Int J Life Cycle Assess (2014) 19:1488–1505
DOI 10.1007/s11367-014-0753-y

Integrating triple bottom line input–output analysis into life cycle sustainability assessment framework: the case for US buildings

Nuri Cihat Onat · Murat Kucukvar · Omer Tatari

Received: 5 November 2013 / Accepted: 8 May 2014 / Published online: 29 May 2014

Abstract
Purpose With the increasing concerns related to integration of social and economic dimensions of the sustainability into life cycle assessment (LCA), traditional LCA approach has been transformed into a new concept, which is called as *life cycle sustainability assessment* (LCSA). This study aims to contribute the existing LCSA framework by integrating several social and economic indicators to demonstrate the usefulness of input–output modeling on quantifying sustainability impacts. Additionally, inclusion of all indirect supply chain-related impacts provides an economy-wide analysis and a macro-level LCSA. Current research also aims to identify and outline economic, social, and environmental impacts, termed as triple bottom line (TBL), of the US residential and commercial buildings encompassing building construction, operation, and disposal phases.
Methods To achieve this goal, TBL economic input–output based hybrid LCA model is utilized for assessing building sustainability of the US residential and commercial buildings. Residential buildings include single and multi-family structures, while 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 US Department of Commerce. In this analysis, 16 macro-level sustainability assessment indicators were chosen and divided into three main categories, namely environmental, social, and economic indicators.
Results and discussion Analysis results revealed that construction phase, electricity use, and commuting played a crucial role in much of the sustainability impact categories. The electricity use was the most dominant component of the environmental impacts with more than 50 % of greenhouse gas emissions and energy consumption through all life cycle stages of the US buildings. In addition, construction phase has the largest share in income category with 60 % of the total income generated through residential building's life cycle. Residential buildings have higher shares in all of the sustainability impact categories due to their relatively higher economic activity and different supply chain characteristics.
Conclusions This paper is an important attempt toward integrating the TBL perspective into LCSA framework. Policymakers can benefit from such approach and quantify macro-level environmental, economic, and social impacts of their policy implications simultaneously. Another important outcome of this study is that focusing only environmental impacts may misguide decision-makers and compromise social and economic benefits while trying to reduce environmental impacts. Hence, instead of focusing on environmental impacts only, this study filled the gap about analyzing sustainability impacts of buildings from a holistic perspective.

Keywords Buildings · Economic input–output analysis · Life cycle sustainability assessment · Monte Carlo simulation · Triple bottom line

Responsible editor: Alessandra Zamagni

Electronic supplementary material The online version of this article (doi:10.1007/s11367-014-0753-y) contains supplementary material, which is available to authorized users.

N. C. Onat · M. Kucukvar · O. Tatari (✉)
Department of Civil, Environmental, and Construction Engineering, University of Central Florida, 4000 Central Florida Blvd, Orlando, FL 32816, USA
e-mail: tatari@ucf.edu

1 Introduction

The demand for sustainable development is rapidly increasing owing to increased consciousness of environmental, economic, and social concerns. Buildings are often considered as an important and integrated part of sustainable development due to their critical roles in the society, economy, and environment. The US 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 and commercial buildings accounts for roughly 40 % of the total US energy consumption in 2012 (US EIA 2013). Thirty percent of landfill content is composed of construction demolition and debris (NRC 2009). Building construction and operations are responsible for 38.9 % of greenhouse gasses (GHGs) emitted in the USA (EIA 2008). Residential and commercial buildings are also important components of the US 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, and petroleum), transportation (commuting), water use, maintenance, repair, and construction of the buildings (Onat et al. 2014b). Additionally, construction industry is one of the driving sectors in the US economy. The total construction spending in 2012 was 865,989 millions of dollars (US DOC (Census 2012). This is approximately 5.7 % of the US GDP in 2011 (CIA the Worldfact Book 2013). Hence, sustainability of the buildings should be assessed considering environmental and economic constraints, social and political effects, and limits of natural resources (Kibert 2012).

1.1 Life cycle assessment

Life cycle assessment (LCA) is a widely used methodology to quantify the environmental impacts of products or processes from cradle to grave including material extraction and processing, transportation, use, and end-of-life phases (Finnveden et al. 2009). LCA was developed in the early 1990s as powerful methodology in which potential environmental impacts are analyzed in a systematic way. Goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation are the main consecutive steps of the LCA method (Graedel & Allenby 2009). Economic input–output analysis (EIOA) is a powerful tool which has been used for analyzing the supply chain wide resource requirements and environmental impacts of products or systems (Hendrickson et al. 2006). In the literature, I-O methodology has been utilized to analyze the sustainability impacts of infrastructure projects and buildings by using the economic input–output LCA (EIO-LCA) tool, which was developed by the Green Design Institute at Carnegie Mellon University (Carnegie Mellon University Green Design 2008). To name a few, construction sectors were analyzed by (Hendrickson & Horvath 2000), advanced construction processes by (Bilec et al. 2006; Sharrard et al. 2008), building retrofitting by (Beccali et al. 2013; Cellura et al. 2013a), and residential buildings by (Cellura et al. 2013b; Heinonen et al. 2011; Onat et al. 2014b). On the other hand, the ecologically based LCA (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 (Ohio State University 2013). A first detailed Eco-LCA study of construction industry was conducted by Tatari and Kucukvar (Tatari & Kucukvar 2012) where natural resource consumption and atmospheric emissions of the US construction sectors were analyzed. The researchers analyzed the direct and indirect role of ecological resource consumption using several metrics such as mass, energy, and ecological exergy. However, due to the large impacts on the economy and society, it is necessary to account for the direct and indirect social and economic implications from a holistic perspective. While former I-O-based LCA models can only quantify environmental burdens, the triple bottom line (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 I-O framework as an addition to environment.

TBL concept focuses on the three main pillars of sustainability such as environment, economy, and society (Wiedmann & Lenzen 2006; Wiedmann et al. 2009). In the literature, Foran et al. (Foran et al. 2005a) developed a first comprehensive I-O-based TBL model of the industrial sectors of an entire economy for Australia. This model has been named as *Balancing Act* that integrates the I-O tables with environmental, economic, and social metrics for 135 sectors. Researchers from the University of Sydney established the foundation of the I-O model for the Balancing Act study and created a TBL software tool for Australia, UK, and Japan economies. Several studies were conducted using the TBL version of the I-O by presenting first examples of TBL accounting in the I-O context (Foran et al. 2005b; Wiedmann & Lenzen 2009). On the other hand, TBL model of the USA (TBL-LCA) has been created by Kucukvar and Tatari (Kucukvar & Tatari 2013) which was initially used to quantify the TBL implications of seven different US construction sectors. The TBL-LCA model has been also applied to assess sustainability of asphalt pavements (Kucukvar et al. 2014), food manufacturing sectors (Egilmez et al. 2014), and wind turbines (Noori et al. 2013).

The literature is abundant with the applications of LCA addressing environmental impacts of residential (Ardente et al. 2011; Blanchard & Reppe 1998; Cuéllar-Franca & Azapagic 2012; You et al. 2011) and commercial buildings (Junnila et al. 2006; Scheuer et al. 2003; Van Ooteghem & Xu 2012). Most of the LCA studies analyzing buildings are not very easy to compare due to differences in the goal, scope definition, selected system boundary, functional unit, and specific properties such as building type, climate, local regulations, etc. (Cabeza et al. 2014). However, methodology of the LCA studies can be classified under three main groups, process-based LCA (P-LCA), I-O-based LCA, and hybrid LCA, which is the integration of the former two methodologies. While P-LCA is often utilized when a single or several buildings type are analyzed, I-O-based LCA is mostly preferred when studies are subject to a wider scope or larger scale such as studies at national, state, and city level (Peters 2010). The methodology of this paper is a hybrid-based LCA in which the TBL-LCA model and process-based LCA are integrated.

1.2 Motivation and organization of the research

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 (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 (Zamagni 2012). Although previous studies analyzed the life cycle environmental impacts successfully, there is no study assessing and quantifying the sustainability of the US residential and commercial buildings using LCSA framework. This paper aims to identify and outline the TBL hotspots of the US residential and commercial buildings through their life cycle phases encompassing building construction, operation and disposal, and supply chain of those phases. In accordance with the recent developments in LCSA research, this study also aims to contribute the existing LCSA framework in two directions: (1) horizontal direction: integrating several social and economic indicators into LCSA framework and (2) vertical direction: consideration of all indirect supply chain-related impacts within the LCSA framework, which was called as economy-wide macro-level analysis in (Guinée et al. 2011). The TBL impacts are accounted from a broader perspective: direct (on-site) and indirect (supply chain) burdens. Owing to the broader scope of analysis, an I-O-based LCA model is utilized to trace the impacts across the supply chains and direct impacts related to the US buildings. Considering that recent trends also emphasize the inclusion of three pillars of sustainability as economy, society, and the environment as well as supply chain-related indirect impacts, the proposed methodology perfectly fits to the needs of such a comprehensive sustainability assessment understanding (Sala et al. 2012a; Sala et al. 2012b; Zamagni et al. 2012).

To achieve these goals, a hybrid I-O-based industry-by-industry TBL version of the US I-O 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 US Department of Commence detailed output accounts (BEA 2008). Organization of the paper is explained as follows. First, methodology of the model is explained mathematically. Next, data collection, inventory analysis, and the intended use of data are briefly explained. In the following subsection, sustainability indicators of the TBL-LCA model are presented. In Section 3, TBL sustainability impacts of the residential and commercial 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.

2 Methodology

The TBL-LCA, an input–output (I-O)-based LCA model, was utilized to analyze sustainability impacts of residential and commercial buildings including supply chain impacts of each life cycle component. The I-O analysis was developed and introduced by Wassily Leontief in the 1970s for which he was awarded with the Nobel Prize in 1973 (Leontief 1970). The I-O model consists of identical sectors and monetary transactions, among those sectors make up the economic structure of a country (Hendrickson et al. 2006). There are various studies utilizing the I-O-based LCA approach which has been applied to analyze sustainability impacts of corporates (Huang et al. 2009a), products (Joshi 1999), supply chain activities (Weber & Matthews 2008a), final consumption (Cellura et al. 2013b; Wiedmann et al. 2006; Wood & Garnett 2010), energy systems (Kucukvar & Tatari 2011; Wiedmann et al. 2011), manufacturing sectors and systems (Egilmez et al. 2013; Williams 2004), and US buildings (Ochoa et al. 2002; Onat et al. 2014b).

IO-based models integrate the environmental impacts and the financial flow data derived from the supply and use tables of an economy. In addition to environmental impact indicators, the TBL-LCA model merges comprehensive social and economic indicators with the I-O accounts. Many countries publish their I-O tables routinely. Financial flow data are represented by the supply and use tables. The US Bureau of Economic Analysis, as part of the International System of National Accounts, publishes the supply and use tables in the USA (BEA 2002). All sectors within the supply and use tables are classified according to the North American Industry Classification System (NAICS).

In this paper, the supply and use tables, published for the year 2002, are converted into a symmetric I-O table. The supply table shows the supply of goods and services by product. The supply table includes the production matrix of domestic industries and the vector of total imports. On the other hand, the use table shows the use of goods and services by product such as intermediate consumption of industries or by final consumption categories including household demand, private fixed investments, government purchases and investments, and export of good and services. It also contains the value-added components by each sector such as compensation of employees, other taxes with less subsidies on production, and gross operating surplus. Basically, the supply and use framework integrates the supply and use tables in a single matrix (Eurostat 2008; Miller & Blair 2009).

For the integration of supply and use tables into symmetric I-O table, various assumptions are initially made. First, the format of symmetric I-O table is based on the industry-by-industry which is previously used in other I-O models for macro-level TBL analysis (Carnegie Mellon University Green Design 2008; Foran et al. 2005a; Wiedmann et al. 2009). This model basically represents total impacts, which is direct plus indirect (upstream) embodiments of TBL, per unit of final demand of commodities produced by economic sectors. Also, the transformation of supply and use tables to symmetric industry-by-industry I-O table is based on fixed industry sales assumptions which assume that each industry has its own specific sales structure, regardless of its product mix. For detailed information on conversion of the supply and use tables into a symmetric industry-by-industry model, please refer to reference reports published by the Eurostat and United Nations (Eurostat 2008; United Nations 1999). More detailed information about the TBL-LCA model is given in the supporting information (SI) file available at the journal's website.

In addition to the roles of the supply and use framework mentioned above, TBL-LCA framework can also be used in conjunction with various satellite accounts including social accounting matrix (SAM) (income, employment, injuries, etc.), physical inputs (ecological land footprint and water and energy consumption), and other physical outputs related to environmental issues (carbon emissions, hazardous waste, toxic releases, etc.) Then, a vector of sustainability impacts can be formulated as follows (Miller & Blair 2009).

$$\mathbf{r} = \mathbf{M}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{f} \tag{1}$$

In this equation, **r** denotes the total impacts vector that represents the absolute values of TBL sustainability impacts associated with all upstream production processes. **M** is an $m \times n$ matrix where m represents the number of indicators and n is the number of economic sectors. **M** matrix shows TBL indicators across the contributing industries based on per million dollars of economic output. **I** is the $n \times n$ identity matrix, and **f** is the $n \times 1$ total final demand vector for industries. **A** is an $n \times n$ direct requirements matrix that is presented in the Leontief's I-O model. Also, the term $(\mathbf{I}\text{-}\mathbf{A})^{-1}$ represents the total requirements matrix, which is also known as the *Leontief inverse* (Leontief 1970).

Typical processes that are well represented in I-O categories at sector level can be accounted through I-O models, while the rest of the processes can be modeled through process level data (Suh et al. 2004). This approach is known as hybrid LCA, which has been mostly preferred for studies at county, city, and national scales (Peters 2010). I-O 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 to combine the advantages of both the process and I-O models (Suh & Lippiatt 2012). For more information about the different types of hybrid LCA approaches, please see (Suh et al. 2004).

The type of the hybrid LCA utilized in this study is a tiered hybrid approach in which the process level data used to calculate sustainability impacts the final activities. The process level impacts are calculated manually rather than creating a matrix of coefficients which include the foreground units of the processes. Therefore, a single formulation was not applicable for representing the way direct impacts are calculated. For example, process of petroleum combustion is calculated by multiplying the GHG emission factor and the amount of petroleum combusted. Additionally, the TBL-LCA model was utilized to find sector level impacts as a result of final demand from each life cycle activity. More detailed information about the calculation of process level impacts and the related inventory are given in the following section and in the SI file. On the other hand, there are other applications of tiered hybrid-LCA models where the processes are defined as a set of matrixes and integrated into the main I-O model (Suh et al. 2009).

2.1 Data collection

Data used in this study is collected mainly from publicly available sources such as the US Bureau of Economic Analysis (BEA), the Federal Highway Administration (FHWA), the US Environmental Protection Agency (EPA), the US Department of Energy (DOE), and the US Energy Information Administration (EIA). Some of the data are collected through former studies in the literature. Table 1 shows the majority of the data sources in detail. The rest of the data sources are presented within this section.

Majority of data used in the analysis can be divided into two main categories 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 taken from Greenhouse Gas Inventory Protocol (Climate 2008). The second aim was to find supply chain emissions and some of the

Table 1 Data sources

Parameters	Unit	Data		Data source
		Residential	Commercial	
Electricity use	Billion kWh	1,265	1,205	EIA (EIA 2012a)
Electricity price	Cents/kWh	8.44	7.89	EIA (EIA 2012a)
Natural gas use	Billion m^3	138.44	89.03	EIA (EIA 2012b)
Natural gas price	$\$/m^3$	0.278	0.234	EIA (EIA 2012b)
Petroleum use	MBL/day	817	376	EIA (EIA 2012a)
Petroleum price	$/MBL	27.56	27.56	EIA (EIA 2012a)
Water use and wastewater	Billion liters	39,693	14,153	Building Energy Data (Building Energy Data 2005a) Building Energy Data (Building Energy Data 2005b)
Water and wastewater price	$/kL	1.17	1.09	Fisher et al. (Fisher et al. 2008)
Building maintenance and repair	Million ($)	47,379	43,645	BEA (BEA 2002)
Building construction	Million ($)	304,950	129,239	BEA (BEA 2002)
Total commuting distance	Million Km	989,747[a]		FHWA (FHWA 2002a)
Average national gas consumption	KPL	9.35		FHWA (FHWA 2002b)
Automobile maintenance and repair costs	$/km	0.076		Transportation Energy (Transportation Energy 2011a) Transportation Energy (Transportation Energy 2011b)
Injuries during commuting	Number of people	123,170		BTS (2012)
Natural gas energy density factor	J/m^3	38,845,923		Wilcock (2005)
Petroleum energy density factor	J/l	31,700		US DOE (2013)

MBL thousands barrels of petroleum liquid, *kL* kiloliter, *KPL* kilometer per liter

[a] Total commuting distance is divided into two equal pieces in distance by assuming that commuting is a two-way travel between commercial and residential building when the impacts are evaluated separately for each building category

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. For instance, greenhouse gas (GHG) emissions from combustion of natural gas are calculated with process level data given in Table 1, whereas GHGs emitted from the supply chain of natural gas production are determined by using sector level data from the TBL-LCA model. The process of combustion basically has two variables, which determine the amount of greenhouse gas emitted during the activity. First parameter is the amount of the natural gas combusted (unit of volume; please see Table 1). The second parameter is the emission factor per unit of natural gas which is obtained from Greenhouse Gas Inventory Protocol (Climate 2008). When these two are multiplied, the process emission can be obtained. On the other hand, sector level data refers to the emissions from supply chain of related activity. For the case of natural gas, it refers to the emissions from production of natural gas used in the combustion activity. To calculate these emissions, firstly, monetary value of the natural gas consumed is calculated by using the data given in Table 1. Simply, the amount of natural gas (unit of volume) is multiplied by the producer price ($) per volume unit of natural gas. At the end, we obtain a monetary value of the natural gas consumption. Later, this value is entered the Natural Gas Distribution Sector (NAICS 221200) in the TBL-LCA model. The multipliers (impact factor per $M) of the TBL-LCA model is also given in Table 2 in which the supply chain emissions can be calculated manually. Finally, the total emissions from the supply chain are obtained. Sum of those two emissions will give us the total emissions generated as a result of natural gas combustion activity. Similarly, 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, which are also presented in Table 2 (number of people injured per $M economic output of the related sector). Industry multipliers for the indicators of hazardous waste, GHG emission, and water footprint are taken from the EIO-LCA model (Carnegie Mellon University Green Design 2008). The process level impacts are shown in the Table S1 in the Electronic Supplementary Material.

2.2 Sustainability assessment indicators

In this research, 16 macro-level sustainability assessment indicators were chosen and divided into three main categories, which are environmental, social, and economic indicators.

Table 2 Sector multipliers per $M output

	Construction Phase		Use Phase								End of Life
	Const. Act.-Res.	Const. Act.-Com.	Elect. use	Nat. gas use	Petr. use	Water and wastewater	Maint. and rep.-Res.	Maint. and rep.-Com.	Commuting		Const. waste man.
NAICS Sector ID	230201	230101	221100	221200	324110	221300	230302	230301	324110	8111A0	562000
Foreign purchase ($M)	0.107	0.097	0.099	0.391	0.853	0.090	0.109	0.081	0.853	0.969	0.056
Business profit ($M)	0.308	0.233	0.488	0.522	0.545	0.462	0.486	0.232	0.545	0.314	0.369
Income ($M)	0.640	0.730	0.364	0.357	0.345	0.563	0.466	0.729	0.345	0.594	0.587
Government tax ($M)	0.046	0.033	0.143	0.113	0.100	−0.029	0.044	0.035	0.100	0.076	0.039
Injuries (number of worker)	0.941	1.003	0.290	0.322	0.329	0.373	0.692	0.972	0.329	0.865	0.437
Fishery (gha)	0.215	0.169	0.273	0.152	0.153	0.179	0.194	0.152	0.153	0.187	0.385
Grazing (gha)	0.182	0.144	0.174	0.119	0.126	0.152	0.186	0.147	0.126	0.411	0.507
Forestry (gha)	23.18	11.88	1.34	2.21	1.73	3.78	31.00	13.76	1.73	1.59	1.35
Cropland (gha)	20.00	8.52	3.88	2.92	4.67	4.44	24.08	13.55	4.67	3.52	6.41
Carbon fossil fuel (gha)	137.07	123.30	1,853.92	553.73	492.07	248.03	146.77	131.52	492.07	61.90	72.49
Carbon electricity (gha)	32.87	26.03	13.08	28.43	57.46	33.15	29.60	24.50	57.46	34.16	20.80
GHG total (t)	645	578	8,244	3,045	2,777	1,774	685	613	2,777	312	2,535
Total energy (TJ)	8.91	8.40	98.22	33.59	31.57	18.71	9.43	8.69	31.57	4.74	5.19
Water (kL)	28,853	17,582	829,611	104,956	32,305	77,225	28,824	20,616	32,305	19,596	18,126
Haz. Waste (st)	226,266	174,096	125,508	183,542	4,112,658	211,606	219,507	213,310	4,112,658	172,182	2,388,554

GDP multiplier is 1.00 for all sectors

The economic indicators selected for this analysis are foreign purchase (imports), business profit, and gross domestic product (GDP). Considering that US buildings were studied at national level, economic indicators which are more meaningful at national level were preferred. In smaller scales, Life cycle cost (LCC) assessment can be also integrated with the existing indicators to account for economic feasibility and performance of buildings. Since a single lifetime assumption and a certain building characteristic cannot represent the whole building stock in the USA, LCC assessment was not included in this study. Moreover, LCC assessment alone is not sufficient to measure economic impacts at national level. Therefore, traditional economic indicators representing national economic strength such as GDP, imports, and business profit are selected in this study. Moreover, these indicators are important for the US building sector due to its significant role and supply chain interactions with other major sectors within the US economy. Foreign purchase represents the value of imports in dollars to produce domestic services or commodities, which has adverse effect to the economy considering that an excess of imports cause an increase in the current deficit through the flow of money out of the country. Higher exports and lower imports increase the GDP, while reduced exports and higher imports contract GDP. If the gap between imports and exports (trade deficit) shrinks, GDP may be affected positively (Foran et al. 2005a; Foran et al. 2005b). Additionally, GDP and business profit indicators represent contributions to the US economy and business capital of the industries, respectively.

Social indicators of the analysis are income, government tax, and injury. As the building sector interacts with other major sectors such as construction, power generation and supply, petroleum refineries, and natural gas production, etc., the selected social indicators aimed to reflect important characteristics of these sectors. For example, the US construction sector is responsible for the largest share of work-related injuries and illnesses (Waehrer et al. 2007). Injury is a negative social indicator owing to the adverse effect to social well-being and quality of life as a result of work-related injuries and illnesses (Dietzenbacher et al. 2013; Kucukvar & Tatari 2013; Matthews & Lave 2000). Income is considered as a positive social indicator due to its contribution to social welfare of households, which represents the compensation of employees such as salaries and wages. Taxes are chosen in this study 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 (Wiedmann et al. 2009; (Wiedmann & Lenzen 2009).

GHG emissions, energy consumption, water footprint, and hazardous waste generation are accounted to assess environmental impacts of the US buildings. These environmental footprint categories were already used in various LCA studies (Blackhurst et al. 2010; Onat et al. 2014b; Williams 2004). These indicators are very common in most of LCA studies as well as in building LCA studies. As stated previously in the introduction, the energy consumption and GHG emissions from a building are very high in the USA. Besides, majority of electricity used in the US buildings comes from coal-based power plants which are responsible for 40 % of the total water withdrawal in the USA. (Kenny et al. 2009). Therefore, water is also an important indicator for assessing environmental impacts of the US buildings. The ecological footprint indicators are also considered as a part of the environmental dimension, which have already been used as a measure of environmental sustainability in previous input–output studies (McDonald & Patterson 2004; Turner et al. 2007; Zhang et al. 2010). Ecological footprint is a measure of the biologically productive areas required to absorb the waste generated as a result of activities (Wackernagel et al. 1999). In this analysis, the ecological footprint is measured in terms of global hectares (gha) for the following land types: fishery, grazing, forest land, cropland, and CO_2 uptake land. More detailed information about ecological indicators, total footprint amounts per capita, and allocation method are provided in Table S2 in the Electronic Supplementary Material.

3 Results and discussion

Analysis results are presented in the following subsections 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 US buildings. After comparing the TBL impacts of residential and commercial buildings, sensitivity of the model inputs is analyzed.

3.1 Economic impacts

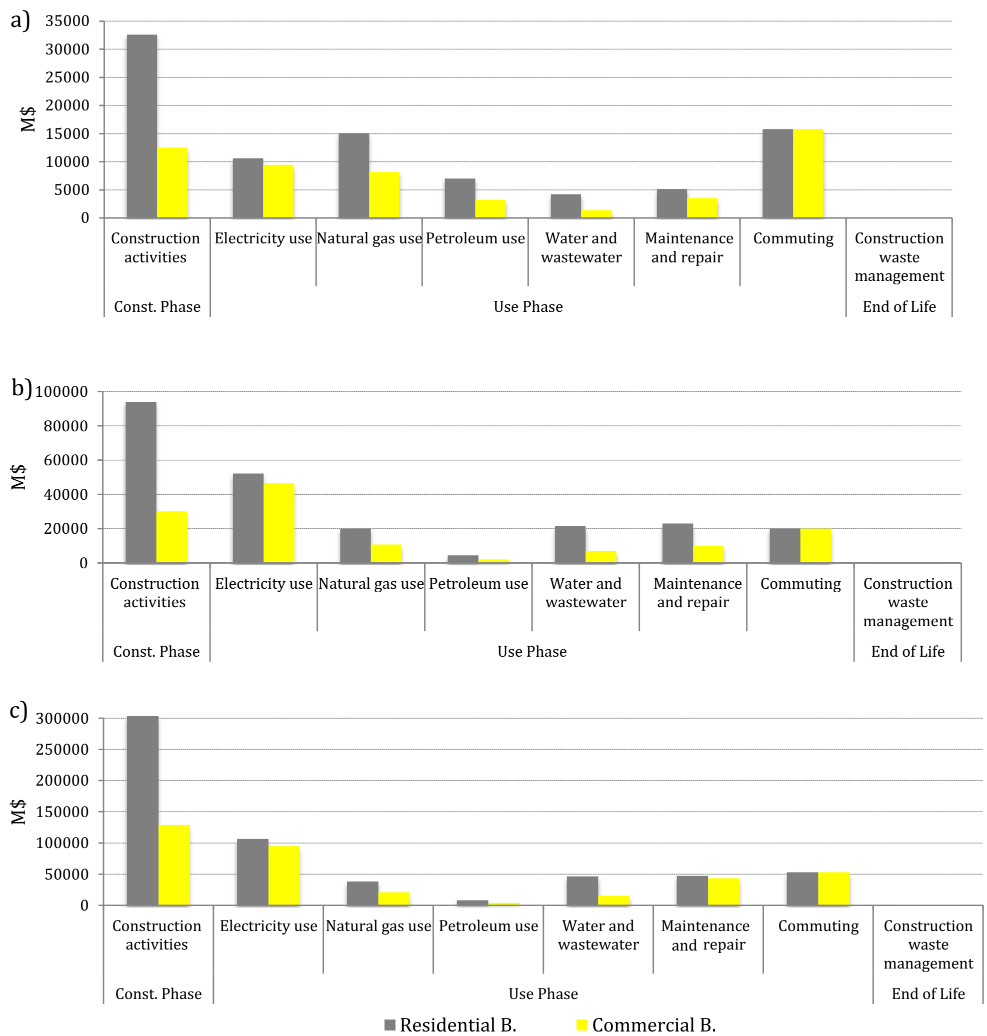
Figure 1 indicates the economic impacts of residential buildings and commercial buildings. Residential construction phase is the most influential component among the economic impact categories and life cycle phases of residential buildings. Residential construction sector and its supply chain are responsible for 36 % of the foreign purchase, 40 % of the business profit, and 50 % of the GDP contribution. Also, electricity use is the second largest contributor to GDP and business profit—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 US economy considering their foreign purchase shares, which add up 70 % of the total foreign purchase. Almost 36 % of residential construction's foreign purchase 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 5 in the supply chain of residential construction rector. However, contribution of these supply chain sectors to the GDP and business profit of the residential construction sector is very low compared to their negative impacts to the economy. More than 40 % of the residential construction phase's contribution to GDP and foreign purchase is coming from the residential building construction sector (NAICS 230201) and its supply chain sectors of real estate (NAICS 531000) and retail trade (NAICS 4A0000).

In commercial buildings, commuting has the largest share of foreign purchase with almost 30 % of the total, whereas contribution to business profit and GDP are only 16 and 15 %, respectively. Hence, reducing commuting distance and related expenditures should be prioritized when developing strategies aiming to improve economic performance of commercial buildings. Also, construction activities, electricity, and natural gas consumption made up significant portion of foreign purchase with more than half of the total. Oil and gas extraction (NAICS 211000) is a major supply chain sector causing foreign purchase of those life cycle components. Construction phase and electricity use constitute more than 55 % of the total GDP and business profit. Especially, electricity consumption is found to have the highest contribution to GDP and business profit among other use phase components. More than 60 % of GDP and business profit generated by electricity consumption in commercial buildings are coming from electric power generation and distribution (NAICS 221100), state and local government electric utilities (NAICS S00202), and oil and gas extraction sectors (NAICS 211000).

3.2 Social impacts

Social impacts of residential buildings are represented in Fig. 2. 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 other hand, construction sectors and commuting are responsible for more than 80 % of the injuries.

Fig. 1 Economic impacts of residential and commercial buildings. **a** Foreign purchase ($M), **b** business profit ($M), **c** contribution to GDP ($M)



Fifty percent 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.

Income generated during life cycle phases of commercial buildings highly depends on construction phase, which has slightly lower share than that of residential buildings. On the other hand, electricity consumption of commercial buildings is driving the government tax category with more than 50 % share and 82 % of it is collected through power generation sector (NAICS 221100) directly. Commuting and construction activities are the main sources of the work-related injuries with 43 and 34 %, respectively. Sixty-three percent of injuries in construction phase of commercial buildings are resulted from on-site construction activities. Also, 75 % of commuting-related injuries occurred during the commuting, whereas 25 % of injuries took place in automotive maintenance and repair (NAICS 8111A0), petroleum refineries (NAICS 324110), and their supply chain. Construction phase, electricity consumption, and commuting are the major components of social impacts of commercial buildings overall.

3.3 Environmental impacts

Figure 3 indicates the environmental impacts of residential and commercial buildings. According to the analysis results, natural gas and electricity use account for 72 and 78 % of the total energy consumed in the residential and commercial 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 US 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, business profit, and government tax should be taken into account, and the tradeoff 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

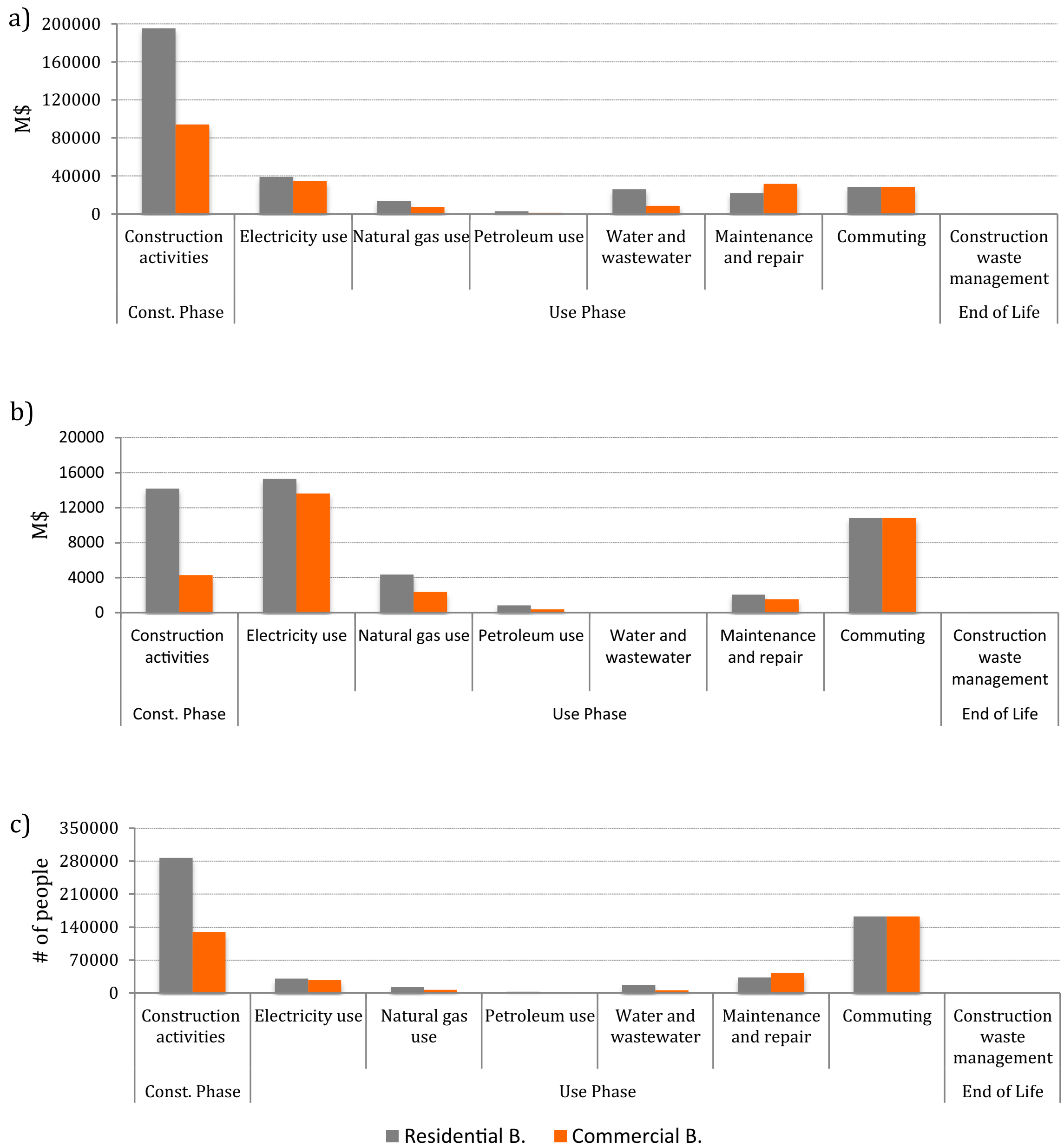


Fig. 2 Social impacts of residential and commercial buildings. **a** Income ($M), **b** government tax ($M), **c** injuries (number of people)

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 (Onat et al. 2014b). 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. Water withdrawal due to electricity consumption in commercial buildings is 78 % of the total water consumption of commercial buildings, which is fivefold of direct water consumption in commercial buildings.

Construction activities and commuting are the major hazardous waste sources in residential and commercial buildings. When the supply chain of 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 both residential and commercial buildings. Petroleum

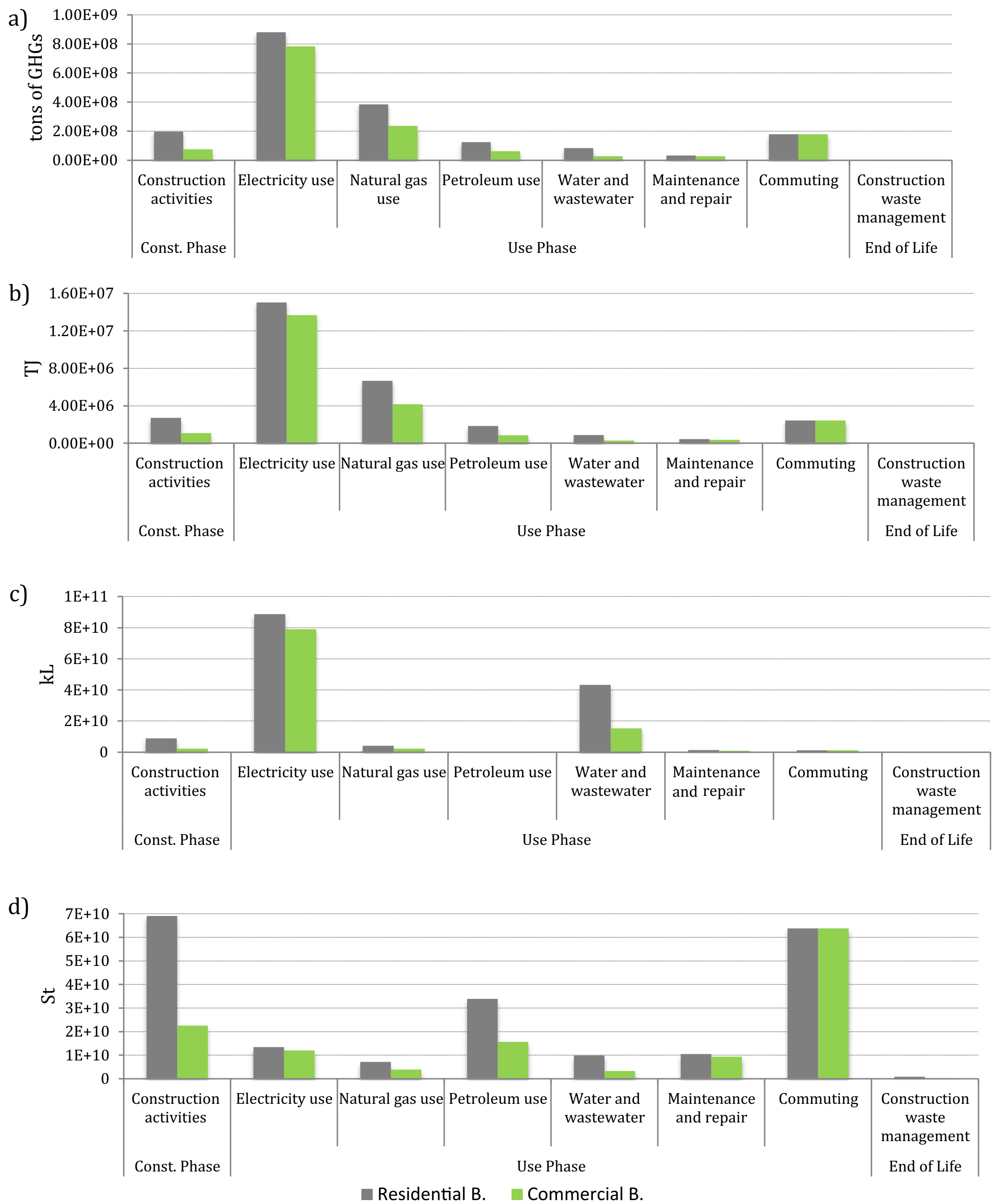


Fig. 3 Environmental impacts of residential and commercial buildings. **a** GHG total (t), **b** total energy (TJ), **c** water consumption (kL), **d** hazardous waste (st)

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.

The ecological footprint trend is very similar in both types of buildings. As can be seen from Fig. 4, electricity use has the highest ecological footprint, which made up 45 and 54 % of the ecological footprints of residential and commercial buildings, respectively. High use of fossil fuels in power generation sector is the primary reason of its high ecological footprint. Influence 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 US buildings. It is also the largest contributor to the world's current ecological footprint (GFN 2005; GFN 2010).

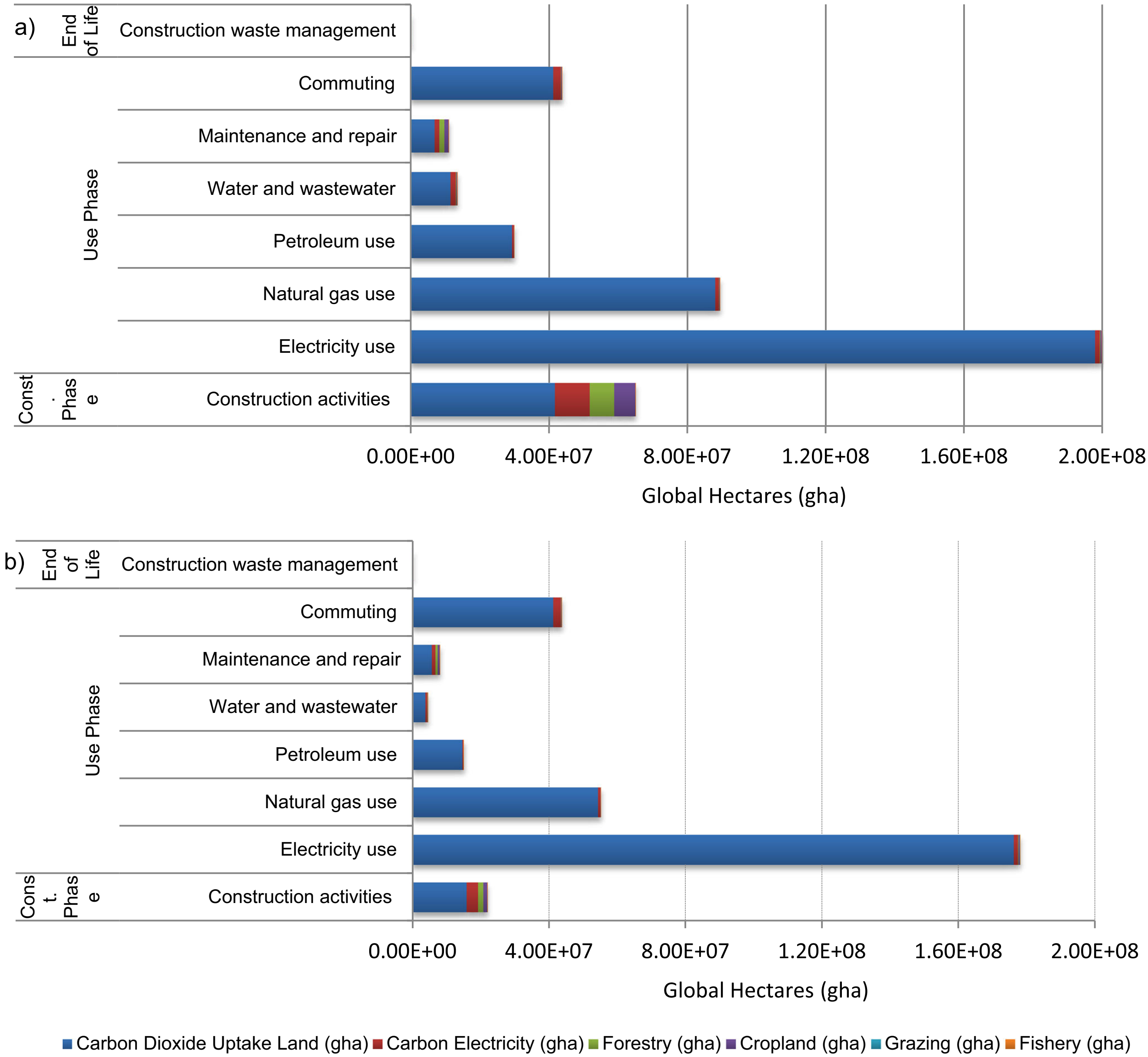


Fig. 4 Ecological footprint results. **a** Residential buildings, **b** commercial buildings

The total CO_2 uptake land footprint of the US 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 absorb annual $C0_2$ emissions of the US buildings in a year 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 US buildings are found to be less than 1 %.

3.4 Comparison of TBL impacts of residential and commercial buildings

Table 3 indicates that residential buildings have higher impact in all of the sustainability impact categories. The impact share of residential buildings ranges from 57 % (share of residential buildings within the total energy consumption in the US buildings) to 79 % (share of residential buildings within the total deforestation of US buildings) at maximum. As it was explained in the previous sections, construction phase, electricity use, and commuting played important roles in much of the sustainability impact categories, so the differences in demand, supply chain elements, and the energy consumption

Table 3 Comparison of TBL impacts of residential and commercial buildings

	Sustainability indicators	Residential	Share (%)	Commercial	Share (%)
Economic	Foreign purchase ($M)	9.05E+04	63	5.41E+04	37
	Business profit ($M)	2.36E+05	65	1.27E+05	35
	GDP ($M)	6.03E+05	63	3.60E+05	37
Social	Income ($M)	3.28E+05	61	2.07E+05	39
	Government tax ($M)	4.75E+04	64	2.66E+04	36
	Injuries (number of worker)	5.45E+05	59	3.76E+05	41
Environmental	GHG total (t)	1.88E+09	58	1.39E+09	42
	Total energy (TJ)	3.00E+07	57	2.29E+07	43
	Water (kL)	1.48E+11	59	1.01E+11	41
	Haz. waste (st)	2.08E+11	61	1.30E+11	39
Ecological	Fishery (gha)	1.29E+05	65	7.05E+04	35
	Grazing (gha)	1.14E+05	64	6.51E+04	36
	Forestry (gha)	9.04E+06	79	2.46E+06	21
	Cropland (gha)	8.22E+06	77	2.41E+06	23
	CO_2 uptake land (gha)	4.17E+08	57	3.12E+08	43
	Carbon electricity (gha)	1.81E+07	66	9.16E+06	34

of the sectors shaped majority proportional variations in sustainability impact categories. Another reason of this domination of residential buildings over commercial buildings can be the higher number of existing residential buildings, which can pave the way for greater economic activity and energy demand throughout all of the life cycle stages. For example, the amount of economic and some of the social impacts are directly affected by demand of residential and commercial construction sectors because the economic output of the residential construction sector (NAICS 230201) is almost 2.5 times greater than that of commercial construction sector (NAICS 230101) (BEA 2008).

As can be seen from Table 3, the proportional differences in much of the sustainability impacts have similar trend due to the abovementioned reasons. On the other hand, the forestland footprint (forestry) can be thought as an outlier because of its high variation of shares between building types. However, if the supply chains of residential and commercial building construction are compared, the main reason for the high share of residential building's forestland footprint can be understood better. Economic activity of some supply chain sectors of residential building construction such as sawmills and wood preservation (NAICS 321100), logging (NAICS 113300), veneer and plywood manufacturing (NAICS 32121A), and

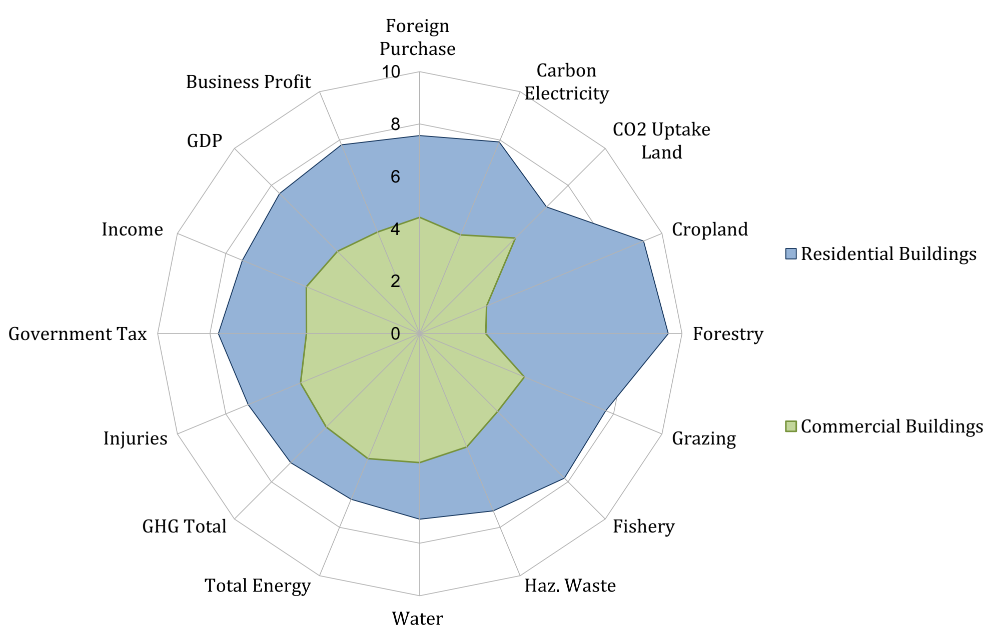


Fig. 5 Spider diagrams of TBL impacts of residential and commercial buildings

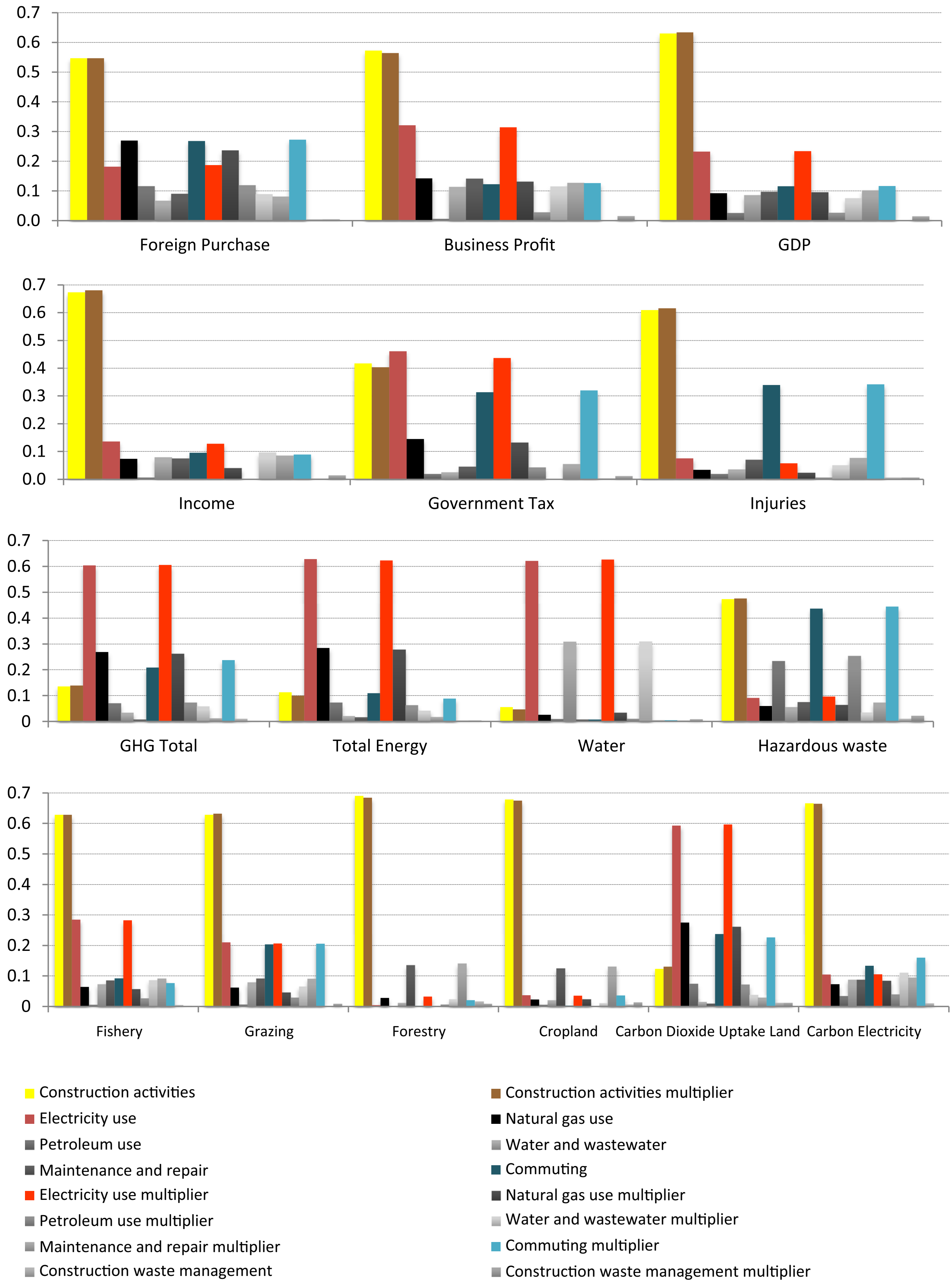


Fig. 6 Sensitivity analysis of critical input parameters of residential buildings (moment correlation)

reconstituted wood product manufacturing (NAICS 321219) are approximately four times greater than that of the commercial building construction sector. In other words, use of wood material is much higher in residential buildings. One the other hand, the shares for total energy, GHG emissions, and CO_2 uptake land are relatively similar, which indicate that majority energy sources of the US buildings are mainly provided through fossil fuels due to the high correlation between the energy use and GHG emissions. Additionally, the relative TBL impacts of residential and commercial buildings according to 16 sustainability indicators can be seen from Fig. 5.

3.5 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 sustainably impacts by category were investigated. Similar sensitivity analysis was also conducted by Tatari et al. (Tatari et al. 2012). The software utilized to run Monte Carlo simulation was Risk Solver Pro (Frontline Risk Solver 2013). The model inputs were divided into two main categories. First input type was the final demand of sectors related with life cycle component of the US buildings. These inputs were calculated by using the data given in Table 1. 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 in the TBL-LCA model. Deterministic values of the inputs were assumed as the average values of the distributions.

The other input 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, and energy use) per million dollar output of each sector. These multipliers incorporate the characteristics of sectors including their technological level. In addition, the multipliers were improved by including the energy prices and impacts of some of the processes that are not presented in the TBL-LCA model such as emissions from combustion process of natural gas in the US buildings. After calculating the modified multipliers, a normal distribution whose standard deviation is 10 % of the average was assigned to all multipliers. In total, 16 inputs were defined and 10,000 iterations were made in the Monte Carlo simulation. While half of the inputs are the sectorial demand values, the other half is the corresponding multipliers related to each life cycle activity and associated sectors. Figure 6 illustrates the associated sensitivity results by showing how each of the input parameters correlates with the total sustainability impact for each category.

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 (energy consumption, GDP, government tax, GHG emissions, water use, etc.). The main picture intended to be explored is the effect of inputs on the final sustainability impact results. Correlation between input parameters (e.g., electricity use and electricity sector multiplier) is not investigated since they are independent from each other. If more detailed sensitivity analysis such as sensitivity of second or third order multipliers in the supply chain is desired, Monte Carlo analysis may not be the most suitable way. For more information about detailed sensitivity analysis to apply matrix-based LCA models, please see Heijungs's work (Heijungs 2010). 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 ecological impacts are highly correlated with the economic output and multiplier of the residential construction sector. In other words, any improvement in residential construction sector can be a sound strategy to improve overall social, economic, and ecologic effects of 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, energy, and water consumption, so this analysis identified that possible reductions in electricity consumption and improvements in electricity multiplier are a vital strategy to reduce the environmental impacts of residential buildings. Improving the electricity multiplier means reducing the environmental impacts per million dollar output of the electric power generation sector. This can be achieved by increased energy efficiency of power generation sector and shifting to renewable energy sources to generate electricity. Also, on-site renewable energy systems can be a good strategy to avoid energy losses in the transmission lines which is about 7 % of the electricity generated at power plants (Building Energy 2010).

4 Conclusions

Since the general picture was explored and TBL effects were quantified, effective sustainable development strategies can be generated, and these effects can be optimized based on priorities of the decision-makers. According to the analysis results, construction activities, electricity consumption, and commuting are more dominant compared to other life cycle components. In general, the electricity consumption of the US buildings has more environmental impacts, while the construction activities are more effective on the amount of social and economic impacts. Although natural gas and petroleum consumption, maintenance and repair, water and wastewater, and construction waste management have relatively lower impacts, making policy impacts of those components should not be neglected. This is because the importance of these life cycle components may vary based on the requirements of different policymakers and geographic regions. For instance, reducing water footprint might be prioritized in some regions where there is water scarcity. 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. Differences in sustainability impacts of commercial and residential construction phases are good examples showing how the supply chain characteristics play a vital role on the analysis results. Hence, analyzing supply chain parameters is crucial when conducting a LCSA. Using narrowly defined system boundaries can cause significant underestimation of social, economic, and environmental impacts.

When the results are 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 US population, report their recycle and reuse rates of their construction and demolition (C&D) debris (EPA 2003). Furthermore, what constitutes the C&D debris and definitions of recycling and reuse are not standardized by the states. 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 decisive 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. However, the results of the sensitivity and the TBL-LCA analysis should be evaluated together to avoid possible misinterpretations.

The described TBL-LCA framework might be a good starting point for more comprehensive LCSA of buildings since no study has been found analyzing TBL impacts of US buildings. This study broadens the current building LCA framework from environmental impacts only to inclusion of three pillars of sustainability as economy, society, and environment. Especially, inclusion of social and economic indicators showed that focusing only environmental impacts may misguide decision-makers and compromise social and economic benefits while trying to reduce environmental impacts. For instance, in the case of reducing electricity-related emissions through increased energy efficiency or less electricity consumption will decrease the amount of taxes collected through power generation sector. Similar tradeoffs can be observed among the other sustainability indicators as well. Another critical approach of this research was to consider both the direct and indirect TBL impacts associated with the chain of supply paths of buildings because many studies have been found in the literature showed that neglecting indirect impacts can cause significant underestimations of sustainability impacts (Cellura et al. 2013a; Cellura et al. 2013b; Huang et al. 2009b; Lenzen 2000; Lenzen et al. 2003; Matthews et al. 2008).

Although I-O analysis comprehensively analyzes the TBL of buildings considering supply chain wide interactions, there are certain limitations that should be taken into account when making policies from obtained results. To name a few, I-O analysis use aggregated sector data in which several subsectors are included under the same main sector. This will increase the uncertainty in LCA results that can be solved by using a hybrid LCA methodology (Suh et al. 2004). In addition, current paper uses the supply and use tables of the USA. However, regional variations can be significant, and regional US I-O model will be important to analyze region-specific sustainability impacts of buildings (Cicas et al. 2007). Another important limitation of this study that quantified sustainability impacts of imported products are assumed to be produced with domestic technologies. Since the I-O tables at national level assume domestic production of imports, bringing I-O tables into global dimension can help to eliminate those errors. For example, total number of employment and income (by gender and age group) can significantly change based on the location of production and, thus, using single-region I-O models can result in large uncertainties in SLCA results. Therefore, multi-regional I-O models should be developed to link international trades into LCSA models. The importance of developing multi-regional I-O-based models can be found in the literature (Lenzen et al. 2004; Turner et al. 2007; Weber & Matthews 2008b; Wiedmann 2009). Additionally, the data used in this analysis is from 2002, which was the latest available in US national I-O accounts.

It is also important to note that our analysis is based on the annual data in which a certain time frame is not defined to represent whole buildings in the USA. It is rather a snapshot of the benchmark year 2002, where each life cycle phase is represented with their annual projections. Defined time frame for the buildings' life cycle is a significant parameter to interpret the life cycle contributions. A longer life cycle time may bring associated uncertainties. Some other comparable studies found in the literature show that buildings whose life cycle length is assumed as 50 years indicated very similar results for the proportions of some of the environmental impacts attributed to each life cycle phase (Blanchard & Reppe 1998; Cuéllar-Franca & Azapagic 2012; Junnila et al. 2006; Sharma et al. 2011; Van Ooteghem & Xu 2012; You et al. 2011). Although it was possible to assign a lifetime and functional unit for the buildings analyzed, we preferred this approach to account for impacts at national level. On the other hand, no study has been found to compare results of social and economic impacts of buildings.

In conclusion, this study assessed the sustainability impacts of the US buildings from a holistic perspective. The model utilized in this study is a static model in which the variations over time were not taken into account. While static models are useful for policy impactions targeting near term sustainability goals, temporal variables of systems can be captured and estimated with dynamic models. Considering the dynamic structure of sustainability problems and interactions among the life cycle components and the sectors, the problems addressing the sustainability of US buildings should be studied with dynamic modeling approach to develop future strategies that consider the temporal variables of the system (Onat et al. 2014a). In this regard, the future work will assess the effectiveness of policies to optimize sustainability impacts of the US buildings with a dynamic system approach. 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.

References

Ardente F, Beccali M, Cellura M, Mistretta M (2011) Energy and environmental benefits in public buildings as a result of retrofit actions. Renew Sustain Energy Rev 15:460–470

BEA (2002) Benchmark input–output data. In: U.S. Bur. Econ. Anal. http://www.bea.gov/iTable/iTable.cfm?ReqID=5&step=1#reqid=5&step=100&isuri=1&406=3&403=2&404=7. Accessed 5 Jun 2013

BEA (2008) 2002 Benchmark Input–output - Item Output Detail. http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&cad=rja&ved=0CDYQFjAB&url=http://www.bea.gov/industry/xls/2002DetailedItemOutput.xls&ei=nxqHUbT-EIie8QSn74HgCA&usg=AFQjCNEOABYqv8MJKxkgHKmjU54cTqMCxQ&sig2=4eDqdCLk_kuEpu6PgEu9Dg. Accessed 5 May 2013

Beccali M, Cellura M, Fontana M et al (2013) Energy retrofit of a single-family house: life cycle net energy saving and environmental benefits. Renew Sustain Energy Rev 27:283–293

Bilec M, Ries R, Matthews HS, Sharrard AL (2006) Example of a hybrid life-cycle assessment of construction processes. J Infrastruct Syst 12:207–215

Blackhurst BM, Hendrickson C, Vidal JSI (2010) Direct and indirect water withdrawals for U.S. industrial sectors. Environ Sci Technol 44:2126–30

Blanchard S, Reppe P (1998) Life cycle analysis of a residential home in Michigan. University of Michigan, Ann Arbour

Building Energy DataBook (2010) Residential Sector. http://buildingsdatabook.eren.doe.gov/ChapterIntro2.aspx. Accessed 5 Jun 2013

Building Energy Data Book (2005a) Residential sector water consumption. http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=8.2.1. Accessed 5 Jun 2013

Building Energy Data Book (2005b) Commercial sector water consumption. http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=8.3.1. Accessed 5 Jun 2013

BTS (Bureau of Transportation Statistics) (2012) Injured persons by transportation mode. Table 2–2

Cabeza LF, Rincón L, Vilariño V et al (2014) Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review. Renew Sustain Energy Rev 29:394–416

Carnegie Mellon University Green Design Institute (2008) Economic Input–output Life Cycle Assessment (EIO-LCA). http://www.eiolca.net/index.html. Accessed 5 Jun 2013

Cellura M, Di Gangi A, Longo S, Orioli A (2013a) An Italian input–output model for the assessment of energy and environmental benefits arising from retrofit actions of buildings. Energy Build 62:97–106

Cellura M, Guarino F, Longo S et al (2013b) The role of the building sector for reducing energy consumption and greenhouse gases: an Italian case study. Renew Energy 60:586–597

CIA the Worldfact Book (2013) United States. https://www.cia.gov/library/publications/the-world-factbook/geos/countrytemplate_us.html. Accessed 5 Jun 2013

Cicas G, Hendrickson CT, Horvath A, Matthews HS (2007) A regional version of a US economic input–output life-cycle assessment model. Int J Life Cycle Assess 12:365–372

Climate Leaders (2008) Greenhouse Gas Inventory Protocol Core Module Guidance-Direct Emissions from Stationary Combustion Sources. 3–30

Cuéllar-Franca RM, Azapagic A (2012) Environmental impacts of the UK residential sector: life cycle assessment of houses. Build Environ 54:86–99

Dietzenbacher E, Lenzen M, Los B et al (2013) Input–output analysis: the next 25 years. Econ Syst Res 25(4):369–389

Egilmez G, Kucukvar M, Tatari O (2013) Sustainability assessment of U.S. manufacturing sectors: an economic input output-based frontier approach. J Clean Prod 53:91–102

Egilmez G, Kucukvar M, Tatari O (2014) Supply chain sustainability assessment of the U.S. food manufacturing sectors: a life cycle-based frontier approach. Resour Conserv Recycl 82:8–20

EIA (2008) Annual Energy Outlook. In: Energy Inf. Adm. U.S. Dep. Energy. http://www.eia.gov/forecasts/aeo/index.cfm. Accessed 5 Jun 2013

EIA (2012a) Annual Energy Review. 219–252

EIA (2012b) Annual Energy Review. http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0605. Accessed 5 Jun 2013

EPA (2003) Estimating Building-Related Construction and Demolition Materials Amounts. 22

Eurostat (2008) Eurostat manual of supply, use and input–output tables. Luxembourg

FHWA (2002a) National Household Travel Survey Daily Travel Quick Facts. In: Natl. Househ. Travel Surv. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/subject_areas/national_household_travel_survey/daily_travel.html. Accessed 5 Jun 2013

FHWA (2002b) Highway Statistics-Analysis of motor fuel use. In: U.S. Dep. Transp. http://www.fhwa.dot.gov/policy/ohim/hs02/mf.htm. Accessed 15 Jun 2013

Finnveden G, Hauschild MZ, Ekvall T et al (2009) Recent developments in life cycle assessment. J Environ Manage 91:1–21
Fisher DC, Whitehead CD, Melody M (2008) National and Regional Water and Wastewater Rates For Use in Cost-Benefit Models and Evaluations of Water Efficiency Programs. 1–19
Foran B, Lenzen M, Dey C (2005a) Balancing Act a triple bottom line analysis of the Australian economy volume 1. Act. CSIRO, Canberra City, p 277
Foran B, Lenzen M, Dey C, Bilek M (2005b) Integrating sustainable chain management with triple bottom line accounting. Ecol Econ 52:143–157
Frontline Risk Solver (2013) Version 12.0. Frontline Systems Inc, Nevada, USA
GFN (2005) National footprint and biocapacity accounts. In: Glob. Footpr. Netw. http://www.footprintnetwork.org. Accessed 15 Jun 2013
GFN (2010) Calculation methodology for the national footprint accounts. In: Glob. Footpr. Netw. http://www.footprintnetwork.org/images/uploads/National_Footprint_Accounts_Method_Paper_2010.pdf. Accessed 15 Jun 2013
Graedel T, Allenby B (2009) Industrial ecology and sustainable engineering, 2nd edn. Prentice Hall, Upper Saddle River
Guinée JB, Heijungs R, Huppes G et al (2011) Life cycle assessment: past, present, and future. Environ Sci Technol 45:90–96
Heijungs R (2010) Sensitivity coefficients for matrix-based LCA. Int J Life Cycle Assess 15:511–520
Heinonen J, Säynäjoki A, Junnila S (2011) A longitudinal study on the carbon emissions of a new residential development. Sustainability 3:1170–1189
Hendrickson C, Horvath A (2000) Resource use and environmental emissions of US construction sectors. J Constr Eng Manag 126:38–44
Hendrickson CT, Lester BL, Matthews HS (2006) Environmental life cycle assessment of goods and services: an input–output approach. Washington DC
Huang YA, Lenzen M, Weber CL et al (2009a) The role of input–output analysis for the screening of corporate carbon footprints. Econ Syst Res 21:217–242
Huang YA, Weber CL, Matthews HS (2009b) Categorization of scope 3 emissions for streamlined enterprise carbon footprinting. Environ Sci Technol 43:8509–8515
Joshi S (1999) Product environmental life-cycle assessment using input–output techniques. J Ind Ecol 3:95–120
Junnila S, Horvath A, Guggemos AA (2006) Life-cycle assessment of office buildings in Europe and the United States. J Infrastruct Syst 12:10–17
Kenny JF, Barber NL, Hutson SS et al. (2009) Estimated use of water in the United States in 2005. Circ 1344 1344:52
Kibert CJ (2012) Sustainable construction: green building design and delivery, 3rd ed., pp 8–9
Kloepffer W (2008) Life cycle sustainability assessment of products. Int J Life Cycle Assess 13:89–95
Kucukvar M, Tatari O (2011) A comprehensive life cycle analysis of cofiring algae in a coal power plant as a solution for achieving sustainable energy. Energy 36:6352–6357
Kucukvar M, Tatari O (2013) Towards a triple bottom-line sustainability assessment of the U.S. construction industry. Int J Life Cycle Assess 18:958–972
Kucukvar M, Noori M, Egilmez G, Tatari O (2014) Stochastic decision modeling for sustainable pavement designs. Int J Life Cycle Assess. doi:10.1007/s11367-014-0723-4
Lenzen M (2000) Errors in conventional and input–output-based life-cycle inventories. J Ind Ecol 4:127–148
Lenzen M, Murray SA, Korte B, Dey CJ (2003) Environmental impact assessment including indirect effects—a case study using input–output analysis. Environ Impact Assess Rev 23:263–282
Lenzen M, Pade L-L, Munksgaard J (2004) CO_2 multipliers in multi-region input–output models. Econ Syst Res 16:391–412
Leontief W (1970) Environmental repercussions and the economic structure: an input–output approach. Rev Econ Stat 52:262–271
Matthews HS, Lave LB (2000) Applications of environmental valuation for determining externality costs. Environ Sci Technol 34:1390–1395
Matthews HS, Hendrickson CT, Weber CL (2008) The importance of carbon footprint estimation boundaries. Environ Sci Technol 42:5839–5842
McDonald GW, Patterson MG (2004) Ecological footprints and interdependencies of New Zealand regions. Ecol Econ 50:49–67
Miller RE, Blair PD (2009) Input–output analysis: foundations and extensions, 2nd edn. Cambridge University, Cambridge
Noori M, Kucukvar M, Tatari O (2013) A macro-level decision analysis of wind power as a solution for sustainable energy. Int J Sustain Energy. doi:10.1080/14786451.2013.854796
NRC (2009) Sustainable critical infrastructure systems: a framework for meeting 21st century imperatives. Washington DC
Ochoa L, Hendrickson C, Asce M, Matthews HS (2002) Economic Input–output Life-cycle Assessment of U.S. Residential Buildings. pp 132–138
Ohio State University (2013) Ecologically-based life assessment (Eco-LCA). http://resilience.eng.ohio-state.edu/ecolca-cv/. Accessed 15 Jun 2013
Onat NC, Egilmez G, Tatari O (2014a) Towards greening the U.S. residential building stock: a system dynamics approach. Build Environ. doi:10.1016/j.buildenv.2014.03.030
Onat NC, Kucukvar M, Tatari O (2014b) Scope-based carbon footprint analysis of U.S. residential and commercial buildings: an input–output hybrid life cycle assessment approach. Build Environ 72:53–62
Peters GP (2010) Carbon footprints and embodied carbon at multiple scales. Curr Opin Environ Sustain 2:245–250
Sala S, Farioli F, Zamagni A (2012a) Progress in sustainability science: lessons learnt from current methodologies for sustainability assessment: Part 1. Int J Life Cycle Assess 18:1653–1672
Sala S, Farioli F, Zamagni A (2012b) Life cycle sustainability assessment in the context of sustainability science progress (part 2). Int J Life Cycle Assess 18:1686–1697
Scheuer C, Keoleian GA, Reppe P (2003) Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energy Build 35:1049–1064
Sharma A, Saxena A, Sethi M et al (2011) Life cycle assessment of buildings: a review. Renew Sustain Energy Rev 15:871–875
Sharrard AL, Matthews HS, Ries RJ (2008) Estimating construction project environmental effects using an input–output-based hybrid life-cycle assessment model. J Infrastruct Syst 14:327–336
Suh S, Lippiatt BC (2012) Framework for hybrid life cycle inventory databases: a case study on the building for environmental and economic sustainability (BEES) database. Int J Life Cycle Assess 17:604–612
Suh S, Lenzen M, Treloar GJ et al (2004) System boundary selection in life-cycle inventories using hybrid approaches. Environ Sci Technol 38:657–664
Suh S, Ferrao P, Nhambiu J (2009) Handbook of input–output economics in industrial ecology. 219–229. doi: 10.1007/978-1-4020-5737-3
Tatari O, Kucukvar M (2012) Sustainability assessment of U.S. construction sectors: ecosystems perspective. J Constr Eng Manag 138:918–922
Tatari O, Nazzal M, Kucukvar M (2012) Comparative sustainability assessment of warm-mix asphalts: a thermodynamic based hybrid life cycle analysis. Resour Conserv Recycl 58:18–24

Transportation Energy Databook (2011a) Car Operating Cost per Mile, 1985–2011. Table 10.13
Transportation Energy Databook (2011b) Fixed Car Operating Costs per Year, 1975–2011. Table 10.14
Turner K, Lenzen M, Wiedmann T, Barrett J (2007) Examining the global environmental impact of regional consumption activities—part 1: a technical note on combining input–output and ecological footprint analysis. Ecol Econ 62:37–44
U.S. Department of Energy (2013) Alternative fuels data center—fuel properties comparison. http://www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf. Accessed 5 Jun 2013
US DOC Census (2012) Value of Construction Put in Place at a Glance. http://www.census.gov/construction/c30/pdf/totsa.pdf. Accessed 15 Jun 2013
United Nations (1999) UN (1999) Studies in methods: handbook of national accounting. New York, USA
U.S. EIA (Energy Information Administration) (2013) Annual Energy Outlook 2013. Retrieved from http://eia.gov. Accessed 5 May 2013
USGS (2009) Use of minerals and materials in the United States from 1900 through 2006
Van Ooteghem K, Xu L (2012) The life-cycle assessment of a single-storey retail building in Canada. Build Environ 49:212–226
Wackernagel M, Onisto L, Bello P et al (1999) National natural capital accounting with the ecological footprint concept. Ecol Econ 29:375–390
Waehrer GM, Dong XS, Miller T et al (2007) Costs of occupational injuries in construction in the United States. Accid Anal Prev 39:1258–1266
Weber CL, Matthews HS (2008a) Food-miles and the relative climate impacts of food choices in the United States. Environ Sci Technol 42:3508–3513
Weber CL, Matthews HS (2008b) Quantifying the global and distributional aspects of American household carbon footprint. Ecol Econ 66:379–391
Wiedmann T (2009) A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Ecol Econ 69:211–222
Wiedmann T, Lenzen M (2006) Triple-bottom-line accounting of social, economic and environmental indicators—a new life-cycle software tool for UK businesses. Bottomline pp 1–13
Wiedmann T, Lenzen M (2009) Unravelling the impacts of supply chains—a new triple-bottom-line accounting approach and software tool. Manag Account Clean Prod 24:65–90
Wiedmann T, Minx J, Barrett J, Wackernagel M (2006) Allocating ecological footprints to final consumption categories with input–output analysis. Ecol Econ 56:28–48
Wiedmann TO, Lenzen M, Barrett JR (2009) Companies on the scale: comparing and benchmarking the sustainability performance of businesses. J Ind Ecol 13:361–383
Wiedmann TO, Suh S, Feng K et al (2011) Application of hybrid life cycle approaches to emerging energy technologies—the case of wind power in the UK. Environ Sci Technol 45:5900–5907
Wilcock W (2005) Energy content of fuels. In: ENVIR215 Lect. notes. http://www.ocean.washington.edu/courses/envir215/energynumbers.pdf. Accessed 15 Jun 2013
Williams E (2004) Energy intensity of computer manufacturing: hybrid assessment combining process and economic input–output methods. Environ Sci Technol 38:6166–6174
Wood R, Garnett S (2010) Regional sustainability in Northern Australia—a quantitative assessment of social, economic and environmental impacts. Ecol Econ 69:1877–1882
You F, Hu D, Zhang H et al (2011) Carbon emissions in the life cycle of urban building system in China—a case study of residential buildings. Ecol Complex 8:201–212
Zamagni A (2012) Life cycle assessment and sustainability. Int J Life Cycle Assess 86:256–263
Zamagni A, Guinée J, Masoni P, Heijungs R (2012) Life cycle sustainability analysis. In life cycle assessment handbook: a guide for environmentally sustainable products. doi: 10.1002/9781118528372
Zhang Y, Baral A, Bakshi BR (2010) Accounting for ecosystem services in life cycle assessment. Part II: toward an ecologically based LCA. Environ Sci Technol 44:2624–2631