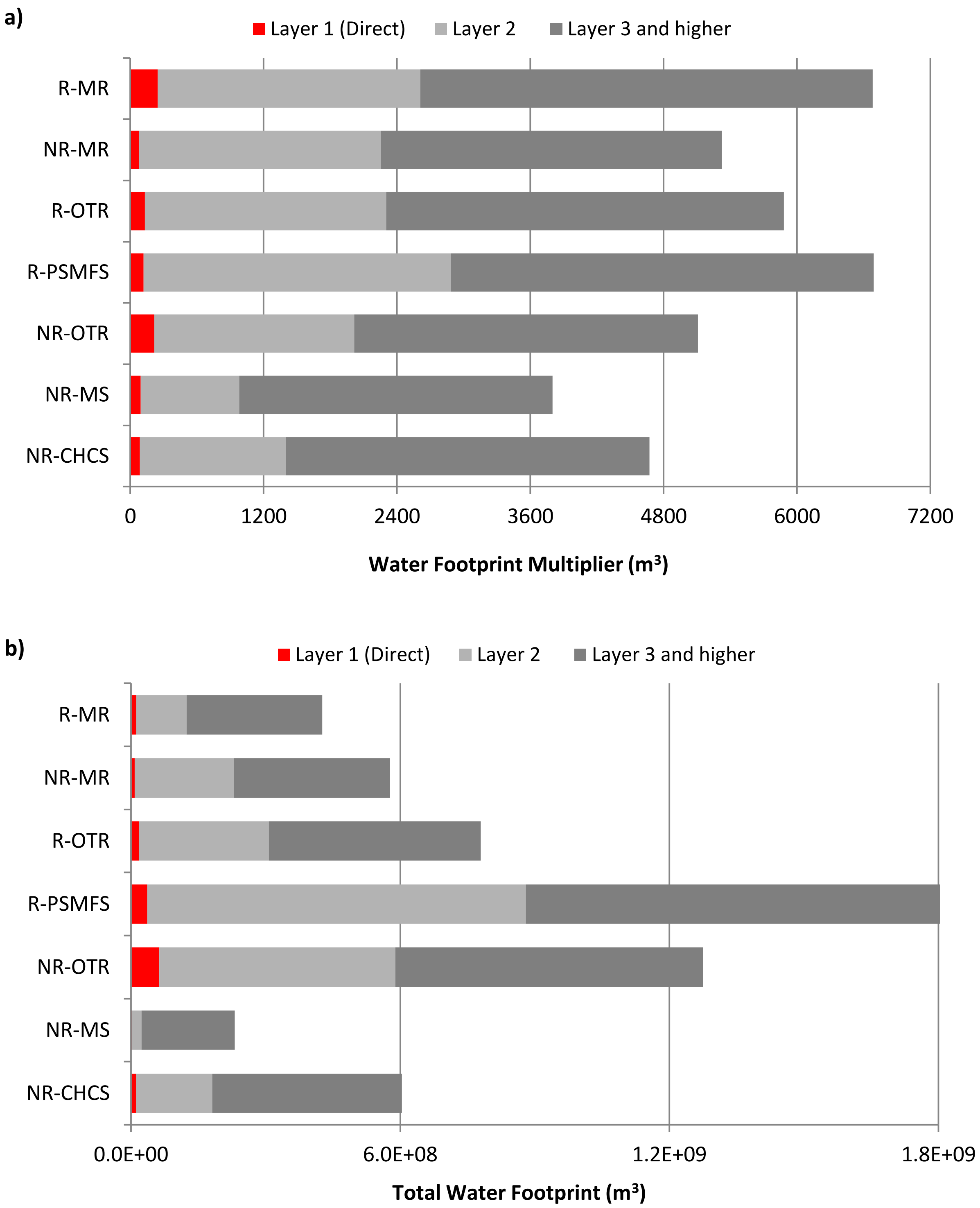


Figure 14. Environmental impacts (a) Water footprint multiplier (m3) b) Total water footprint (m3)

3.6.3. Scope-based Carbon Footprint Analysis

EIO analysis is also able to identify the biggest carbon hot-spots across the entire supply-chain, and past studies suggest that using narrowly-defined system boundaries will generally lead to significant underestimates of carbon emissions for providing products and services (Mathews et al. 2008; Huang et al. 2009b). Hence, the EIO analysis is used to account for the Scope 1, 2 and 3 carbon emissions of different construction sectors.

To have a better insight into the emissions of construction sectors, carbon footprint multiplier, which accounts for the total GHG emissions per $M output of each sector, has been firstly presented in Figure 15a. Analysis results revealed that R-MR, R-PSMFS, and NR-MR are found to have the highest carbon footprint multipliers compared to other construction sectors. For R-MR, NR-OTR, and R-PSMFS, Scope 3 emissions are found to be over 70% of total GHG emissions. In addition, NR-MR and NR-CHCS show the highest Scope 1 emissions due to higher fossil fuel consumption per $M economic output. For all construction sectors, Scope 2 emissions, which account for electricity production related GHG emissions, have the lowest contribution to overall carbon footprint compared to Scope 1 and 3 GHG emissions. Another important point to be made with regard to carbon emissions is that sectors with higher total energy multiplier, such as R-MR, NR-MR, and R-PSMFS show high total carbon footprint multiplier in respect to other sectors. This is basically due to the fact that carbon footprint calculations of construction sectors are based on the fossil fuel consumption, such as natural gas, oil and diesel.

Figure 15b presents the total carbon footprint results based on different scopes. R-PSMFS have the highest amount of carbon footprint in comparison with others. This sector is followed by NR-OTR and RS-OTR, respectively. On the contrary, NR-MS and R-MR have the lowest GHG emissions compared to other construction sectors. Although the latter has the highest total carbon footprint per M$ economic output, it is found to have the lowest total GHG emissions due to its low economic output.

As can be seen from previous discussion, Scope 3 emissions are responsible for the highest GHG emissions compared to Scope 1 and 2. It is critical to note that although energy reduction in on-site construction activities through increased energy efficiency of building machinery or reduced electricity consumption is important, the largest portion of total carbon footprint is still found in the supply chain of these sectors. Therefore, the improvements aiming to minimize the supply chain related carbon footprints can make a significant impact on overall carbon emissions. When looked more closely at supply sectors, “Electric Power Generation, Transmission, and Distribution”, “Iron and Steel Mills and Ferroalloy Manufacturing”, “Cement Manufacturing”, “Oil and Gas Extraction”, “Petroleum Refineries”, and “Truck Transportation” sectors are found to have the largest contributions to total Scope 3 emissions. These sectors are approximately responsible for 80% of total Scope 3 emissions for U.S. construction sectors. To achieve a cost-effective carbon footprint reduction, the special focus might be given on these supply chain sectors to minimize the net carbon footprint.

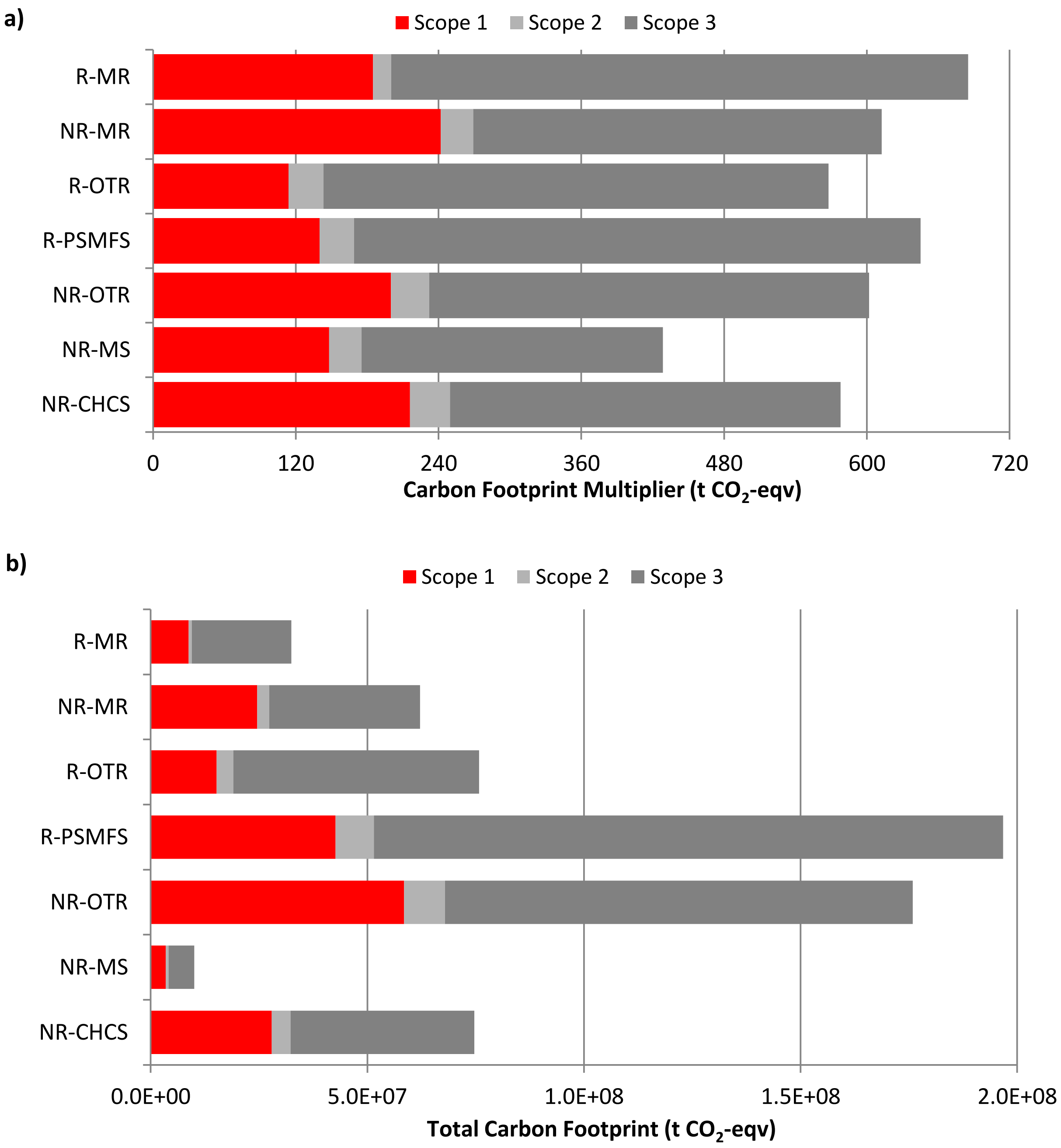


Figure 15. Scope 1, 2 and 3 carbon footprint analysis results (a) Carbon footprint multiplier (t CO_2-eqv) (b) Total carbon footprint (t CO_2-eqv)

3.7. Ecological Footprint Analysis

Presented in this section are the ecological footprint analysis results that are in the unit values of global hectares (gha). First, ecological footprint multiplier, which presents total ecological footprints per $M output of each construction sector, have been quantified, and presented in Fig. 16a. Analysis results reveal that R-MR, R-PSMFS, and R-OTR have the highest total ecological footprint multiplier in comparison with non-residential construction sectors. On the contrary, three non-residential construction sectors, such as NR-MS, NR-CHCS and NR-OTR are found to have the lowest total ecological footprint per $M economic output. Among the ecological footprint categories, CO_2 uptake land, which is required for sequestering CO_2 emissions related to fossil fuel combustion and electricity generation, is responsible for the highest ecological footprint for all construction sectors. Followed by this is both the cropland and forestry land footprints, respectively. On the other hand, total fishery and grazing land footprints are found to be minimal when compared to other ecological footprint categories.

Fig. 16b also presents the total ecological footprints of U.S. construction sectors based on their total economic outputs. The results indicate that R-PSMFS and NR-OTR are found to have the largest ecological footprints, respectively. On the contrary, NR-MS and R-MR have the lowest cumulative ecological footprint compared to other sectors. Although the latter has the highest total ecological footprint multiplier, it shows the lowest cumulative ecological footprint due to a low total economic output. In general, total forestland footprints are found to be higher for residential construction sectors. This result can be related to the higher use of wood products such as timber in building construction as opposed to heavy construction. Among the ecological footprint categories, CO_2 uptake lands represent the highest land consumption values for all residential and non-residential construction sectors. Therefore, special emphasis should be placed on reducing the total GHG emissions by considering the Scope 3 carbon footprints which have the largest share.

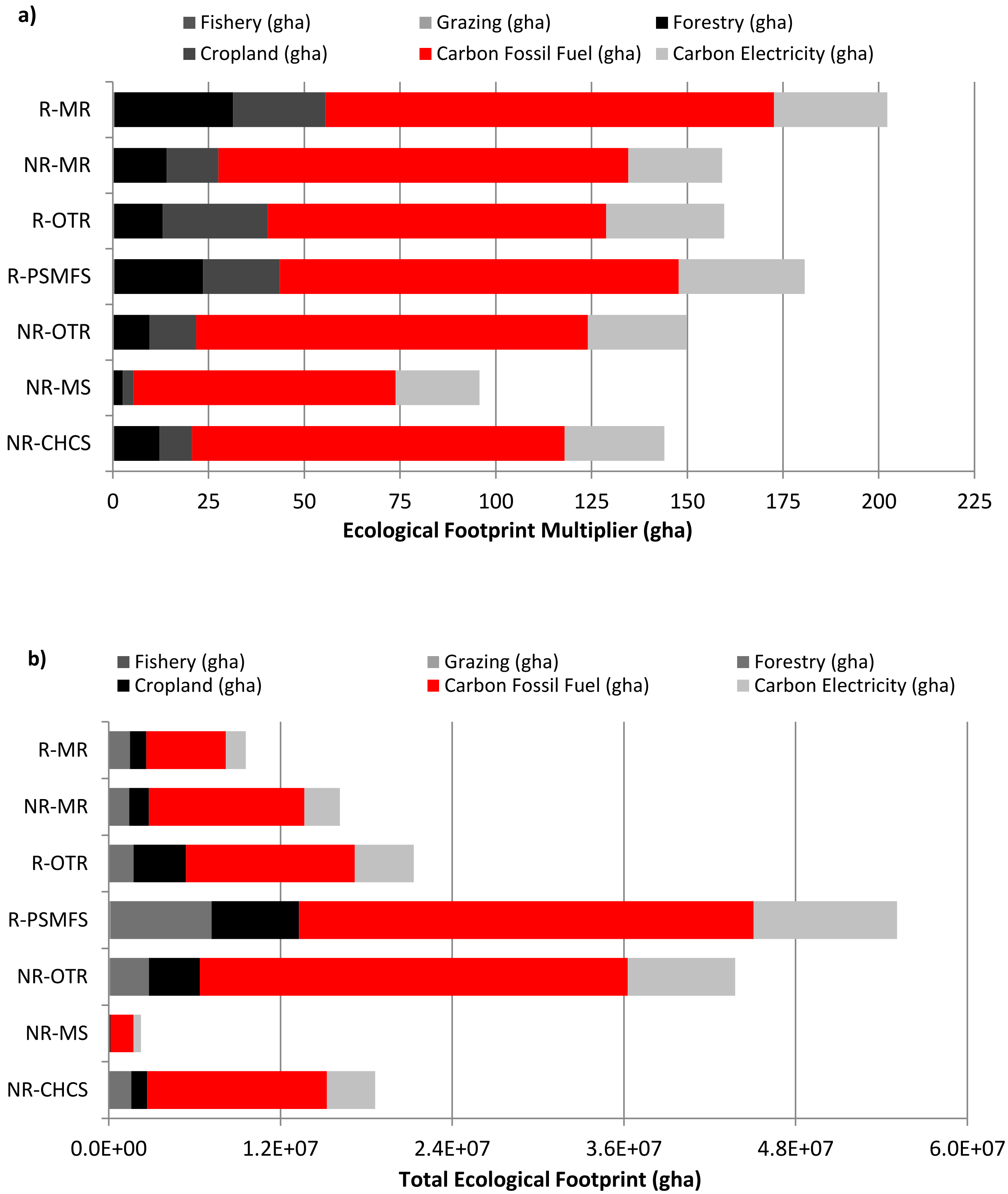


Figure 16. Ecological impacts (a) Ecological footprint multiplier (gha) (b) Total ecological footprint (gha)

CHAPTER 4. TRIPLE BOTTOM LINE LIFE CYCLE ANALYSIS OF THE U.S. RESIDENTIAL BUILDINGS

4.1. General Remarks

The demand for sustainable development is rapidly increasing owing to increased consciousness of environmental, economic, and social concerns. What triggers and creates the problems of human race is that the society and individuals try to maximize their benefit without limiting their short-term gains, while the environment is deteriorated in long-term (Hardin 1968). Understanding the essence of sustainability is vital to solve the problems of the society and the environment. Informing the most effective decision makers such as United Nations (UN), government organizations, and industry leaders should be one of priorities to achieve the goals sustainable development. In this regard, LCA is an important tool which is capable to quantify environmental impacts of decisions through all of the life cycle phases (Kibert 2012a).

The U.S. buildings consume significant amount of energy and natural resources through all of their life cycle phases from construction to disposal. For example, construction sectors are the largest raw material consumers in mass (USGS 2009). Energy consumption of residential buildings accounts for roughly 40% of the total U.S. energy consumption in 2012 (EIA 2013). 30% of landfill content is composed of construction demolition and debris (NRC 2009). Building construction and operations are responsible for 38.9% of GHGs emitted in the U.S. (EIA 2008).

Residential buildings are also important components of the U.S. economy considering the large volume of economic activity as a result of building related needs of the occupants such as energy consumption (electricity, natural gas, petroleum), transportation (commuting), water use, maintenance and repair of the buildings, and construction of the buildings (Onat et al. 2013b). Additionally, construction industry is one of the driving sectors in the U.S. economy. The total construction spending in 2012 was 865,989 millions of dollars (U.S. Census 2012). Hence, sustainability of the buildings should be assessed considering environmental and economic constraints, limits of natural resources, social and political effects (Kibert 2012b).

4.2. Motivation and Organization of the Chapter

The U.S. buildings consume significant amount of energy and natural resources as well as provide direct and indirect social and economic impacts through all of their life cycle phases. Analysis of these impacts stimulated a tremendous interest by policy makers to propose economically viable, socially acceptable and environmentally friendly green building strategies. In this regard, current research aims to identify and outline economic, social and environmental impacts of the U.S. residential and commercial buildings from cradle to grave encompassing building construction, operation and disposal, and supply chain of those phases.

Although previous studies analyzed the life cycle environmental impacts successfully, there is no study assessing and quantifying social and economic interventions of the U.S. residential buildings holistically. To realize this goal, TBL-LCA model is utilized for assessing building sustainability. In this analysis, residential buildings are composed of single and multi-family structures. Medical buildings, hospitals, special care buildings, office buildings, including financial buildings, multi-merchandise shopping, beverage and food establishments, warehouses, and other commercial structures are classified as commercial buildings according to the U.S. Department of Commence detailed output accounts (BEA 2008).

Organization of the chapter is explained as follows. First, the EIO methodology is explained mathematically. Next, data collection is briefly explained. In the following subsection, sustainability indicators of the TBL-LCA model are presented. Then, TBL sustainability impacts of the residential buildings are presented with details. Next, sensitivity analysis of critical input parameters is conducted. Finally, results are discussed and the future work is pointed out.

4.3. Data Collection

Data used in this research is collected mainly from publicly available sources such as the U.S. Bureau of Economic Analysis (BEA), the Federal Highway Administration (FHWA), the U.S. Environmental Protection Agency (EPA), the U.S. Department of Energy (DOE) and the U.S. Energy Information Administration (EIA). Some of the data is collected through former studies in the literature. Table 10 shows majority of the data sources with corresponding data sources (Onat et al. 2013a). Rest of the data sources are presented within this section.

Table 10. Data source for residential buildings

Parameters	Unit	Amount	Data source
Electricity use	Billion Kwh	1265	EIA (2012a)
Electricity price	Cents/Kwh	8.44	EIA (2012a)
Natural gas use	Billion scf	4889	EIA (2012b)
Natural gas price	$/scf	7.89	EIA (2012b)
Petroleum use	MBL/day	817	EIA (2012a)
Petroleum price	$/MBL	27.56	EIA (2012a)
Water use and wastewater	Billion gal.	10,486	Building Energy Data Book (2005a),(2005b)
Water and wastewater price	$/kgal	4.43	Fisher et al. (2008)
Building Maintenance and repair	Million($)	47,379	BEA (2002)
Building construction	Million($)	304,950	BEA (2002)
Total commuting distance	Million miles	615,000	FHWA (2002a)
Average national gas consumption	Mpg	22	FHWA (2002b)
Automobile maintenance and repair costs	$/mile	0.13/mile	Transportation Energy Databook (2011a), (2011b)
Injuries during commuting	Number of people	123170	BEA (2012)
Natural gas energy density factor	J/SCF	1.1×10^6	Wilcock (2005)
Petroleum energy density factor	J/gal	120000	DOE (2013)
Hazardous waste multipliers	t/$	Vary for each activity	CMU (2002)
Other sustainability multipliers	Indicator unit/$	Vary for each activity	TBL-LCA

Majority of data used in the analysis can be divided into two main category based on the intended use. First intention was to determine process-based sustainability impacts such as GHGs emitted as a result of fossil fuel combustion in buildings. The process based emission factors are obtained from the Greenhouse Gas Inventory Protocol (Climate Leaders 2008). The second aim was to find supply chain emissions and some of the process emissions at sector level such as fossil fuel combustion to generate electricity in the power plants which are in the first tier in the supply chain of the electricity generation industry.

In this analysis, the process level data and the sector level data are integrated to find the total sustainability impacts. Hence, a hybrid input-output approach is used. For instance, GHG emissions from combustion of natural gas are calculated with process level data, whereas GHGs emitted from supply chain of natural gas production are determined by using sector level data from the TBL-LCA model. On the other hand, the typical processes that are well represented in input-output categories at sector level can be accounted through EIO model, while the rest the processes can be modeled through process level data (Suh et al. 2004). For example, the number of injuries during the commuting activity is collected from process level data, while the injuries recorded in automobile maintenance and repair industry, petroleum production and supply chain of those industries are determined by sector-level data of the TBL-LCA model.

Also, hybrid LCA approach has been used for carbon footprint accounting at county, city and national scales (Peters 2010). Because, EIO models are powerful methods capturing direct and indirect emissions from the entire supply chain which constitutes the economy at large scale (Huang et al. 2009a). Moreover, with the hybrid approaches, it is possible combine the advantages of both the process and EIO models (Suh and Lippiatt 2012).

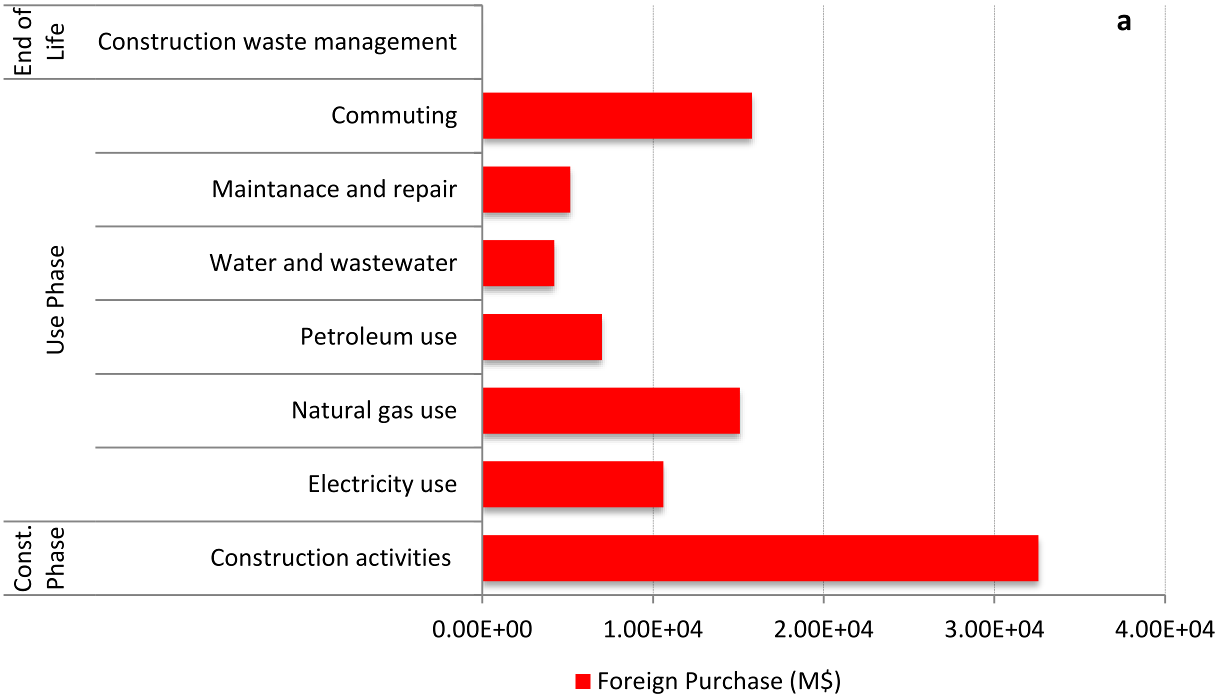
4.4. Sustainability assessment indicators

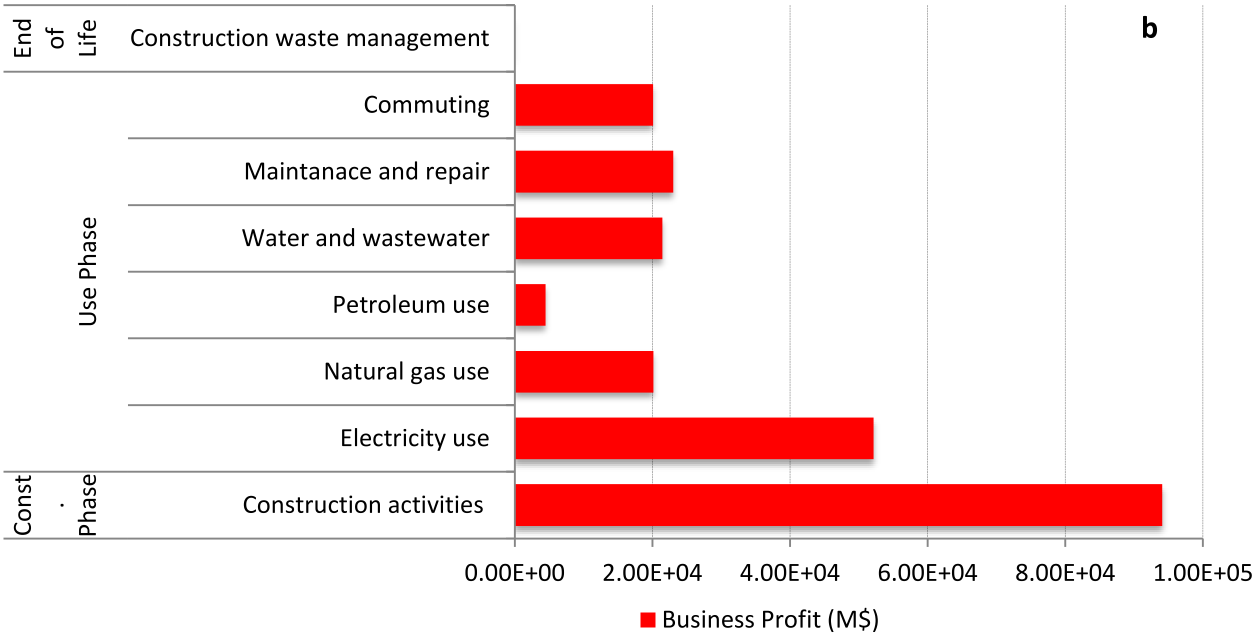
Analysis results are presented in the following sub-sections based on economic, social, and environmental impact categories. The environmental impacts are represented and discussed considering the social and economic impacts of the life cycle components of the U.S. buildings. After quantifying the TBL impacts of residential buildings, sensitivity of the model inputs is analyzed.

4.4.1. Economic Impacts

Fig. 17 indicates the economic impacts of residential buildings. Residential construction phase is the most dominant component among the economic impact categories and life cycle phases of residential buildings. Residential construction sector and its supply chain are responsible for 36% of the import, 40% of the GOS, and 50% of the GDP contribution. Also, electricity use is the second largest contributor to GDP and GOS. That makes the electricity consumption the most positive component of the use phase of residential buildings according to economic indicators.

On the other hand, construction activities, natural gas, and commuting have more negative impact to the U.S. economy considering their import shares, which add up 70% of the total import. Almost 36% of residential construction's imports stems from sectors of oil and gas extraction (NAICS 211000), sawmills and wood preservation (NAICS 321100), iron and steel mills and ferroalloy manufacturing (NAICS 331110), reconstituted wood product manufacturing (NAICS 321219), lighting fixture manufacturing (NAICS 335120), and motor vehicle parts manufacturing (NAICS 336300). These sectors constitute the top five in the supply chain of residential construction rector. However, contribution of these supply chain sectors to the GDP and GOS of the residential construction is very low compared to their negative impacts to the economy. More than 40% of the residential construction phase's contribution to GDP and import is coming from the residential building construction sector (NAICS 230201) and its supply chain sectors such as real estate (NAICS 531000) and retail trade (NAICS 4A0000).


a
End of Life
Construction waste management
Use Phase
Commuting
Maintanace and repair
Water and wastewater
Petroleum use
Natural gas use
Electricity use
Const. Phase
Construction activities
0.00E+00
1.00E+04
2.00E+04
3.00E+04
4.00E+04
🟥 Foreign Purchase (M$)


b
End of Life
Construction waste management
Use Phase
Commuting
Maintanace and repair
Water and wastewater
Petroleum use
Natural gas use
Electricity use
Const. Phase
Construction activities
0.00E+00
2.00E+04
4.00E+04
6.00E+04
8.00E+04
1.00E+05
🟥 Business Profit (M$)

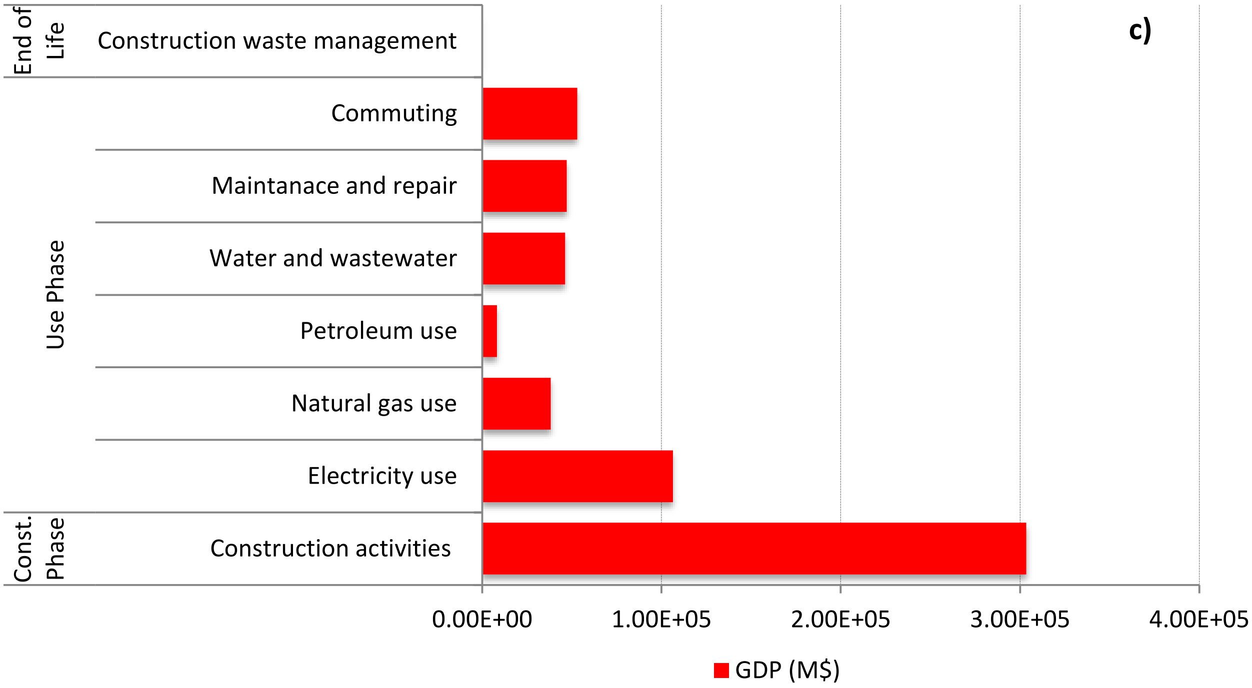
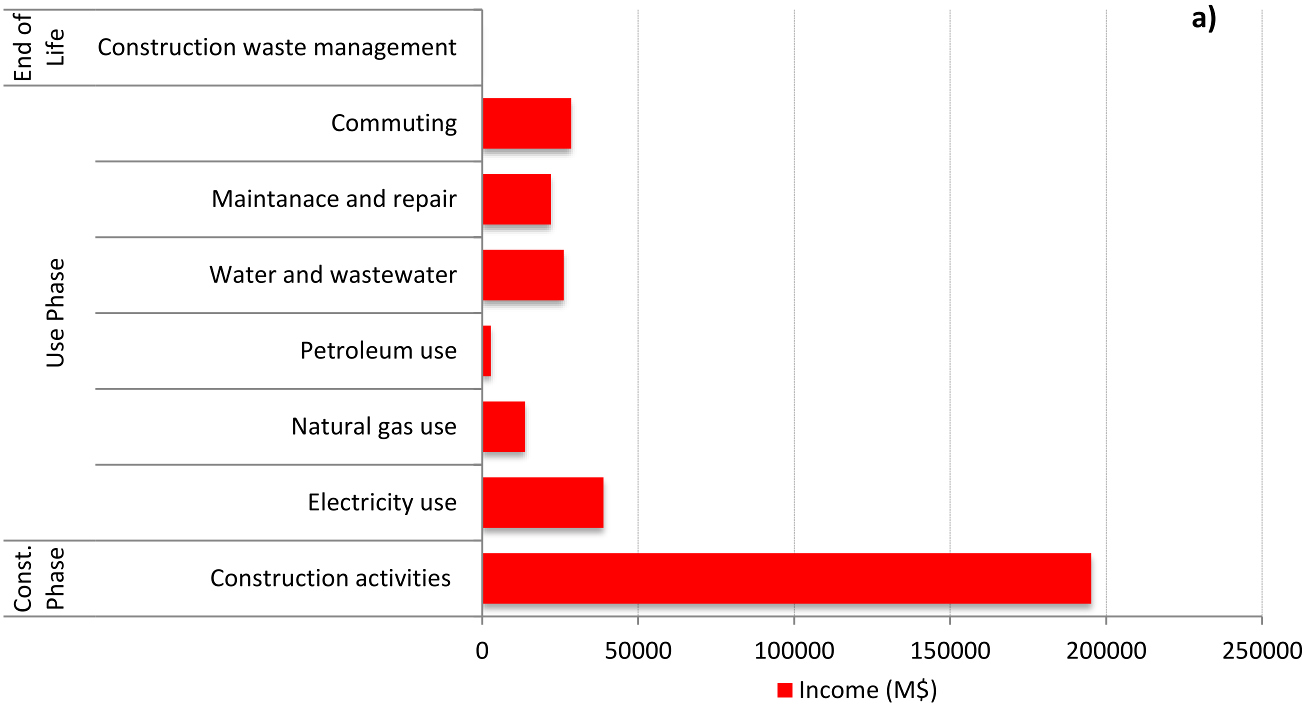


Figure 17. Economic impacts of residential buildings (a) Import (b) GOS (c) GDP

4.4.2. Social Impacts

Social impacts of residential buildings are represented in Fig. 18. Construction phase has the largest share in income category with 60% of the total income generated through residential building's life cycle. Almost half of the residential construction phase income is produced by supply chain of the residential building construction sector (NAICS 230201). Also, electricity use, construction activities, and commuting are the driving components of the government tax category with 85% of the total. On the contrary, construction sectors and commuting are responsible for more than 80% of the injuries. 50% of residential construction related injuries are direct on-site injuries. In general, construction phase is one of the most critical components of social impacts of residential buildings compared to other components.



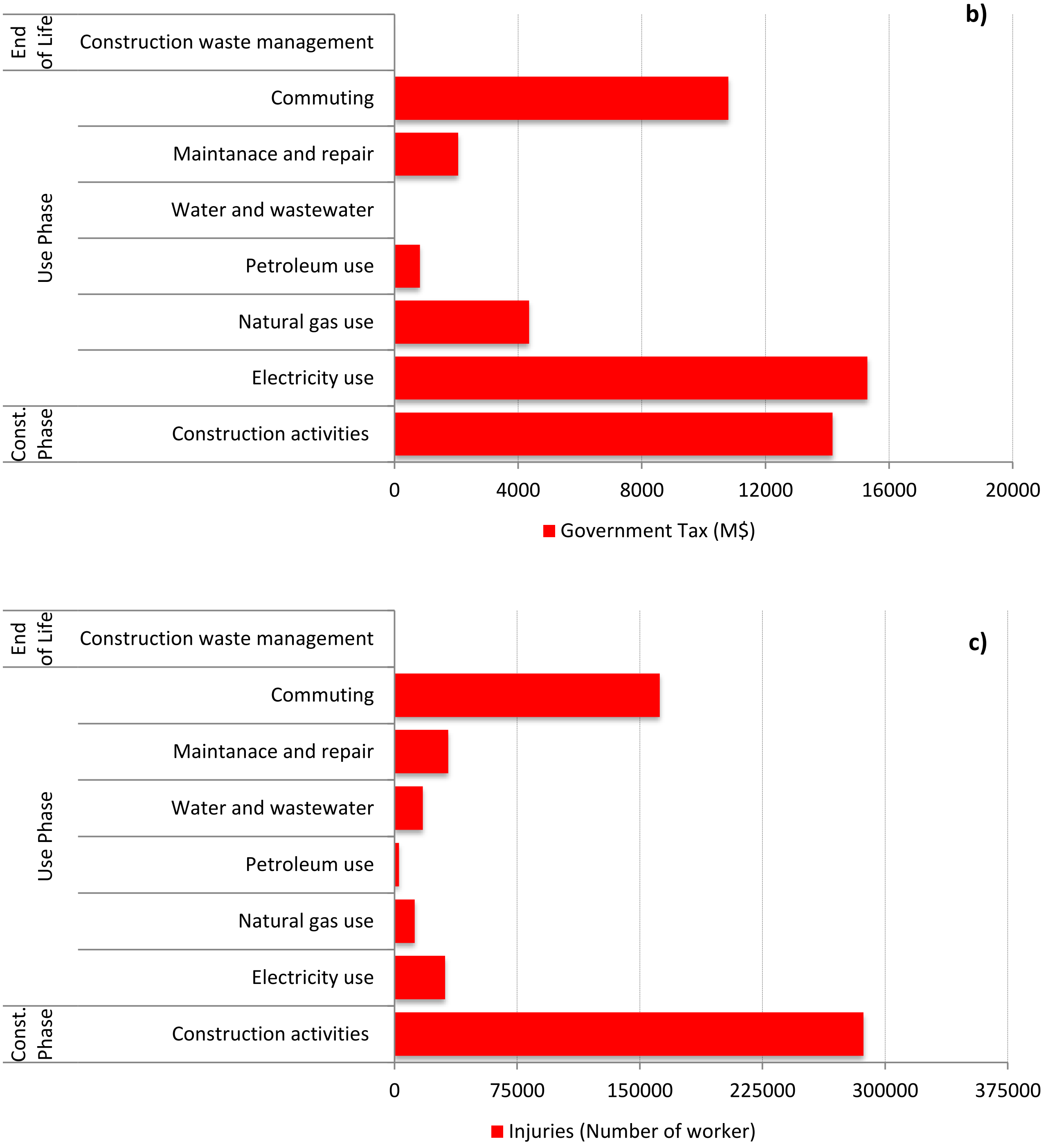
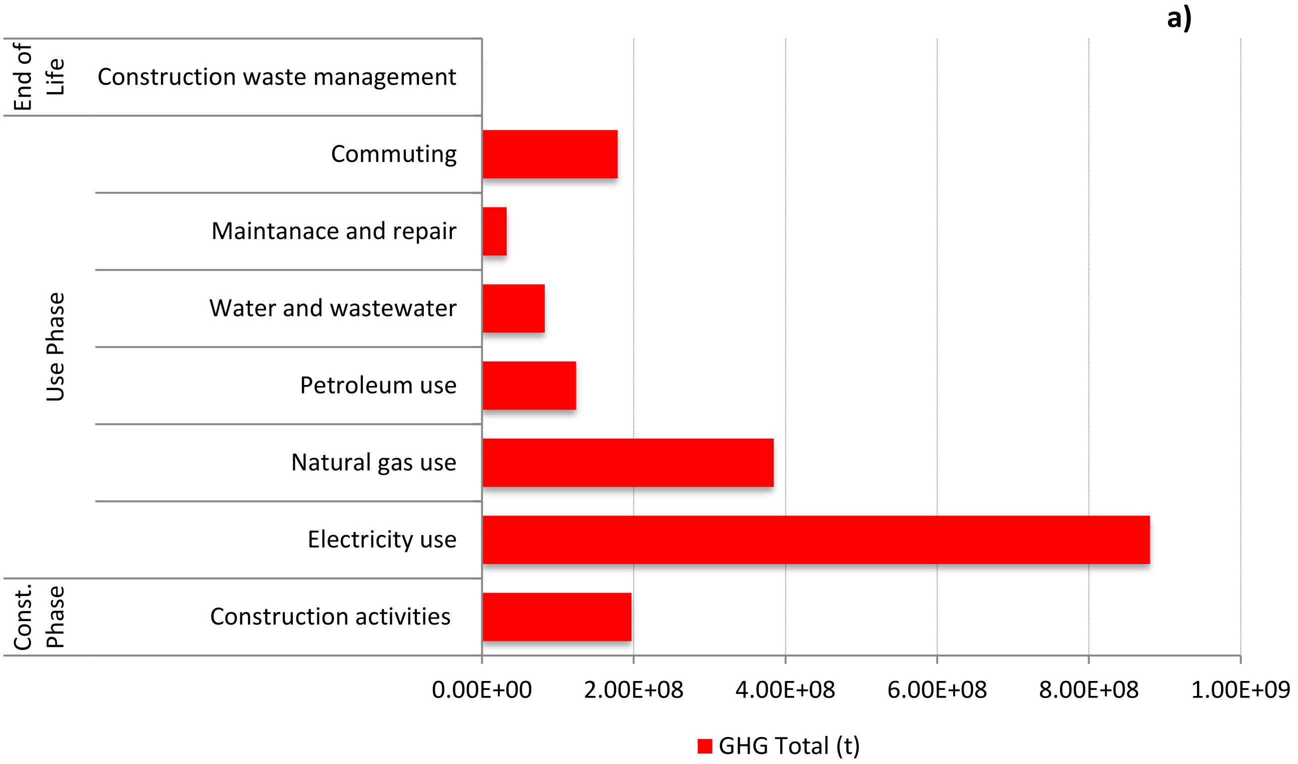


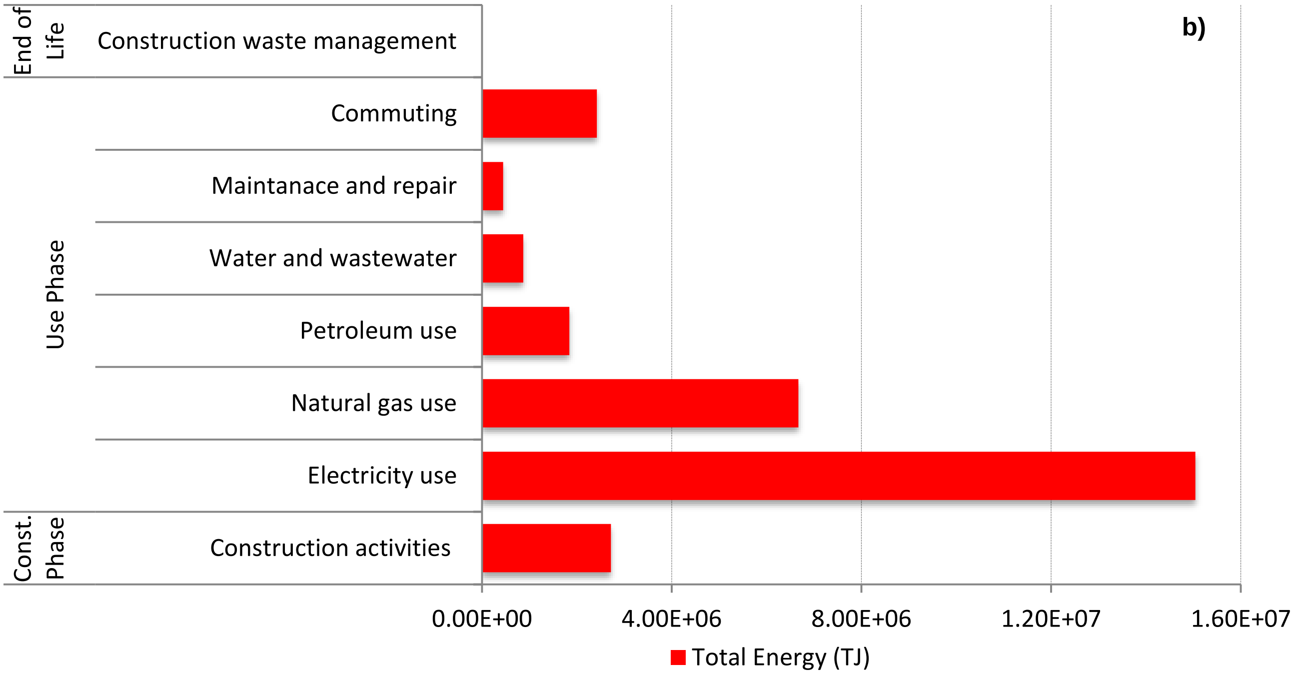
Figure 18. Social impacts of residential buildings (a) Income (b) Government Tax (c) Injuries

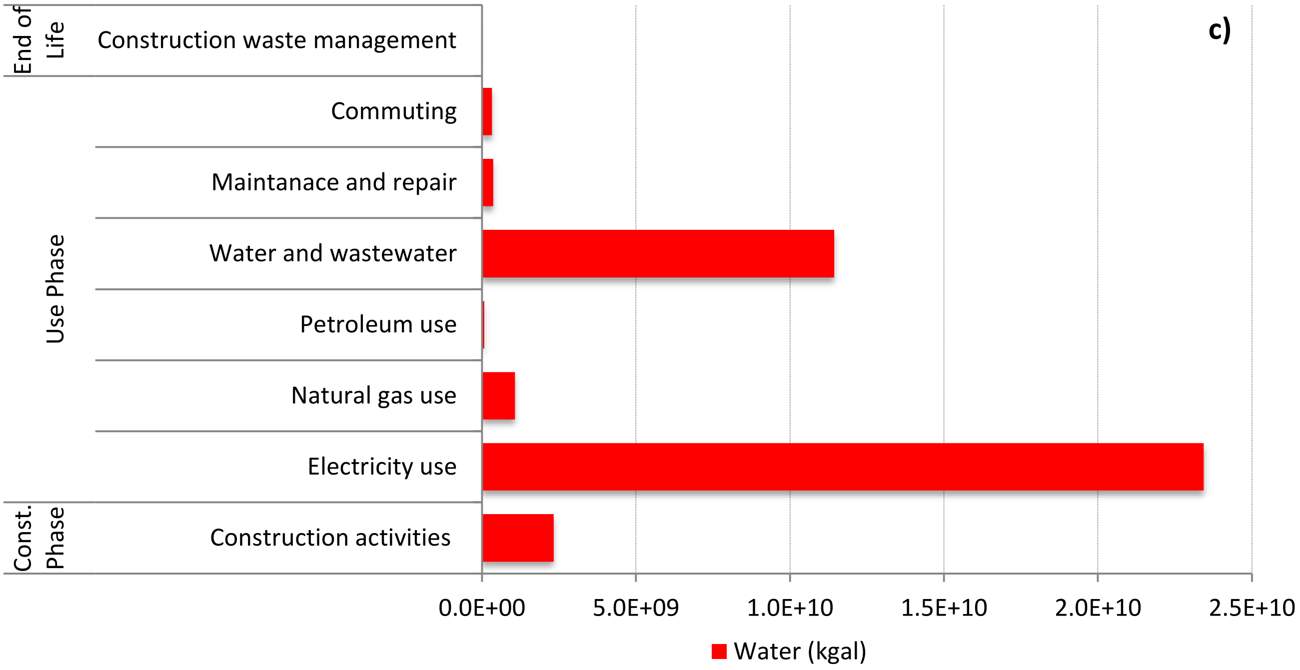
4.4.3. Environmental impacts

Fig. 19 indicates the environmental impacts of residential buildings. According to the analysis results, natural gas and electricity use account for 72% and 78% of the total energy consumed in the residential buildings, respectively. Also, the electricity use is the most dominant component of the environmental impacts with more than 50% of GHGs emitted and energy used through all life stages of the U.S. buildings. Although electricity use can be the first domain needs to be focused on due to high carbon footprint and energy consumption, its contribution to GDP, GOS and government tax should be taken into account and the trade-off among the TBL impacts should be optimized.

When making policies to reduce environmental impacts of electricity consumption, its supply chain and factors triggering the high share of environmental impacts of electricity consumption should be analyzed. Some of the main reasons of high carbon footprint share of electricity consumption are related to high use of fossil fuels for electricity generation, losses in electricity transmission lines, and poor energy efficiency of existing building stock. Moreover, electricity generation is responsible for 60% of the total water withdrawal of residential buildings, which is even greater than the direct water consumption in residential buildings.


a)
End of Life
Construction waste management
Use Phase
Commuting
Maintanace and repair
Water and wastewater
Petroleum use
Natural gas use
Electricity use
Const. Phase
Construction activities
0.00E+00
2.00E+08
4.00E+08
6.00E+08
8.00E+08
1.00E+09
🟥 GHG Total (t)


b)
End of Life
Construction waste management
Use Phase
Commuting
Maintanace and repair
Water and wastewater
Petroleum use
Natural gas use
Electricity use
Const. Phase
Construction activities
0.00E+00
4.00E+06
8.00E+06
1.20E+07
1.60E+07
🟥 Total Energy (TJ)



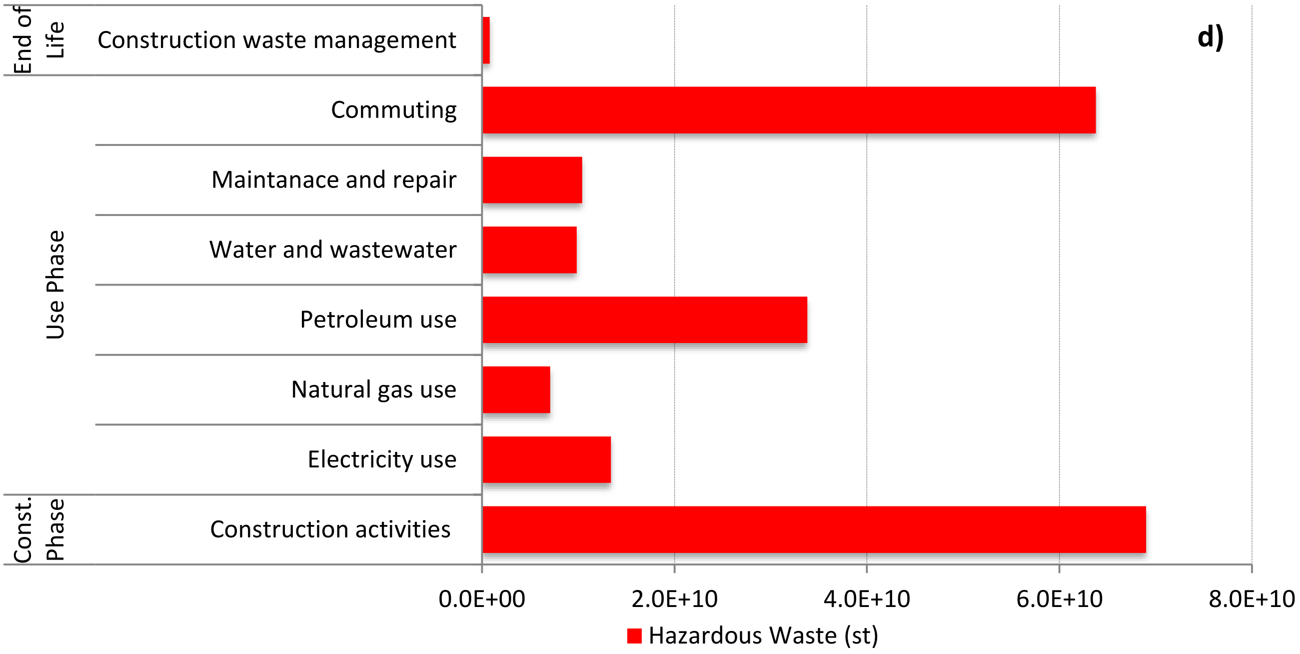


Figure 19. Environmental impact results of residential buildings (a) GHG (b) Total Energy (c) Water (d) Hazardous Waste

Construction activities and commuting are the major hazardous waste sources in residential buildings. When the supply chain of the these construction sectors are analyzed through the EIO-LCA model, sectors of petroleum refineries (NAICS 324110), basic organic chemical manufacturing (NAICS 325190), plastics material and resin manufacturing (NAICS 325211), and iron and steel mills (NAICS 331110) are found as the major drivers of the hazardous waste generation in construction activities. Those sectors constitute 81% of the total hazardous waste of the residential construction sector. In addition, hazardous waste of the commuting activity is also another significant component for residential construction. Petroleum refineries (NAICS 324110) and automotive maintenance and repair sectors (NAICS 8111A0) are responsible for approximately 88% and 12% of the commuting related hazardous waste, respectively.

As can be seen from Fig. 20, electricity use has the highest ecological footprint, which made up 45% and 54% of the ecological footprints of residential buildings, respectively. High use of fossil fuels in power generation sector (NAICS 221100) is the primary reason of its high ecological footprint. Effectiveness of fossil fuel combustion on ecological footprints can be realized from CO_2 uptake land footprint which made up over 90% of the total ecological footprint of the U.S. residential buildings. It is also the largest contributor to the world’s current ecological footprint (GFN 2010).

The total CO_2 uptake land footprint of the U.S. buildings is calculated as 7.E+08 gha, which is approximately 1.3 times greater than the land area of Amazon rainforest. In other words, the area of the forestland required to sequester CO_2 emissions of the U.S. residential buildings is equal to a forestland that is 1.3 times greater than the Amazon rainforest. Carbon electricity, forestland, and cropland footprints are effective on ecological footprint of construction phases, building maintenance and repair, and commuting while their effect on other life cycle components are negligible compared to that of CO_2 uptake land. Fishery footprints of the U.S. residential buildings are found to be less than 1%.

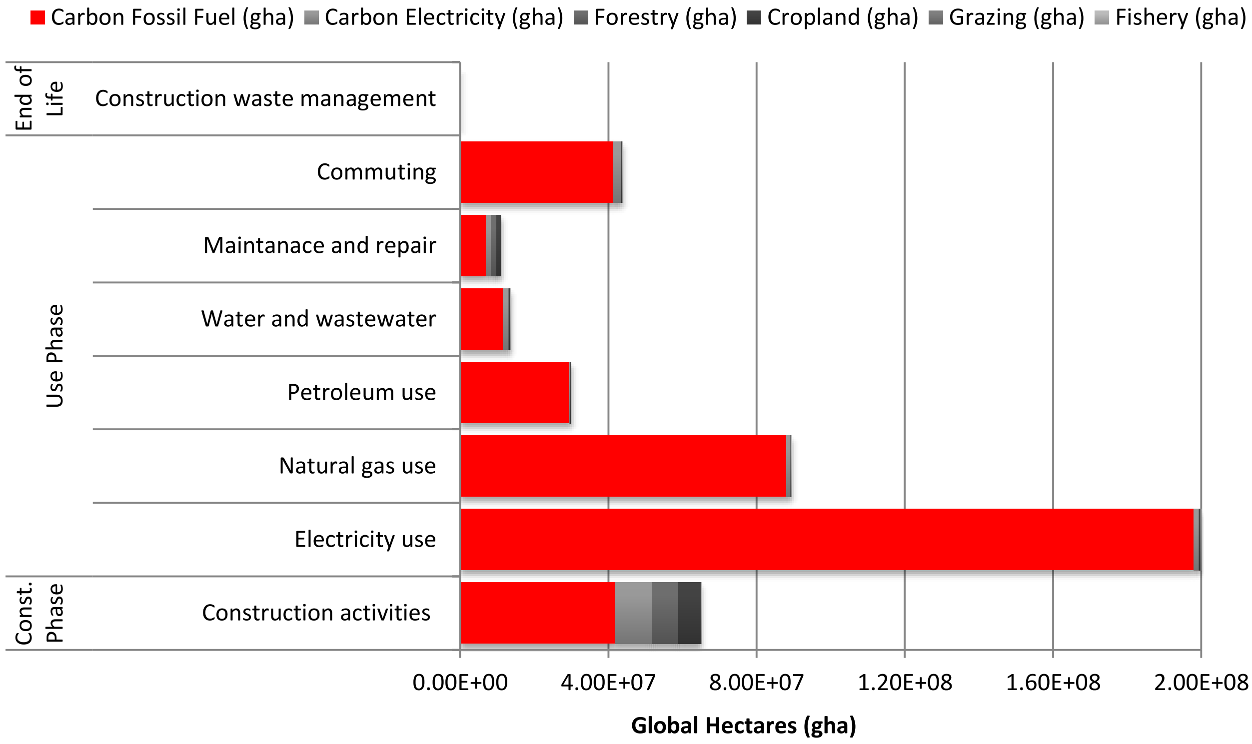


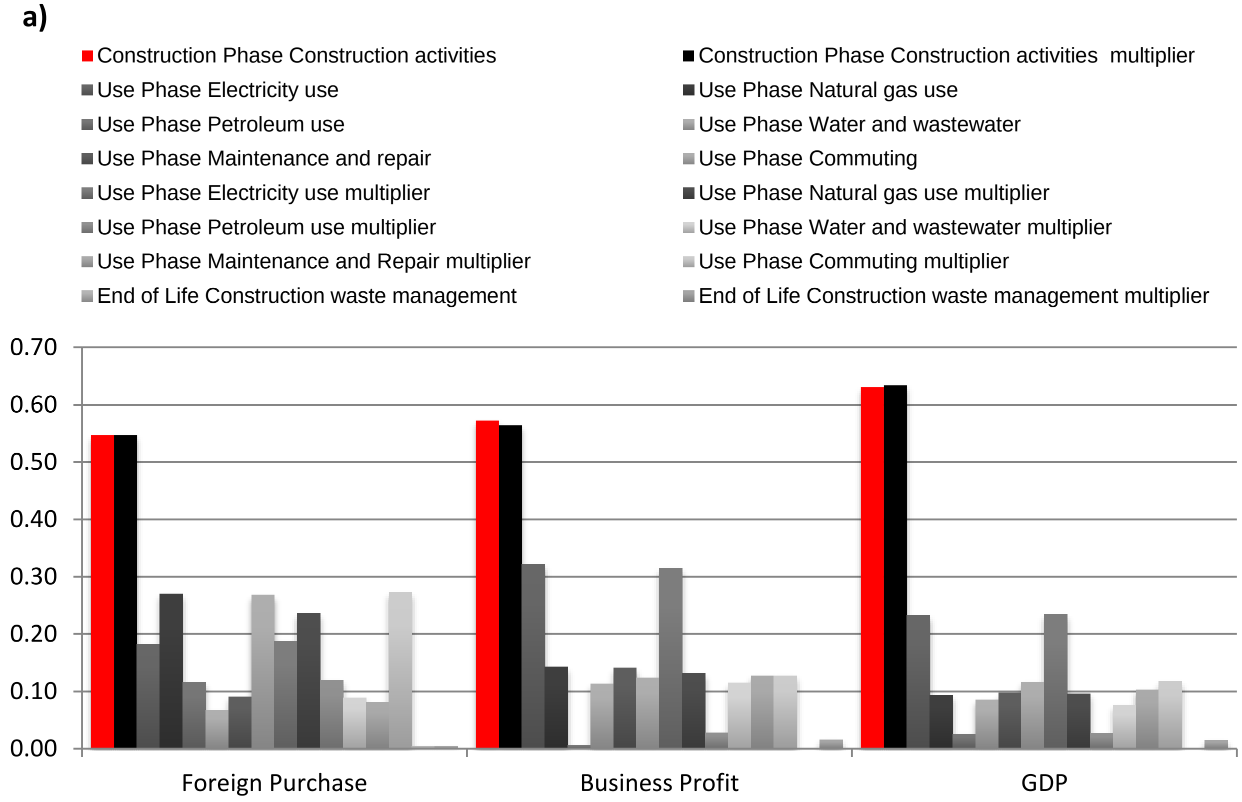
Figure 20. Ecological footprint results for residential buildings

4.5. Sensitivity Analysis

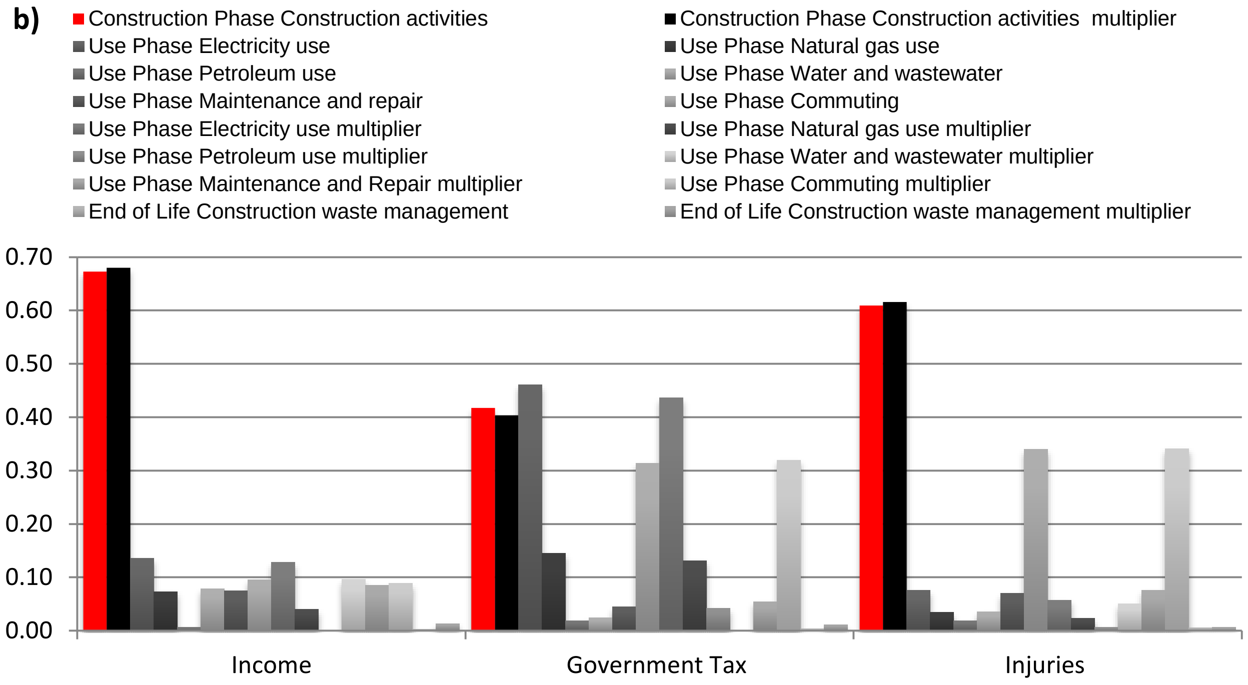
Monte Carlo analysis was conducted to measure the sensitivity of each input dataset of residential buildings. The correlation between the inputs and the total sustainability impacts by category were investigated. Similar sensitivity analysis was also conducted by Tatari et al. (2012). The software utilized to run Monte Carlo simulation was Risk Solver Pro (Frontline Solvers 2013). The model inputs were divided into two main categories. First input type was the economic output of sectors related with life cycle component of the U.S. buildings. These inputs were calculated by using the data given in the Table 6. For instance, after calculating the deterministic monetary value of the petroleum use, a normal distribution whose standard deviation is 10% of the average was assigned to petroleum refineries sector (NAICS 324110) in the TBL-LCA model. Deterministic values of the inputs were assumed as the average values of the distributions. Same method applied to the all sectors representing the life cycle components.

The other variable type used in the sensitivity analysis is the multipliers. In the TBL-LCA model, multipliers represent the direct plus indirect sustainability impacts (e.g., carbon footprint, income, energy use) per $M output of each sector. These multipliers incorporate the characteristics of sectors including their technological level. In addition, the multipliers were improved by including the impacts of some of the processes that are not presented in the TBL-LCA model such as emissions from electricity production in the power plant.

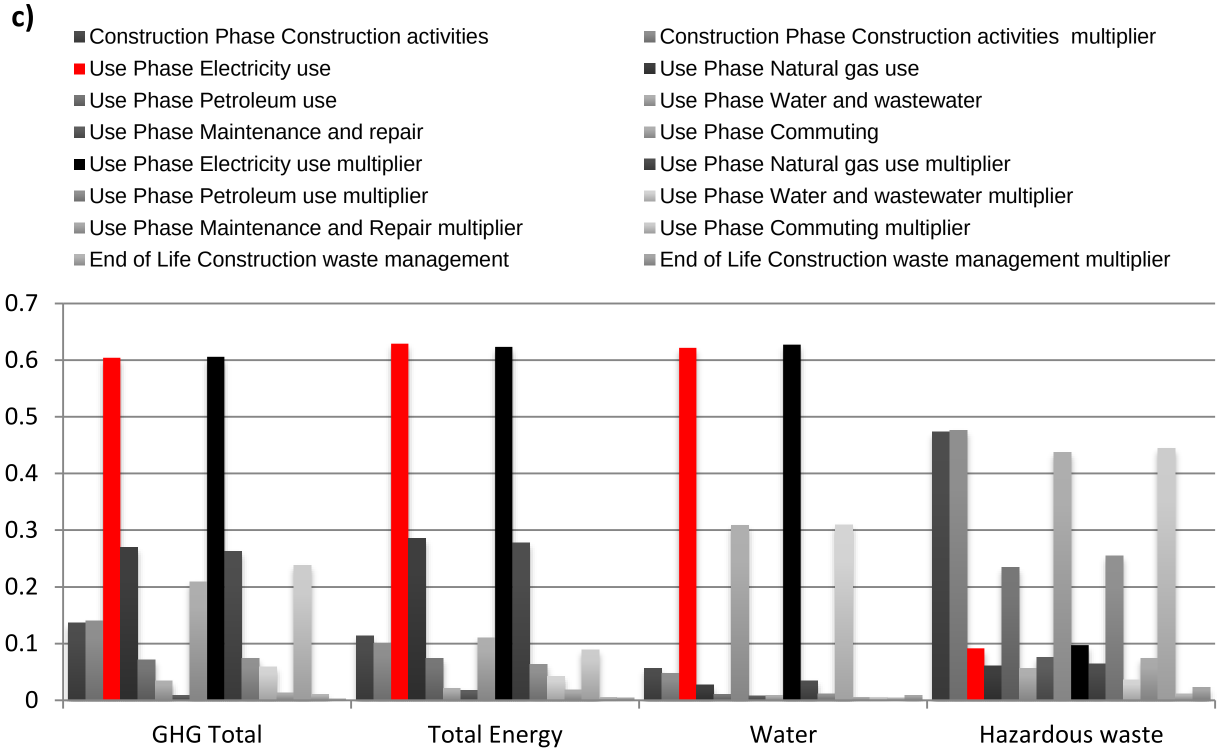
After presenting the multipliers, a normal distribution whose standard deviation is 10% of the average was assigned to the all multipliers. In total, 16 inputs were defined and 10,000 iterations were made in the Monte Carlo simulation. Fig. 21 illustrates the associated sensitivity results by showing how each of the input parameters correlates with the total sustainability impact for each category.



b)


Construction Phase Construction activities
Construction Phase Construction activities multiplier
Use Phase Electricity use
Use Phase Natural gas use
Use Phase Petroleum use
Use Phase Water and wastewater
Use Phase Maintenance and repair
Use Phase Commuting
Use Phase Electricity use multiplier
Use Phase Natural gas use multiplier
Use Phase Petroleum use multiplier
Use Phase Water and wastewater multiplier
Use Phase Maintenance and Repair multiplier
Use Phase Commuting multiplier
End of Life Construction waste management
End of Life Construction waste management multiplier
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Income
Government Tax
Injuries

c)


Construction Phase Construction activities
Construction Phase Construction activities multiplier
Use Phase Electricity use
Use Phase Natural gas use
Use Phase Petroleum use
Use Phase Water and wastewater
Use Phase Maintenance and repair
Use Phase Commuting
Use Phase Electricity use multiplier
Use Phase Natural gas use multiplier
Use Phase Petroleum use multiplier
Use Phase Water and wastewater multiplier
Use Phase Maintenance and Repair multiplier
Use Phase Commuting multiplier
End of Life Construction waste management
End of Life Construction waste management multiplier
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
GHG Total
Total Energy
Water
Hazardous waste

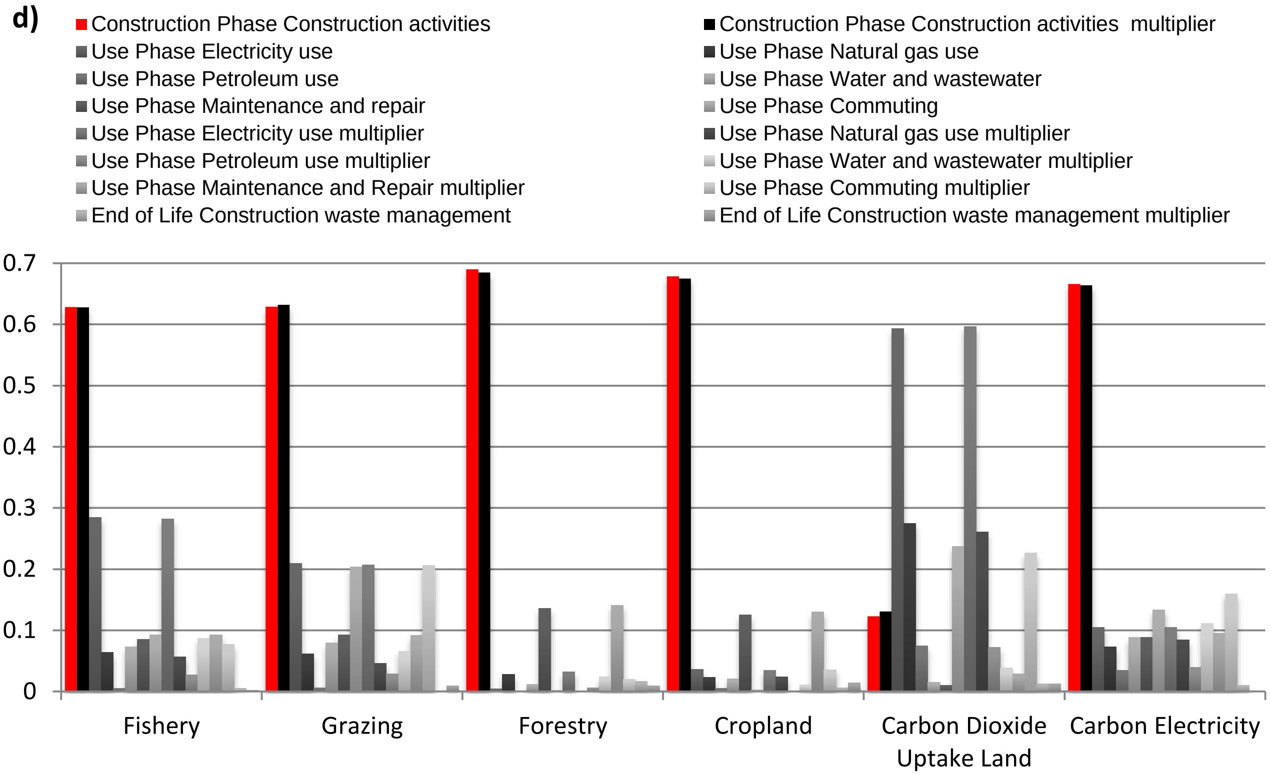


Figure 21. Sensitivity analysis of critical input parameters of U.S. residential buildings (a) Economic (b) Social (c) Environmental (d) Ecological

Higher magnitude of correlation demonstrates that there is a stronger relationship between the input variable and the total amount of a sustainability impact by category. According to the sensitivity analysis results, the most sensitive parameters are construction activities and its multiplier in majority of the sustainability impact categories. Especially, social, economic, and environmental impacts are highly correlated with the economic output and multiplier of the residential construction sector. In other words, any improvement in residential construction sector might be a sound strategy to improve overall social, economic and ecological impacts of the U.S. residential buildings.

However, over 90% of ecological footprint of residential buildings is related to CO_2 uptake land. In this sense, high correlation between electricity demand and CO_2 uptake land shows that improvements in electricity use and its multiplier can be a better strategy to reduce total ecological footprint of residential buildings. Moreover, sensitivity of electricity and its multiplier is also higher in sustainability impact categories of total GHG emissions, energy use, and water consumption. Hence, this analysis identified that possible reductions in electricity consumption and improvements in electricity multiplier is a vital strategy to reduce the environmental impacts of residential buildings. Improving the electricity multiplier means reducing the environmental impacts per $M output of electric power generation sector. This can be achieved by increased energy efficiency of power generation sector and shifting to renewable energy sources to generate clean electricity. Also, on-site renewable energy systems can be a sound strategy to avoid energy losses in the transmission lines, which is almost 6.5 % of the electricity generated at power plants (Building Energy DataBook, 2010).

CHAPTER 5. TRIPLE BOTTOM LINE LIFE CYCLE ANALYSIS OF PAVEMENT DESIGNS

5.1. General Remarks

The United States' road system has one of the greatest network size and usage density in the world with its immense statistics such as four million miles of network size and three million vehicle miles travelled per year (Highway Statistics, 2010). Due to having such a wide network and immense usage characteristics, U.S. roads require tremendous new pavement construction, which results in a considerable amount of expenditures. On the other hand, since there is a rapidly growing trend in total Vehicle Miles Travelled-VMT (i.e. VMT has been doubled in the last 30 years), highway system capacity extension also constitutes a significant expenditure that comes along with maintenance expenditures. Hence, growing pattern in travel trends put a vital burden on U.S. economy which is about \$146 billion annually as highway maintenance and safety expenditure (Spending and Funding for Highways, 2011).

On the other hand, paving such a huge road network and keeping it maintained results in severe environmental burdens. In this context, there are various environmental impact categories that are addressed in previous studies. For example, in terms of toxic release inventory, the total environmental impact as a result of paving ranges around the 35% of total nationwide impacts in toxic water releases, 13% of toxic air releases and 24% of toxic land releases, which constitutes to an overall release share of 14% (Horvath & Hendrickson, 1998).

According to the aforementioned statistics, it is doubtless that U.S. highways are responsible for high resource consumption and environmental emissions, which make the sustainable pavement systems necessary for building greener roads. In this regard, there are several impact categories that can be considered within to scope of sustainable road initiatives. For instance, the impacts of materials used in mining, harvesting, processing and construction phases; the design; scale of disturbance, future energy and resource usage; site impacts (e.g. biodiversity loss); transient construction impacts (e.g. onsite energy use, water and air pollution) social impacts (e.g. road safety, occupational health, urban sprawl, noise) (Pears, 2005). If all of the aforementioned impact domains are considered from a life cycle point of view, it is obvious that the overall impact has substantial effects on the environment, economy, and society. For this reason, assessing pavement designs from a life cycle perspective is crucial and necessary to have a holistic understanding about the complete picture so as to make long term successful policies (Santero et al. 2011).

5.2. Warm-Mix Asphalts

Warm-mix asphalt (WMA) has gained a tremendous interest and considered one of the most environmental friendly technologies for producing asphalt pavements (Rubio et al. 2012). WMAs have been gained popularity in terms of its eligibility of being produced at a lower temperature thus cutting process energy by 30% (Larsen et al. 2004). WMA technology show benefits for the environment because it produces asphalt at temperatures 20–40° lower in comparison to conventional hot-mix asphalt (Rubio et al. 2013).

Among WMAs, Aspha-min® is a manufactured synthetic zeolite that improves the mix workability and aggregate coating at lower temperatures is realized. Sasobit® is a wax-type additive of coal gasification that melts in the asphalt binder at high temperatures. As a result, a reduction in the viscosity during mixing is achieved. However, Evotherm™ uses a high-residue emulsion, which results in the improvement of the adhesion of the asphalt to the aggregate and the enhancement in mixture workability (Chowdhury and Button, 2008). A reduction in energy requirements associated with the production of this mixture of up to 55% has been reported (Kristjánsdóttir et al., 2007). Although these reports show the significance of using different WMA additives towards achieving reduced energy consumption, a life cycle-based assessment model, which expands the system boundary of process life cycle inventories, will be vital for understanding the real impacts of WMA in pavement construction.

5.3. Applications of LCA for Sustainable Pavement Designs

Several applications of LCA are available in the literature to analyze WMAs (Jamshidi 2013; Jullien et al. 2011; Hassan 2010). In general, the results of these studies indicated that the emissions and energy consumption of the mixing process were reduced during the production and placement of WMA mixtures when compared to Hot-mix Asphalt (HMA) mixture. In addition to that, WMA pavement sections showed similar performance to those constructed with HMA mixtures. Although previously mentioned studies have successfully quantified some of the potential environmental impacts of WMA in terms of emissions, material and fuel consumption, the role of the upstream supply chain during the production of asphalt additives, binders, metallic and nonmetallic minerals, and fuels used in different HMA and WMA mixtures, and related social and economic impacts associated with utilization of these resources were generally excluded in the scope of these studies.

In the literature, a first detailed Eco-LCA study was conducted by Tatari et al. (2012) where natural resource consumption and atmospheric emissions of various WMAs were analyzed and compared with HMA using the Eco-LCA software, which was developed by the Center for Resilience at Ohio State University (OSU, 2009). The researchers analyzed the direct and indirect role of ecological resource consumption considering different life cycle phases of pavements. However, due to the large impacts on economy and the society, it is still necessary to account for the direct and indirect socio-economic implications of pavement construction. This can be achieved by using an integrated approach which merges economic and social indicators of the sustainability into EIO framework as an addition to environment.

However, current EIO-LCA tool is designed to quantify the direct and supply-chain originated indirect environmental impacts of products or economic sectors neglecting other dimensions of the sustainability. Several studies have used the EIO modeling to quantify the environmental implications of pavements from cradle to grave (Cass and Mukherjee 2011; Park et al. 2003; Treloar et al. 2004). In addition, the Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) was built to estimate the environmental burdens and life cycle costs associated with the pavement construction. This excel-based tool combined the EIO-LCA data with additional process-specific inventory to create a hybrid LCA framework (Santero et al. 2010). On the other hand, the scopes of current pavement LCA models are bounded by the most commonly used environmental impact categories such as water and energy use, atmospheric emissions, and waste; however little attention paid to large scale economic and social implications of pavements. Hence, there is still a strong need on evaluating macro-level direct and indirect socio-economic implications of new WMA technologies for more comprehensive sustainability assessment.

5.4. Motivation and Organization of the Chapter

In the United States, several studies have been conducted to analyze the energy consumption and atmospheric emissions of Warm-mix Asphalt (WMA) pavements. However, the direct and indirect environmental, social, and economic impacts were not addressed sufficiently. Hence, TBL-oriented sustainability assessment model is developed to evaluate the environmental and socio-economic impacts of pavements constructed with different types of WMA mixtures and compare them to a conventional Hot-mix Asphalt (HMA). The types of WMA technologies investigated in this research include Asphamin® WMA, Evotherm™ WMA and Sasobit® WMA.

The life phases of materials extraction and processing, transportation of pavement materials and ready-mixtures, asphalt mixing process and construction of pavements have been included within the scope. The use phase is not included since pavement sections constructed with equivalent performances. Then, a stochastic compromise programming model is built upon obtained TBL results to determine the optimal asphalt pavement allocation strategy for a functional unit of one km pavement.

In this research, the life cycle phases of materials extraction and processing, transportation of pavement materials, asphalt mixing process and construction of pavements have been included within the scope. The use phase is not included because pavement sections constructed with equivalent performances. First, comprehensive TBL-LCA model is built by using numerous environmental and socio-economic sustainability indicators. Second, the life cycle inventory of pavement designs are presented with corresponding data sources. Next, TBL sustainability impacts of the HMA and WMAs have been calculated. Next, a stochastic compromise programming model is built upon obtained LCA results to determine the optimal asphalt pavement allocation strategy for a functional unit of one-km pavement using sustainability weights ranging between 0 and 1. Finally, the findings are summarized, and the limitations are pointed out. For a general research framework, please see Fig. 22.

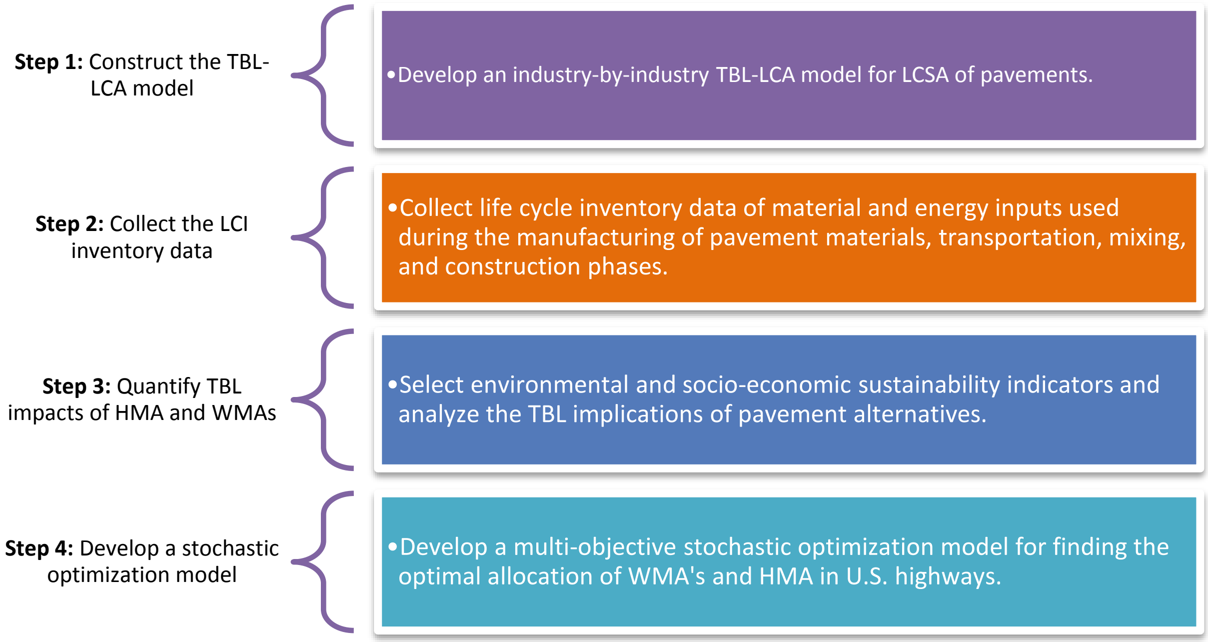


Figure 22. Summary of research framework

5.5. Sustainability Indicators

In this research, since the purpose is to develop a comprehensive EIO based sustainability accounting framework, several TBL indicators are intended to be used. The summary of the selected sustainability indicators are provided in Table 11 with details. The selected sustainability indicators are considered as multipliers, which are mainly used in the EIO framework to quantify each of the 426 sectors' sustainability impacts. To obtain the aforementioned multipliers, several publicly available data sources including Bureau of Economic Analysis (BEA 2002), Energy Information Administration (EIA 2011), Bureau of Labor Statistics (BLS 2002), Global Footprint Network (GFN 2010) and Carnegie Mellon's EIO-LCA software (CMU 2002) are utilized (For a more detailed explanation about the indicator selection, see methodology section).

Table 11. Summary of TBL sustainability indicators

TBL Indicator	Unit	Description	Tool
Environmental			
Carbon Footprint	kg CO_2-eqv	The total GHG emissions of each sector in terms of metric tons of CO_2 equivalent.	EIO-LCA
Water Withdrawal	gal	The total amount of water withdrawals of each sector.	EIO-LCA
Energy Consumption	MJ	The total energy (fossil plus electricity) consumption by sector.	EIO-LCA
Hazardous Waste Generation	kg	The amount of EPA's RCRA hazardous waste generated at each industrial facility.	EIO-LCA
Toxic Releases	kg	The Toxics Release Inventory (TRI) contains toxic chemicals that are released into the atmosphere	EIO-LCA
Fishery	gha	The estimated primary production required to support the fish caught.	TBL-LCA
Grazing	gha	The amount of livestock feed available in a country with the amount of feed required for the livestock produced.	TBL-LCA
Forestry	gha	The amount of lumber, pulp, timber products, and fuel wood consumed by each U.S. sector.	TBL-LCA
Cropland	gha	The most bio-productive of all the land use types and includes areas used to produce food and fiber for human consumption.	TBL-LCA
CO_2 uptake land	gha	The amount of forestland required to sequester given carbon emissions by sectors.	TBL-LCA
Socio-Economic			
Gross Operating Surplus (GOS)	$	The capital available to corporations to repay their creditors, taxes and finance their investments.	TBL-LCA
Employment	emp-min	The full-time equivalent employment minutes for each U.S. sector.	TBL-LCA
Import	$	The value of goods and services purchased from foreign countries	TBL-LCA
Tax	$	The government revenue, which includes the taxes on production and imports.	TBL-LCA
Income	$	The compensation of employees, including wages and salaries.	TBL-LCA
Injuries	employee	The total number of non-fatal injuries related to each U.S sector.	TBL-LCA

5.6. Pavement Design and Life Cycle Inventory

In this research, four pavement sections were designed considering intermediate traffic volume and a generic design structure, which consisted of an asphalt surface layer and a base course layer. In terms of the thickness of the base course layer, 25cm was taken as reference value for all four sections. In the surface layer of the first three sections, Aspha-Min®, Sasobit®, and Evotherm™ WMA mixtures were used. On the other hand, a conventional HMA mixture was used in the fourth section (see Tatari et al. (2012) for more information about the properties of HMA and WMA mixtures). The Mechanistic Empirical Pavement Design Guide (MEPDG) software was used to conduct the pavement analyses. During the pavement analyses, the thickness of the asphalt layer that is required for each section to have an international roughness index (IRI) value of 433 cm/km at the end of the design period was determined. In this context, the IRI is the terminal value recommended by the Federal Highway Administration (FHWA) and used in the MEPDG (FHWA 1998).

The basic assumptions made are as follows. A 30-year design period was used during the pavement analysis. The initial two-way average annual daily truck traffic (AADTT) was assumed to be 2000 vehicles/day considering 50% trucks in the design direction and 95% trucks in the design lane. For the vehicle class distribution, number of axles per truck of each class, and axle configuration categories, the default values given by the MEPDG software were used. The traffic growth rate was assumed 5% per year. The input parameters such as base material, and subgrade soil for the HMA and WMA mixtures were obtained from Hurley et al. (2009).

Based on the conducted MEPDG, the required asphalt layer thickness values were calculated as 12 cm for Aspha-Min®, 11.4 cm for Sasobit®, Evotherm™, and HMA sections. The corresponding volumes of HMA and WMA pavements were quantified by multiplying the width, the depth and the length of the pavement, which was selected to be a two-lane highway with a total width of 7.2m and a length of one-km. Later, the total weight of each of the HMA and WMA mixtures was calculated by multiplying the calculated volumes with corresponding densities. The calculated weights were allocated for each component, such as limestone, natural sand, asphalt binder, RAP, and WMA additives, based on the percentage values of mixture composition provided in Tatari et al. (2012), thus the inventory required for HMA and WMA pavements were determined (see Table 12).

Table 12. Material inventories for asphalt mixtures

Materials	Materials	% by Weight	Total Weight (t)
HMA	Limestone	49.77	1,097.86
	Natural Sand	30.05	662.86
	Aggregates RAP	14.09	310.72
	Bitumen	5.30	116.92
	Binder RAP	0.80	17.65
Aspha-min®	Limestone	49.61	1,155.37
	Natural Sand	29.95	697.58
	Aggregates RAP	14.04	326.99
	Bitumen	5.30	123.44
	Binder RAP	0.80	18.63
	Aspha-Min	0.30	6.99
Evotherm™	Limestone	49.77	1,097.86
	Natural Sand	30.05	662.86
	Aggregates RAP	14.09	310.72
	Bitumen	5.27	116.33
	Binder RAP	0.80	17.65
	Evotherm	0.03	0.58
Sasobit®	Limestone	49.77	1,097.86
	Natural Sand	30.05	662.86
	Aggregates RAP	14.09	310.72
	Bitumen	5.21	114.90
	Binder RAP	0.80	17.65
	Sasobit	0.09	2.02

In this research, limestone, natural sand, and asphalt binder were the main industrial inputs for the all pavements, which were being provided by the following sectors, respectively: Lime and Gypsum Product Manufacturing (NAICS 327410), Sand, Gravel, Clay, and Refractory Mining (NAICS 212320), and Petroleum Refineries (NAICS 324110). Also, Aspha-min® and Evotherm™ were used as chemical additives in the WMA pavements, which were manufactured by the Other Basic Inorganic Chemical Manufacturing sector (NAICS 325180) and Sasobit® was produced by the Petrochemical

Manufacturing (NAICS 325110) sector. Besides, as the main resource used in the transportation of pavement materials to construction site, the Truck Transportation sector (NAICS 484000) is used for calculating TBL impacts of pavement material transport while impacts of construction activities including pavement laying and compaction are quantified by using the sector of the Highway Construction (NAICS 237310) from the EIO table. As the main resource used during the asphalt production in the mixing plant, natural gas was provided by the Natural Gas Distribution sector (NAICS 221200).

Direct and indirect TBL impacts related to consumption of resources during materials production, transportation, mixing, and construction are calculated through the TBL-LCA model. Firstly, the monetary values of each material input are calculated using the producer prices. These monetary values represent the economic input of each related sectors, which are also the calculated demand as a result of a certain activity such as natural gas required for the mixing process. After calculating the monetary values, each of them are multiplied by environmental and socio-economic impact multipliers obtained from the TBL-LCA model. The environmental and socio-economic input-output multipliers of these sectors are presented in Table 13 and 14.

Table 13. Environmental impact multipliers per $M output of each sector

Sectors	**Water (m^3)**	**Energy (TJ)**	**Carbon (t CO_2-eqv)**	**Hazardous waste (t)**	**Toxics (t)**
NAICS 327410	102,206	44.7	5,320	247,000	514
NAICS 212320	273,549	21.6	1,490	158,000	95.4
NAICS 324110	35,620	31.7	2,790	4,120,000	187
NAICS 325180	140,817	32.4	2,180	2,190,000	528
NAICS 325110	79,115	42.3	2,920	5,650,000	414
NAICS 221200	25,286	14.5	1,990	168,000	47.3
NAICS 237310	21,009	8.26	612	222,000	62.7
NAICS 484000	13,097	18.8	1,400	358,000	37.5
	Fishery (gha)	**Grazing (gha)**	**Forestry (gha)**	**Cropland (gha)**	**CO_2 uptake (gha)**
NAICS 327410	0.140	0.177	19.658	31.330	1,172
NAICS 212320	0.126	0.138	1.558	16.586	317.815
NAICS 324110	0.153	0.126	1.729	4.673	492.070
NAICS 325180	0.327	0.189	1.958	12.716	410.777
NAICS 325110	0.214	0.227	2.509	43.542	486.416
NAICS 221200	0.086	0.081	1.664	3.186	257.523
NAICS 237310	0.159	0.137	9.307	12.165	127.964
NAICS 484000	0.126	0.155	1.357	2.296	320.715

Table 14. Socio-economic impact multipliers per $M output of each sector

Sectors	Import ($M)	Income ($M)	GOS ($M)	Tax ($M)	Injury (number of workers)	Employment (emp-min)
NAICS 327410	0.168	0.493	0.457	0.044	0.831	27,180
NAICS 212320	0.085	0.576	0.368	0.051	0.608	31,157
NAICS 324110	0.852	0.345	0.545	0.100	0.329	16,098
NAICS 325180	0.488	0.636	0.289	0.058	0.567	29,684
NAICS 325110	0.616	0.435	0.471	0.081	0.413	20,690
NAICS 221200	0.954	0.292	0.588	0.112	0.275	13,252
NAICS 237310	0.089	0.715	0.248	0.032	0.956	35,438
NAICS 484000	0.104	0.636	0.307	0.047	0.971	36,037

In terms of the mixing energy consumption (MJ per ton WMA and HMA processing), National Center for Asphalt Technology (NCAT)'s field study, which includes the natural gas consumption data, is utilized to calculate the total energy consumed during HMA and WMA mixing phase (Hurley et al. 2009). The total energy consumption per ton asphalt mixing was multiplied with the total weight of the mixtures to obtain the total energy consumption of one-km pavement sections. The GHG emission factors associated with HMA and WMA mixing operations were obtained from the asphalt plant stack emissions report, which was published by the NCAT (Hurley et al. 2009). Remaining on-site impact categories such as toxics, hazardous waste, and water consumption are not included in the scope due to data limitations. Moreover, the amount of diesel consumption during the construction of asphalt pavements were obtained from the previous pavement energy studies (Ang et al. 1993; Zapata and Gambatese 2005). Other environmental loads including on-site and indirect emissions, hazardous waste, water use, and land footprint are calculated by using the multipliers of the Highway Construction sector.

Finally, transportation-related tail-pipe GHG emission data were determined using the emission factors provided by the National Renewable Energy Laboratory (NREL)'s life cycle inventory database for a single-unit truck (NREL 2010). The unit was the per ton-km transportation of the pavement materials to the project field. The distance between pavement materials and construction site is assumed to be 50 km for each pavement system. The emission data consists of GHGs including nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4). Also, all other direct and indirect environmental impacts are calculated using the Truck Transportation sector. First, total ton-km transportation requirement of each pavements calculated by multiplying total weight of materials with total transportation distance. Later on, obtained value is multiplied with unit cost related to per ton-km transportation with trucking in the U.S. (Raballand and Macchi 2008). This economic output is then linked to the Truck Transportation sector of the EIO model. The summary of model parameters is presented in Table 15.

Table 15. Summary of model parameters

Model Parameters	**Descriptions**
LCA Tool	Triple-Bottom-Line EIO Model
Life Time	30 years
Functional Unit	1-km long, 3.6 m wide (each section)
Traffic	5 % Annual Traffic Growth Rate, two-way highway
Number of ADDTT	2000 vehicles/day; 50% trucks in the design direction; 95% trucks in the design lane
Pavement Sections	**1.** HMA (11.4 cm) **2.** Evotherm (11.4 cm) **3.** Aspha-min (12 cm) **4.** Sasobit (11.4 cm)
Life Cycle Phases	**1.** Materials Extraction and Processing **2.** Mixing **3.**Transportation, **4.** Construction
Sustainability Indicators	**1.** Environmental: Water, energy, carbon, hazardous waste, toxics, and ecological land footprint **2.** Socio-Economic: Import, GOS, tax, income, injuries, and employment
Uncertain Variables	**1.** WMA additives **2.** Transportation distance **3.** Mixing energy

5.7. Stochastic Compromise Programming Model

Multi-objective optimization model is critical for finding a feasible alternative that yields the most preferred set of values for the objective, which aims to maximize the TBL sustainability impacts toward selecting optimal pavement selection strategy. In order to realize this goal, a compromise programming model, which is widely used for solving multi-objective linear, nonlinear or integer programming problems, is developed to optimize multiple sustainability objectives.

The compromise programming model measures the distance based on L_a metric. The L_a metric defines distance between two points such as Z^*_k (x) and Z_k (x). As can be seen from the Eq.8, a compromise programming model uses a distance-based function in order to minimize the difference between ideal and compromise solutions. The formulation of L_a metric is presented as follows (Chang 2011):

$$L_a = \mathrm{Min}\left\{\sum \pi_k \left(Z_k^*(x) - Z_k(x)\right)\right\} \tag{8}$$

Each objective function can have different unit, and therefore normalization is needed before the optimization model is constructed. The values after normalization will be confined to a given range such as 0 to 1. The normalization function Z can be expressed as:

$$Z = \frac{Z_k^*(x) - Z_k(x)}{Z_k^*(x)} \tag{9}$$

After completing the normalization procedure, the distance-based compromise programming formulation can be written as (Chang 2011):

$$\mathrm{Min}\ L_a = \mathrm{Min}\left\{\sum \pi_k \left(\frac{Z_k^*(x) - Z_k(x)}{Z_k^*(x)}\right)\right\} \tag{10}$$

Subject to:

$$\sum_{k=1}^{p} \pi_k = 1 \tag{11}$$

In this formulation, $\mathrm{Z}_{\mathrm{k}}^{*}$ represents the ideal solution for objective k. Each objective function should be optimized individually in order to find the amount of $\mathrm{Z}_{\mathrm{k}}^{*}$. Also, the parameter p represents the total number of objectives and π_{k} is a weight that can be arbitrarily selected by the decision makers to account for the relative importance of each objective. Environmental and socio-economic weights are represented by π_{k} , which ranges from 0 to 1 for each of the objective function. After developing the mathematical structure of the compromise programming, this optimization model is coupled with Monte Carlo simulation to account for the uncertainty in the input variables. Uncertainty and variability arise in different life cycle phases of each pavement method. Combining these two methodologies at the same time can be a suitable tool for selecting the best asphalt pavement allocation strategy for the U.S. highways. The optimization model is presented as follows:

Sets:

S: set of sustainability indicators indexed on *i*, where *i*=1............................│S│

P: set of pavement types indexed on *m*, where *m*=1............................│P│

Parameters:

A_{im}: $The\ impact\ of\ pavement\ m\ for\ environmental\ indicator\ i$

B_{im}: $The\ impact\ of\ pavement\ m\ for\ socio-economic\ indicator\ i$

Decision Variable:

$X_{im}: The\ percentage\ use\ of\ pavement\ type\ m\ for\ sustainability\ indicator\ i$

Objective Functions:

$$\mathrm{Z_1(x)} = \sum_{\mathrm{i=1}}^{\mathrm{r}} \sum_{\mathrm{m=1}}^{\mathrm{p}} \mathrm{A_{im} X_{im}} \tag{12}$$

$$\mathrm{Z_2(x)} = \sum_{\mathrm{i=1}}^{\mathrm{s}} \sum_{\mathrm{m=1}}^{\mathrm{p}} \mathrm{B_{im} X_{im}} \tag{13}$$

Subject to:

$$\sum_{\mathrm{m=1}}^{\mathrm{p}} \mathrm{X_{im}} = 1 \qquad \text{for i} = 1,2,\ldots \mathrm{r} \tag{14}$$

$$\mathrm{X_{im}} \geq 0 \qquad \text{for i} = 1,2,\ldots \text{r and for m} = 1,2,\ldots,\mathrm{p} \tag{15}$$

$\mathrm{Z_1(x)}$ denotes the environmental objective function and $\mathrm{Z_2(x)}$ represents the socio-economic objective function. A_{im} is denoted as the environmental impact of pavement type m for the indicator i whereas B_{im} is denoted as the socio-economic impact (see eq.12, 13). The total of X_{im} is 1 (Eq.14). Consequently, a stochastic multi-objective optimization model is combined with the LCA results to optimize the multiple environmental and socio-economic objectives, simultaneously. MATLAB® programming software is then used for coding the Monte Carlo simulation and compromise programming algorithms (MATLAB 2012). A uniform distribution was assumed for each selected input variable and 10,000 replications have been applied for each Monte Carlo simulation. Using the simulation outputs, which present the value of each TBL indicator in a given range, a stochastic compromise programming model has been utilized for finding the optimal allocation of different pavement types.

5.8. Analysis Results

The research findings are based on TBL sustainability impact analysis and stochastic compromise programming which are presented in the following sub-sections.

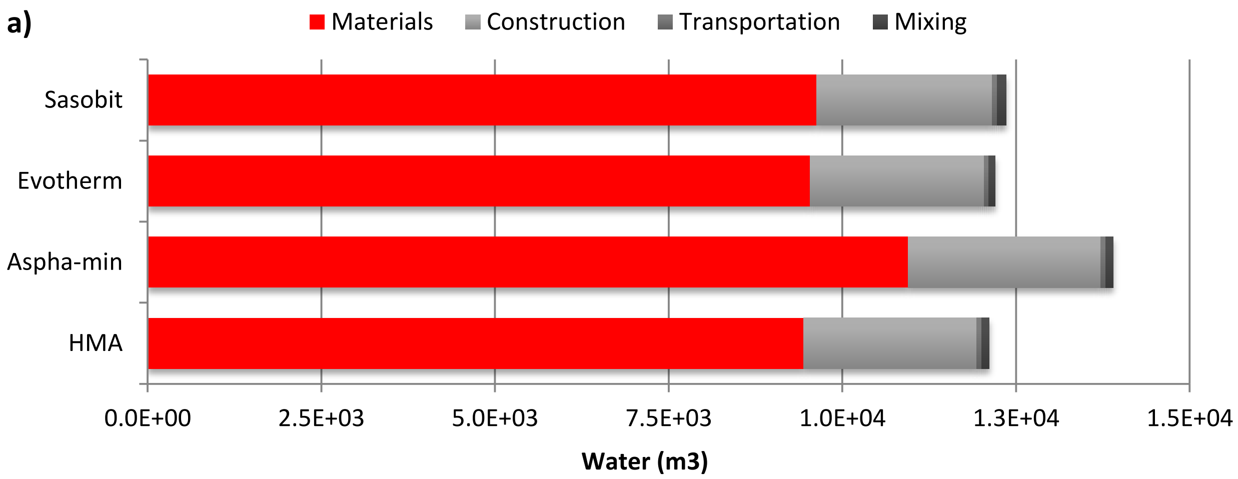
5.8.1. Environmental Impacts of Pavements

The environmental impacts of each of the analyzed pavements are computed in terms of water and energy consumption, GHG emissions, hazardous waste generation and toxic releases. As shown in Fig.23, Asphamin® has the highest environmental impacts than other pavement types with an exception of GHG emissions. This pavement type is followed by Evotherm™ and Sasobit®, respectively. In terms of LCA phases, materials extraction and processing and construction are found to have the largest contributions. On the contrary, for GHG emissions, mixing phase has the second largest impact after manufacturing of pavement materials. Especially, total GHG emissions are found to be the highest for Evotherm™, which also has the largest emissions during the mixing phase (see Fig. 23). NCAT's field experiment results indicate that Evotherm™ used 14.5% more energy than HMA and emitted larger GHGs. On the contrary, the total natural gas consumption is reduced by 8.8% for Asphamin® and 17.9% for Sasobit® (Hurley et al. 2009). In terms of

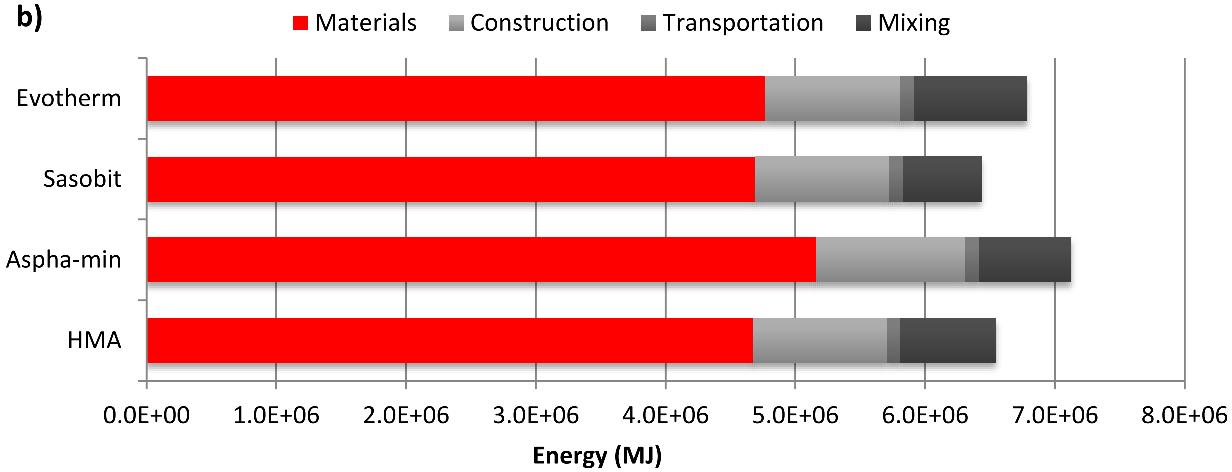
GHG emissions and energy consumption, Sasobit® shows the minimum values compared to other WMAs and HMA control mix.

Fig. 23 also presents the net land footprint of each pavement design in terms of global hectares (gha). Based on the total land use results, HMA has the lowest footprint with an exception of CO_2 uptake land when compared to other pavements. When looked more closely at life cycle phases, materials extraction and processing and construction phases represent two dominant phases for land footprint categories such as fishery, grazing, forestry, and cropland. For CO_2 uptake land, after materials extraction and processing, mixing phase has the second largest contribution to overall ecological land footprint. In addition, this land footprint category is responsible for the highest footprint compared to other land use types. Asphamin® and Evotherm™ represent the pavement mixtures with maximum CO_2 uptake land utilization due to high emissions in pavement material production and energy requirement during the mixing phase whereas Sasobit® has the lowest land footprint result, which is also parallel to total GHG emission findings.

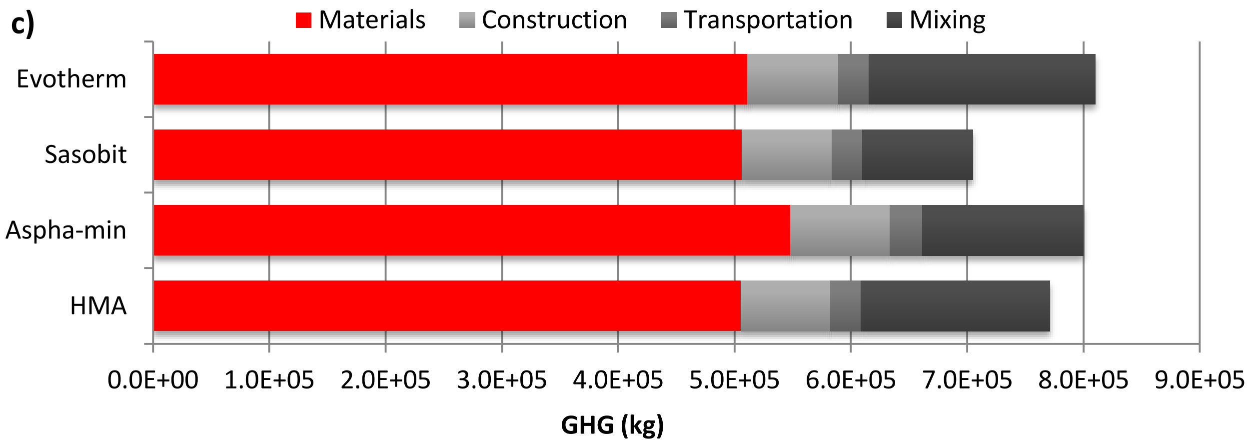
a)


🟥 Materials
Construction
Transportation
Mixing
Sasobit
Evotherm
Aspha-min
HMA
0.0E+00
2.5E+03
5.0E+03
7.5E+03
1.0E+04
1.3E+04
1.5E+04
Water (m3)

b)


🟥 Materials
Construction
Transportation
Mixing
Evotherm
Sasobit
Aspha-min
HMA
0.0E+00
1.0E+06
2.0E+06
3.0E+06
4.0E+06
5.0E+06
6.0E+06
7.0E+06
8.0E+06
Energy (MJ)

c)


🟥 Materials
Construction
Transportation
Mixing
Evotherm
Sasobit
Aspha-min
HMA
0.0E+00
1.0E+05
2.0E+05
3.0E+05
4.0E+05
5.0E+05
6.0E+05
7.0E+05
8.0E+05
9.0E+05
GHG (kg)

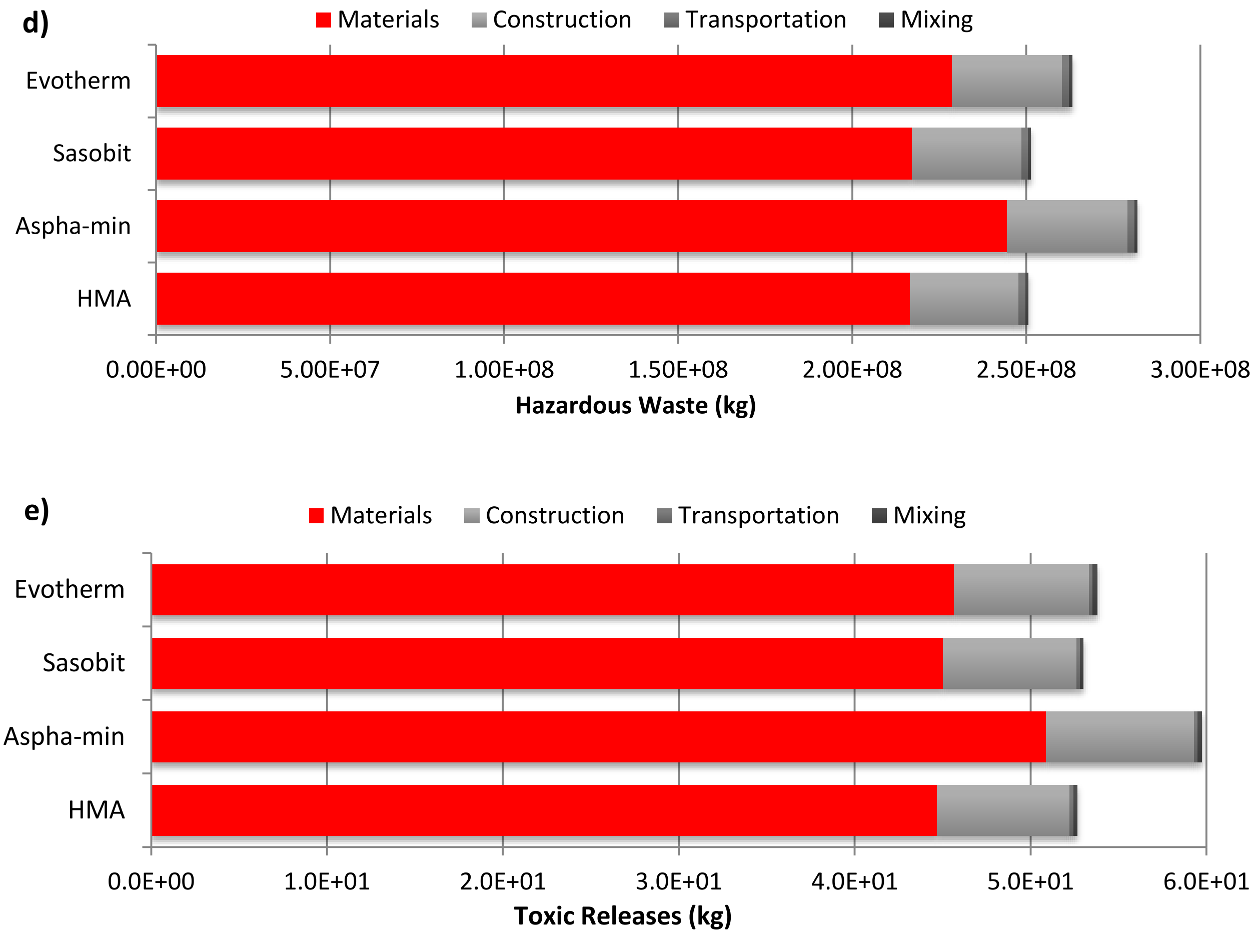
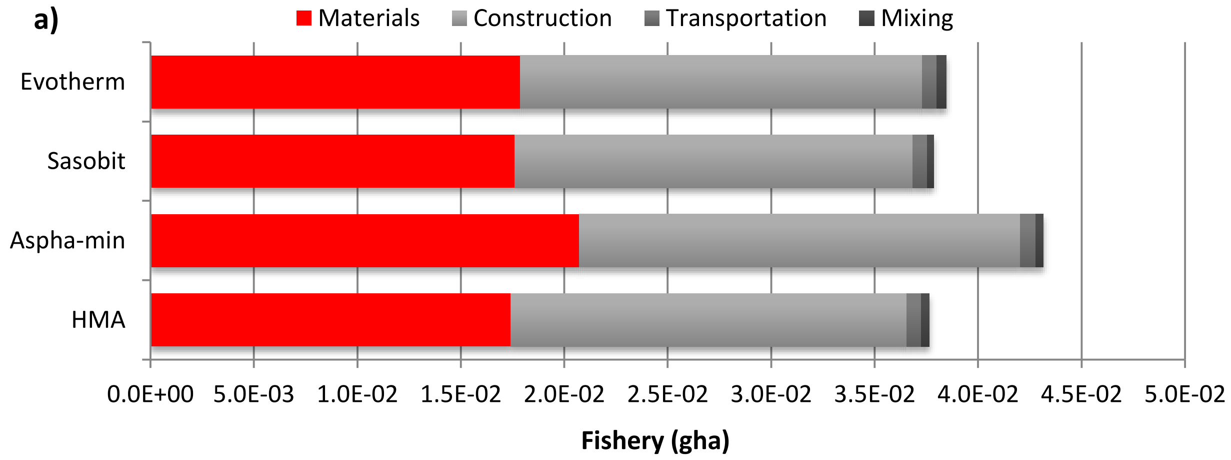
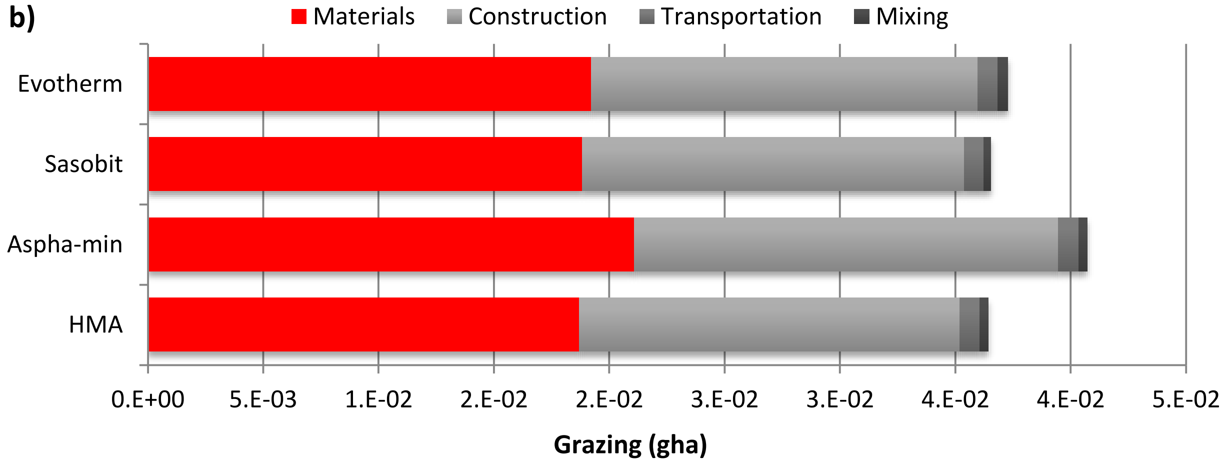


Figure 23. Environmental impacts (a) Water (b) Energy (c) GHG (d) Hazardous Waste (e) Toxic releases

Fig. 24 also presents the net land footprint of each pavement design in terms of global hectares (gha). Based on the total land use results, HMA has the lowest footprint with an exception of CO_2 uptake land when compared to other pavements. When looked more closely at life cycle phases, materials extraction and processing and construction phases represent two dominant phases for land footprint categories such as fishery, grazing, forestry and cropland. For CO_2 uptake land, after materials extraction and processing, mixing phase has the second largest contribution to overall ecological land footprint. In addition, this land footprint category is responsible for the highest footprint compared to other land use types. Asphamin® and Evotherm™ represent the pavement mixtures with maximum CO_2 uptake land utilization due to high emissions in pavement material production and energy requirement during the mixing phase whereas Sasobit® has the lowest land footprint result which is also parallel to total GHG emission findings.





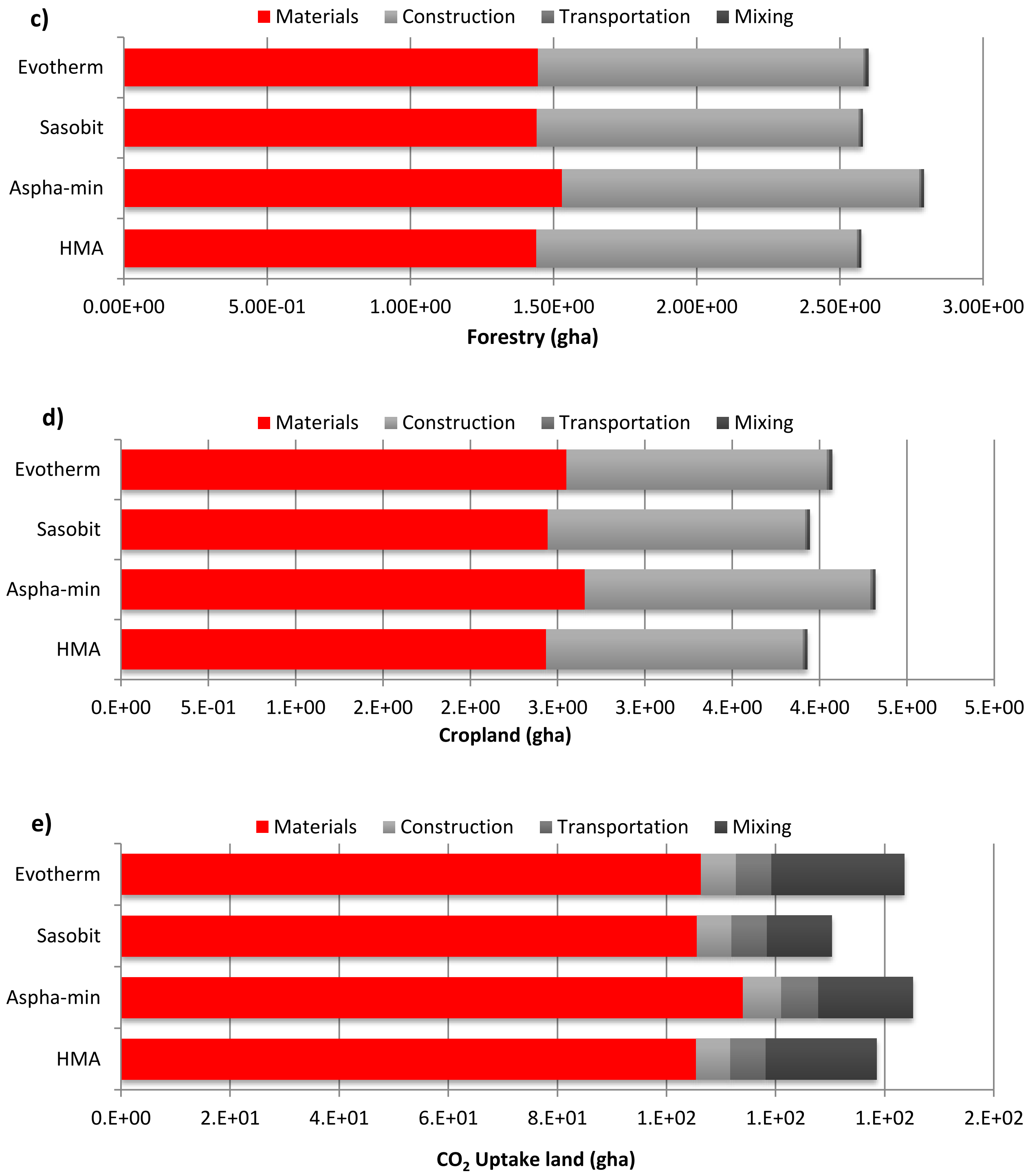
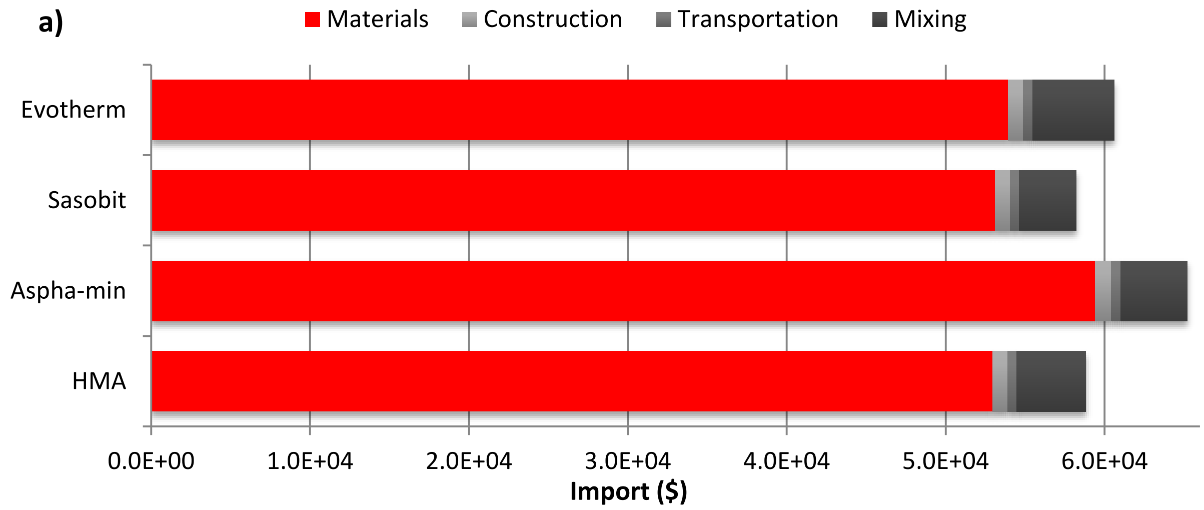


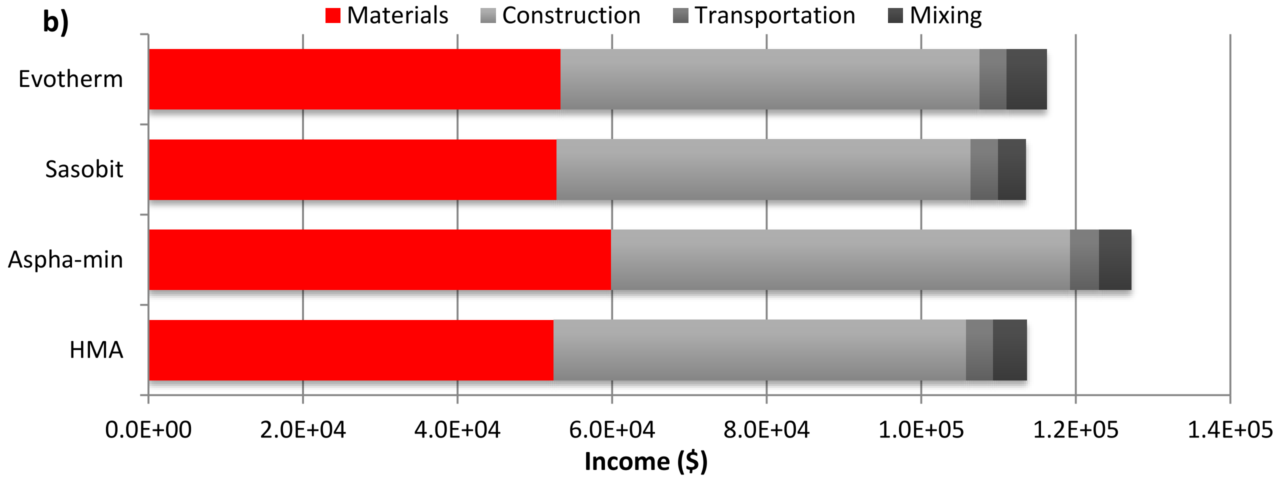
Figure 24. Ecological footprint results of pavement systems (a) Fishery (gha) (b) Grazing (gha) (c) Forestry (gha) (d) Cropland (gha) (e) CO_2 Uptake Land (gha)

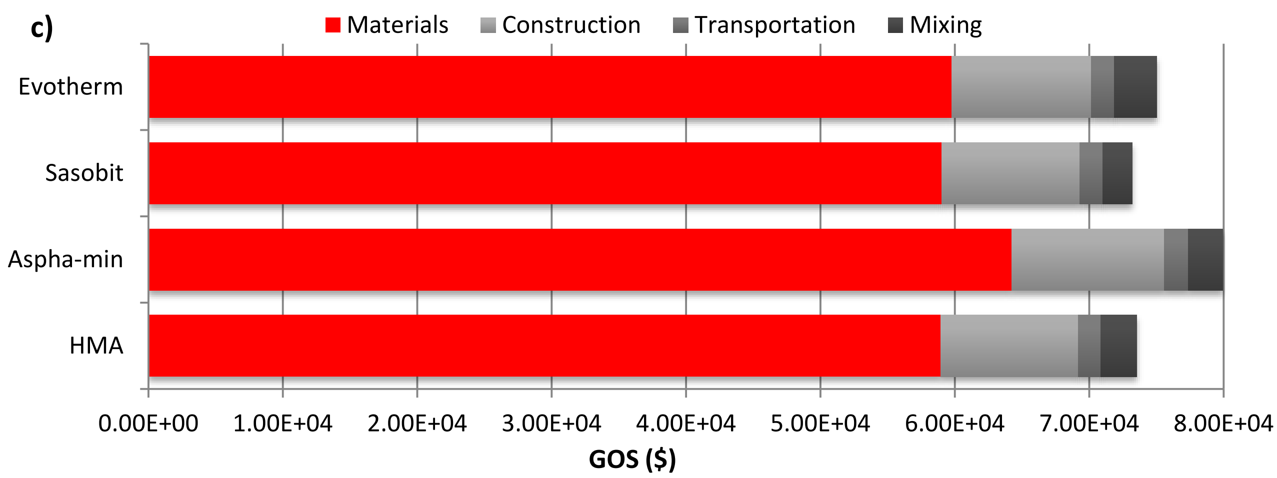
5.8.2. Socio-Economic Impacts of Pavements

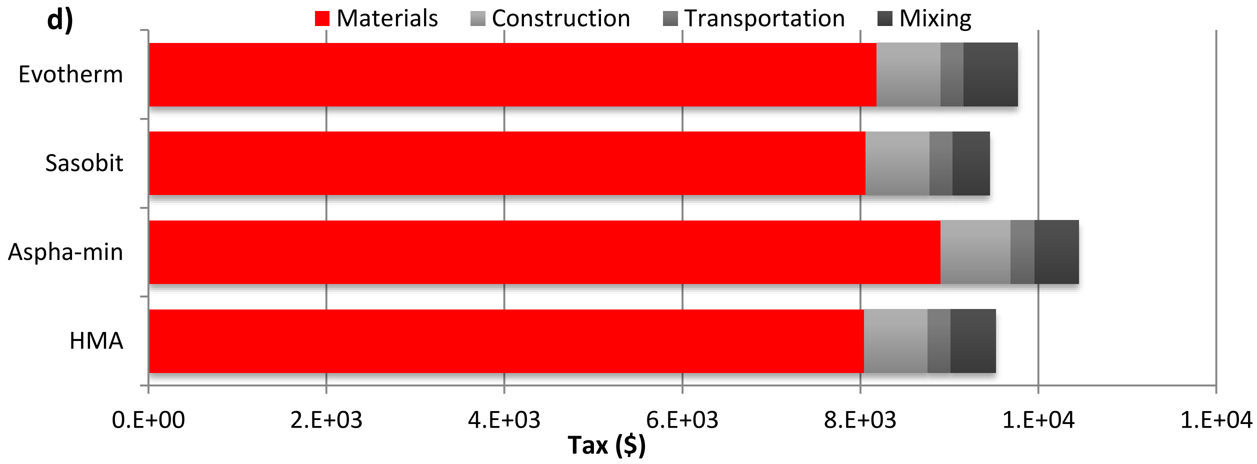
As can be seen from Fig.25, Asphamin® has the highest socio-economic impacts than other pavement types. The differences in thickness of the Asphamin® design played an important role in this finding because more materials extracted and processed for construction of this pavement structure, which in turn required more transport and construction fuel. This pavement technology is followed by Evotherm™. On the contrary, Sasobit® and HMA control-mix have shown similar performances in terms of analyzed socio-economic indicators. For import, GOS and government tax indicators, materials extraction and processing phase has the dominant contribution. The use of bitumen, which is used as a binder in asphalt mixture, resulted in the highest import values compared to other materials. In addition, construction of pavements has the second largest impact on the overall employment, income, and work-related injuries after manufacturing phase.

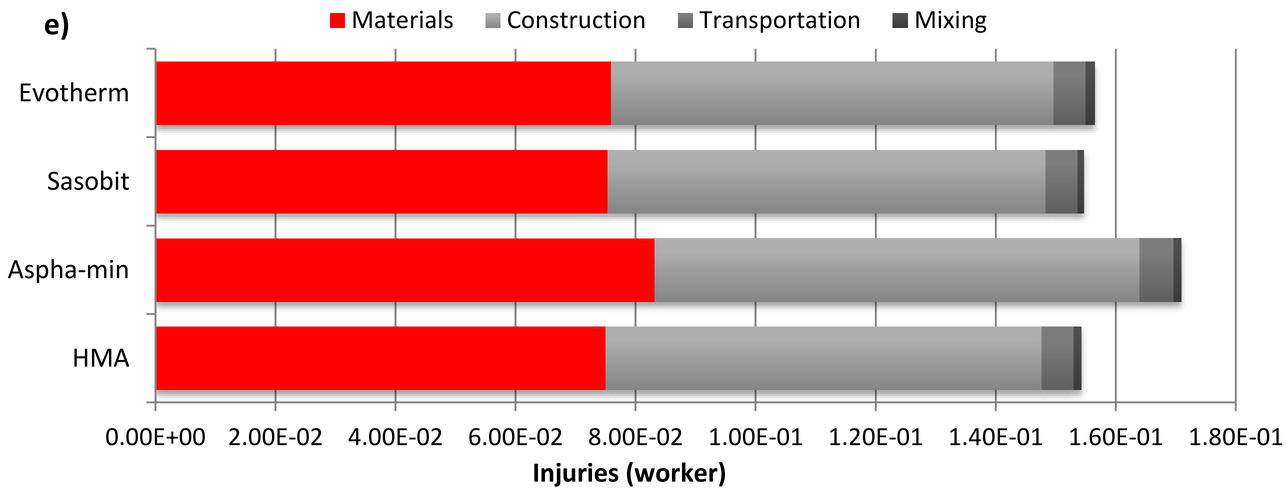
Conversely, socio-economic impacts are found to be minimal for transportation and mixing phases. When looked more closely at injury results, pavement materials manufacturing and construction phases have the highest values, which indicate the importance of work safety in production and construction processes when paving the U.S. highways. It is also important note that to there is a positive correlation between total income and number of injuries. In general, sector with high income rate generated more employment, which resulted in higher amount of work-related injuries. This is because the number of full-time employees is multiplied with corresponding injury rates to obtain the total number of injuries. The overall socio-economic impact results are presented in Fig.25.


a)
Materials
Construction
Transportation
Mixing
Evotherm
Sasobit
Aspha-min
HMA
0.0E+00
1.0E+04
2.0E+04
3.0E+04
4.0E+04
5.0E+04
6.0E+04
Import ($)


b)
Materials
Construction
Transportation
Mixing
Evotherm
Sasobit
Aspha-min
HMA
0.0E+00
2.0E+04
4.0E+04
6.0E+04
8.0E+04
1.0E+05
1.2E+05
1.4E+05
Income ($)


c)
Materials
Construction
Transportation
Mixing
Evotherm
Sasobit
Aspha-min
HMA
0.00E+00
1.00E+04
2.00E+04
3.00E+04
4.00E+04
5.00E+04
6.00E+04
7.00E+04
8.00E+04
GOS ($)


d)
Materials
Construction
Transportation
Mixing
Evotherm
Sasobit
Aspha-min
HMA
0.E+00
2.E+03
4.E+03
6.E+03
8.E+03
1.E+04
1.E+04
Tax ($)


e)
Materials
Construction
Transportation
Mixing
Evotherm
Sasobit
Aspha-min
HMA
0.00E+00
2.00E-02
4.00E-02
6.00E-02
8.00E-02
1.00E-01
1.20E-01
1.40E-01
1.60E-01
1.80E-01
Injuries (worker)

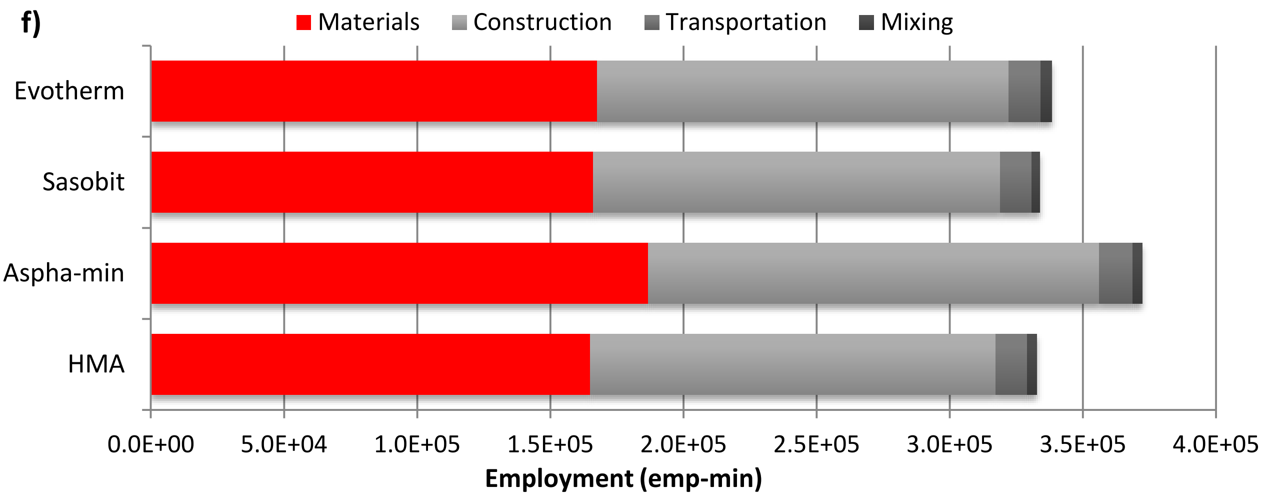


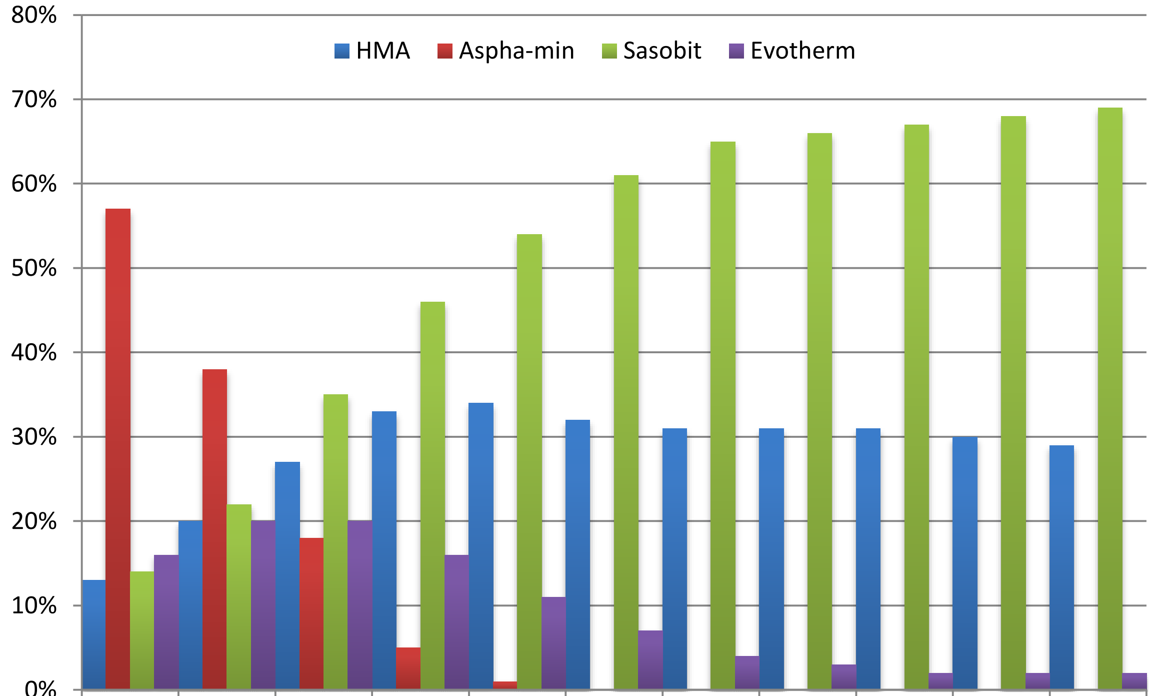
Figure 25. Socio-economic impacts of pavements (a) Import ($) (b) Income ($) (c) GOS ($) (d) Tax ($) (e) Injuries (worker) (f) employment (emp-min)

5.8.3. Stochastic Compromise Programming Results

In the previous sections, it was assumed that the input parameters were known with certainty. Therefore, the model outputs, including environmental and socio-economic results, did not address the variability that is inherent in the input variables. In order to account for the variability of critical input variables, a Monte Carlo simulation was performed. The utilization of a Monte Carlo simulation enabled us to estimate the impact of the variability in consumption of WMA additives (-30% to +30%), the transportation distance of the pavement materials to mixing sites (50-500 km) and the amount of mixing energy (-10% to +10%). A uniform distribution was assumed for each selected variable and 10,000 replications have been applied for each Monte Carlo simulation. Similar uncertainty ranges were also used in previously published LCA study for uncertainty analysis (Tatari et al. 2012). In this analysis, a compromise programming model is combined with Monte Carlo simulation in order to select the most appropriate pavement alternatives based on different weights of environmental and socio-economic indicators. As shown in Fig.26, the percentage rates of allocation of each pavement methods has been ranged between 0 and 1. As mentioned before, Asphamin® WMA has the highest socio-economic impacts among other alternatives, and therefore when the socio-economic weight (SEW) is critical, this method has the highest allocation rate with more than 50%. The percentage of allocation of this method is very sensitive to the change of weights, as it drops dramatically by increasing environmental weight (EW). While EW is greater than 0.4, Asphamin® WMA is not a suitable option among other alternatives.

Moreover, in a balanced weighting situation in which environmental and socio-economic indicators have equal importance, Sasobit® has higher percentage with a share of 61%. This is followed by HMA at 32% and Evotherm at 7%, respectively. Interestingly, the allocation %age of HMA stays almost the same for the rest of EWs (greater than 0.5), with only 3 % changes in allocation results. In addition, when environmental indicators have more importance compared to socio-economic indicators, Sasobit® WMA is still the most preferred method. Specifically, while EW is greater than 0.5, this pavement technology is selected between 65% and 69%. Also, when the weights vary between 0.5 and 1, the percentage of allocation of Evotherm™ stays almost the same, with only 2% variation.

It is also critical to note that in 2010, approximately 360 million tons of asphalt pavement materials produced in the United States in which 42 million tons (makes up to 12 %) were produced using WMA technologies (DOT 2010). According to the compromise programming results, it is found that U.S. pavements utilize approximately 2.8 times more HMA than the scenario where environmental and socio-economic indicators are equally important. Hence, the results clearly support the significance of an increase in WMA use for sustainable pavement construction. The optimal utilization of each pavement mixture is presented in Fig. 26 based on varied environmental and socio-economic weights.



	EW: 0 SEW: 1	EW: 0.1 SEW: 0.9	EW: 0.2 SEW: 0.8	EW: 0.3 SEW: 0.7	EW: 0.4 SEW: 0.6	EW: 0.5 SEW: 0.5	EW: 0.6 SEW: 0.4	EW: 0.7 SEW: 0.3	EW: 0.8 SEW: 0.2	EW: 0.9 SEW: 0.1	EW: 1 SEW: 0
HMA	13%	20%	27%	33%	34%	32%	31%	31%	31%	30%	29%
Aspha-min	57%	38%	18%	5%	1%	0%	0%	0%	0%	0%	0%
Sasobit	14%	22%	35%	46%	54%	61%	65%	66%	67%	68%	69%
Evotherm	16%	20%	20%	16%	11%	7%	4%	3%	2%	2%	2%

Figure 26. Percentage of selection of each pavement method for different environmental and socio-economic weights

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

In Chapter 3, the TBL sustainability implications of construction industry were analyzed by proposing a distinction between seven different U.S. construction sectors. The results of such a holistic EIO analysis will provide valuable insights into the location of sustainability impacts, and can propose a vital guidance for decision makers to develop sound policies for sustainable construction. Especially, LEED which is a well-known and widely used building rating system in the U.S can benefit from such an analysis in order to develop effective green building rating strategies considering the construction supply chain. Based on research findings, the followings are highlighted:

- The results indicated that upstream suppliers of construction sectors had the largest impacts compared to on-site activities. Hence, using narrowly defined estimation models by neglecting supply chain-related impacts can result in large underestimates of sustainability impacts of the U.S. construction industry.
- NR-OTR and R-PSMFS were found to have the largest total sustainability impacts for all sustainability impact categories. Scope 3 carbon emissions were responsible for the highest share of total GHG emissions for all construction sectors. Also, approximately 95 % of total water use of construction sectors can be attributed to indirect suppliers, which are located in L2, L3 and higher layers. In terms of work-related injuries, non-residential construction sectors presented higher injury multiplier in comparison with residential construction sector, and on-site construction works accounted for over 60 % of total injuries.

- Although the findings of this research could be very helpful to decision makers to analyze and compare the sustainability implications of construction sectors by proposing an alternative methodology, it has several limitations that should be taken into account for future studies. First, the analysis results are based on the U.S. national input-output accounts, and therefore there are certain uncertainties in data due to regional variations. For example, Scope 2 carbon footprints can vary from state to state or region to region depending upon electricity generation from mixes, including coal, natural gas, oil, nuclear, hydro power, solar, and other sources. Hence, these types of geographic variations in emissions should be considered for future carbon footprint estimations.
- It is also important to note that the environmental interventions related to construction phase and different end-of-life scenarios are not well accounted in pure EIO analysis and hybrid LCA model which combines the P-LCA and EIO-LCA can provide more specific and detailed LCSA of construction work, particularly for construction, demolition, and waste disposal. Although a comprehensive EIO model is developed, there are still important uncertainties embedded in the results due to the use of aggregate data for construction sectors. For instance, heavy civil infrastructures, including highway, bridge, dams, water treatment facilities, sewer systems, petroleum, gas and power plants, and communication lines are analyzed the under the construction sector of NR-OTR. For more detailed LCSA model, these construction sectors could be disaggregated and analyzed under NR-OTR as separate sub-sectors.

- The methodology described in this research has been used to answer the question related to sustainable construction using several key sustainability metrics. Data collection process for these metrics required a considerable time and effort, and most were obtained from publicly available data sources. Several other sustainability assessment indicators should also be added to extend the environmental footprint metrics to provide a more robust sustainability accounting model for the U.S. construction sectors. As an example, the built-up land footprint, which is calculated based on the area of land used by human infrastructure, such as transportation, housing, industrial structures and reservoirs for hydroelectric power generation, can be allocated to each construction sector.

In Chapter 4, life cycle sustainability impacts of residential buildings effects were quantified. Using the findings of this research, effective sustainable development strategies can be generated and these effects can be optimized based on priorities of the decision makers. According to analysis results, the followings are highlighted:

- Construction activities, electricity consumption and commuting are more dominant compared to other life cycle components. The electricity consumption of the U.S. buildings had more environmental impacts, while the construction activities are more influential on the amount of social and economic impacts. Although natural gas and petroleum consumption, maintenance and repair, water and wastewater, and construction waste management had relatively lower impacts, when making policies impacts of those components should not be neglected. This was because the importance of these life cycle components may vary based on the requirements of different policy makers and geographic regions.

- Also, the supply chains of some of the sectors were explained in detail to give better insight about the results and factors affecting the total sustainability impacts of each category. Especially, different supply chain characteristics and the demand of sectors caused significant differences in magnitude of sustainability impacts. Moreover, the analysis results showed that the order of the most effective supply chain elements for the same sector can vary by the selected impact category. Hence, analyzing supply chain parameters is crucial when conducting a LCSA.
- When the results evaluated based on the life cycle phase, the use phase is driving in the majority of sustainability impact categories, whereas impacts of the end of life phase are almost negligible. A comparable study that assesses the life cycle of residential buildings shows similar result for the end of life category (Ochoa et al. 2002). However, the limited data availability for recycled and reused content of the building demolition debris should also be considered. Only eight states, representing only 21% of the U.S population, report their recycle and reuse rates of construction and demolition (C&D) debris (EPA 2003). As more states start to report their data on this issue, better studies can be developed focusing on the end of life phase.

- In the sensitivity analysis, economic output and multipliers of same sectors showed similar trend. The results of the sensitivity analysis indicate that the economic output of residential sector, electricity demand, and the multipliers defining the sectorial characteristics of those sectors are more correlated to the total sustainability impacts in most of the categories. Economic output of the residential construction sector and its multiplier are dominant in most of the social and economic impact categories, whereas the electricity demand and its multiplier are more influential on most of the environmental impacts.
- Consequently, this research assessed the sustainability impacts of the U.S. residential buildings from a holistic perspective. However, considering the dynamic structure of the U.S. buildings and interactions among the life cycle components and the sectors, the problems addressing the sustainability of U.S. buildings should be studied with dynamic modeling approach to develop future strategies that consider the temporal variables of the system. Some of the vital policies that should be evaluated dynamically are the energy efficient building retrofitting and shifting to renewable energy sources for electricity generation.

In Chapter 5, a comprehensive hybrid TBL-LCA model was developed to evaluate macro-level environmental and socio-economic implications of using WMA technologies in construction of asphalt pavements in the U.S. This holistic analysis complemented previous LCA studies by evaluating pavements not only from emissions and energy consumption standpoint, but also from socio-economic perspectives. Furthermore, compromise programming results provide a vital guidance for policy makers when selecting pavement types based on different environmental and socio-economic priorities. The key findings are summarized as follows:

- Asphamin® WMA was found to have the highest environmental and socio-economic impacts in comparison with other pavement designs.
- WMAs did not perform better in terms of environmental impacts compared to HMA. However, they appeared to perform better when socio-economic indicators of sustainability were considered.
- Among the life cycle phases, material extraction and processing was found to have the highest contribution to all environmental impact indicators that showed the importance of cleaner production strategies for sustainable pavement construction.
- The overall GHG emissions were to be highest for Evotherm™ due to higher energy use and mixing emission factors. On the contrary, Sasobit® had the best performance in terms of minimum carbon footprint.
- Although WMA generally performed better in terms of reduced mixing emissions, inclusion of direct and indirect manufacturing related impacts have changed the overall comparisons. Materials extraction and processing had the dominant impact on overall carbon and toxic emissions results.
- In terms of socio-economic impact results, materials extraction and processing and construction phases were found to have the largest contributions when compared to mixing and transportation of pavement materials.

- Stochastic compromise programming results also indicate that when environmental criteria have more importance, Sasobit® is favored. On the other hand, if only socio-economic aspects were considered, Asphamin® WMA had the highest percentage of selection compared to other WMA types.
- In a balanced weighting scenario where environmental and socio-economic weights were equal (EW: 50%, SEW: 50%), Sasobit® was selected at 61%, HMA at 32%, and Evotherm™ at 7%. In all cases, HMA mixture was also selected within the allocation model ranging from 13% to 34%.
- When considering current HMA consumption amounts in the U.S. highways, it is likely to conclude that there is a strong need on increasing the percentage share of WMA mixtures in order to achieve more balanced sustainability performance goals for future. This policy recommendation is proven by the optimization model findings.
- Even though mixing phase was important, it should not be the only criteria to evaluate the overall sustainability performance of WMA and HMA pavements. The supply chain, which includes the contribution of all indirect economic sectors for materials extraction and processing, is also critical for a more holistic analysis. In addition, extending the system boundary by considering the interactions between U.S. sectors helped us to capture all indirect impacts which might minimize errors related to using narrow system boundaries for impact analysis.

- An important source of uncertainty was related to transportation because current article used the truck transportation sector to calculate TBL impacts of pavement material transport. Truck transportation is a very non-homogenies service sector that comprises several establishments primarily engaged in providing general freight. The detailed LCA of freight transportation by modes is critical and can be found in the literature (Facanha and Horvath 2007).
- It is important note that variability ranges chosen for transportation distance, mixing energy use, and chemical additive consumption were also subject to uncertainties. With changing variability ranges, a stochastic compromise programming model might give different results for the allocation of WMAs. For future research, other WMA technologies such as Synthetic Zeolite and WAM-Foam should be assessed as more TBL sustainability indicators become readily available using more process-specific life cycle inventory data.

In combination with relevant environmental data, EIO analysis is useful for understanding the supply chain related indirect environmental impacts, and can minimize the underestimation of environmental interventions due to narrowly defined system boundaries. However, sustainability is not only limited to the environment, and other indicators of sustainability, such as economic and social should also be taken into consideration for a more holistic analysis. LCA studies that consider all dimensions of sustainability impacts of the built environment are very limited, and the current research is an important attempt, which integrates economic and social indicators with the input-output framework as an addition to environmental indicators.

This TBL-LCA methodology can also be advanced in several ways. For example, current methodology uses the supply and use tables of the U.S. However, regional variations can be significant and regional input-output models will be important to analyze region specific sustainability impacts of the built environment. The importance of developing regional version of the existing U.S. EIO-LCA model can be found in the literature (Cicas et al. 2007). Especially, regional EIO models with disaggregated electricity production sector will be critical because regional electricity mix proportions vary as so the sustainability impacts of each region may differ and require different strategies towards shifting to renewable energy source.

Last but not least, the sustainability impacts of imported materials used by U.S. sectors are assumed to be produced with domestic technology even though they are imported from other countries. To have a trade-linked EIO model, multi-regional input-output (MRIO) models can be developed in order to account for the impacts of international trade in a way that sustainability analysis results will account for the technological differences related to production of imported materials. An importance of applying MRIO frameworks in input-output analysis can be found in the literature (Lenzen et al. 2004; Hertwich and Peters 2009; Kanemoto et al. 2011; Tukker et al. 2009).

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