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Carbon Footprint Stock Analysis of U.S. Manufacturing: A Time Series Input-Output LCA

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Abstract

Purpose- This paper provides an Input-Output Life Cycle assessment model to estimate the carbon footprint of U.S. manufacturing sectors. To achieve this, the paper sets out the following objectives: 1) Develop a time series carbon footprint estimation model for U.S. manufacturing sectors; 2) Analyze the annual and cumulative carbon footprint; 3) Analyze and identify the most carbon emitting and carbon intensive manufacturing industries in the last four decades; and 4) Analyze the supply chains of U.S. manufacturing industries to help identify the most critical carbon emitting industries.

Design/Methodology/Approach- Initially, the economic input output tables of U.S. economy and carbon footprint multipliers were collected from EORA database (Lenzen et al., 2012). Then, Economic Input Output Life Cycle Assessment (EIO-LCA) models were developed to quantify the carbon footprint extents of the U.S. manufacturing sectors between 1970 and 2011. The carbon footprint is assessed in metric tons of CO_2-equivalent, whereas the economic outputs were measured in million dollar economic activity.

Findings- The salient finding of this paper is that the carbon footprint stock has been increasing substantially over the last four decades. The steep growth in economic output unfortunately over-shadowed the potential benefits that were obtained from lower CO_2 intensities. Analysis of specific industry results indicate that the top 5 manufacturing sectors based on total carbon footprint share are “petroleum refineries”, “Animal (except poultry) slaughtering, rendering, and processing”, “Other basic organic chemical manufacturing”, “Motor vehicle parts manufacturing”, and “Iron and steel mills and ferroalloy manufacturing”.

Originality/value- This paper proposes a state-of-art time series input-output-based carbon footprint assessment for the U.S. manufacturing industries considering direct (onsite) and indirect (supply chain) impacts. In addition, the paper provides carbon intensity and carbon stock variables that are assessed over time for each of the U.S. manufacturing industries from a supply chain footprint perspective.

Key words: Sustainable manufacturing; input-output modeling; life cycle assessment; carbon intensity; green supply chains

Paper Type: Research paper

1. Introduction

Climate change and carbon footprint are fundamental topics of industrial sustainability assessment and sustainable development policy making. Unfortunately, we are well behind the objectives targeted in the meetings of United Nations Climate Change Committee, and yet no worldwide commitment for taking the necessary actions has been reached based on the 2015 Paris meeting. Among the industrial and service activities in a country or across the world, manufacturing activities play a substantial role in meeting the expectations of consumers. Substantial environmental impacts result from these activities. In any discussion about sustainable development, sustainable manufacturing has to be a significant topic for assessment and policy making across the world.

1.1 Sustainable manufacturing

Reducing greenhouse gas (GHG) emissions is of critical importance toward achieving sustainable development. Nearly a third of GHG emissions are attributed to manufacturing, especially in the major U.S manufacturing industries including electricity and heat production, agriculture, forestry, and other land use, chemical, iron and steel, cement, and paper sectors. (Egilmez et al., 2013). Therefore, the need for achieving sustainable manufacturing has reached a crucial milestone as these activities continue their deteriorating effects on the earth's carrying capacity (Park et al., 2015). The U.S Department of Commerce's report defines sustainable manufacturing as the "creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers'' (Westkämper, 2000).

1.2. Carbon footprint analysis and life cycle assessment

Life cycle assessment (LCA) as a methodology has played a critical role in accounting for carbon footprint analysis. In the initial era of LCA, mostly process-based models were employed on various domains including products and processes. LCA has been used by researchers to study a whole host of products and processes including but not limited to, rainwater for irrigation and toilets (Devkota et al., 2015), concrete road pavements using industrial by-products (Anastasiou et al., 2015), biodegradable packaging materials (Rossi et al., 2015), disposable baby diapers (Cordella et al., 2015), household refrigerators (Xiao et al., 2015), alternative fertilization practices for rapeseed (Queirós et al., 2015), photovoltaics (Gong et al., 2015), natural gas (Dale et al., 2013) and water tourism (Scheepens et al., 2015).

From a macroeconomic perspective, most of the industries such as transportation, construction, and agricultural sectors are interrelated, each of whom plays as a critical role as a contributor in the overall supply chain. The U.S. economy consists of 400+ industries where each industry hypothetically has over 400 supplier industries in its supply chain. Therefore, studying complex sustainability assessment problems from a holistic viewpoint, where onsite and supply chain activities are considered in an integrative fashion is of vital importance towards realizing the sustainable development goals of the U.S. (Egilmez et al., 2013; 2014). Reducing carbon footprint in the supply chain is a cooperative work between consumer goods production, distribution, and retail companies, influencing all players in the supply chain system to deliver significance emissions reduction (Bocken and Allwood, 2012). The organization of the study is as follows. Section two describes the methodology and data. Section three provides the results and highlights the findings. And, section four provides concluding remarks, limitations of the current study and future directions of the research study.

2. Literature Review

2.1. Background: Input output Life Cycle Assessment Applications

Input Output Life Cycle Assessment (IO LCA) is an increasingly important and useful methodology of assessing the impacts of industrial and human activities on the environment and sustainability efforts. In this section, we present some of the more recent applications of this methodology. LCA models help quantify the environmental impacts of human activities from cradle to grave. Literature identifies three widely used LCA models namely, Process-based LCA (P-LCA), economic input output-based LCA (EIOLCA), and hybrid LCA (Suh and Huppes, 2005). Several modifications/enhancements and combinations of the IO LCA models have been used in various applications in literature. Park et al. (2014) provide a brief overview of the life cycle assessment methodology as it pertains to environmental assessments. Sustainability assessment, environmental impacts, and natural resource consumption aspects of various processes and industries are addressed by means of life cycle assessment (Finnveden et al., 2009; Jiménez-González et al., 2011). The IO methodology has been successfully implemented in various problem domains in literature including food preparations (Lozano et al., 2009; Calderón et al., 2010), soft drinks industry (Amienyo et al., 2013), construction (Kucukvar et al., 2014), food supply chains (Egilmez et al., 2013; 2014; Kucukvar et al., 2014; Park et al., 2016), manufacturing activities and supply chain impacts (Egilmez et al., 2013, 2014; Gumus, et al., 2015; Park et al., 2016).

More recently, we have seen this methodology being applied to the U.S. manufacturing sector. In a series of articles Egilmez and fellow researchers have developed various input-output-based life

cycle assessment (I-O LCA) models to assess the sustainability footprint of the U.S. manufacturing, transportation, construction, and other industries. For example, in Egilmez, Kucukvar, and Tatari, (2013), they study the sustainability of the U.S. manufacturing sectors using the IO frontier approach and couple it with Data Envelopment Analysis (DEA). Their analyses depicts that five manufacturing sectors, namely; "Petroleum and Coal Products Manufacturing", "Food Manufacturing", "Printing and Related Support Activities", "Ordinance and Accessories Manufacturing", and "Motor Vehicle Manufacturing" are 100% eco-efficient compared to the other manufacturing sectors. However, the results also indicated that 90% of the U.S. manufacturing sector need considerable improvements in their life cycle performance and therefore, the study provides policy makers with considerable data to formulate policy decisions. Egilmez and Park, 2014 applied the methodology to the U.S. manufacturing sectors and the carbon, energy and water footprints of the transportation associated with manufacturing. In a 2015 article by Egilmez and Park, IO LCA methodology has been applied to the Transport manufacturing nexus in the U.S. using the TRACI (Tools for Reduction and assessment of chemical and other environmental impacts). The results of the study indicated that the top 10 manufacturing sectors account for 55% of the environmental impacts in each category. In another article (Egilmez et al., 2016); present an application of the approach to 33 food manufacturing sectors in the U.S., they couple the IO approach with fuzzy data envelopment analysis (Fuzzy-DEA) where set of seven environmental impact categories were considered along with economic output. The intent was to determine which sectors were inefficient in terms of sustainability. Analyses showed that vast majority of sectors were inefficient (31/33) providing stakeholders insights into their sustainability performance (Egilmez et al., 2016). In this paper, the researchers adopt the ecologically LCA methodology to evaluate the supply chain sustainability of the U.S. manufacturing. The study posits that different manufacturing sectors have different impacts on the thermodynamic efficiencies when considering renewable and non-renewable resource consumption patterns. Under the renewable resources, fish and CO_2 were the dominant resources consumed by the US manufacturing sectors, but under the non-renewable resources, copper ore was found to be dominant.

Guan et. al., (2016) discussed the application of the IO hybrid LCA model to China's recent construction boom. They endeavor to capture the building embodied energy by adopting the IO model with the LCA approach and propose several measures to limit building embodied energy. In addition, Zhang and Wang (2016) developed a framework by using hybrid IO model to estimate environmental impacts when technical innovations are introduced in production in the Chinese construction sector. In Europe, Kjaer et al., (2015) applied the methodology to corporate and

product environmental footprints. They used a hybrid IO approach and looked at 3 cases in the Danish region. Furthermore, Rodríguez-Alloza et al., (2015) study the impact of asphalt mixtures and the resulting GHGs. They use a hybrid LCA methodology to assess environmental impact of warm asphalt mixtures and show that when upstream supply chain is taken into account, the warm asphalt mixtures help to reduce energy usage by reducing GHG emissions. The aforementioned IO LCA applications successfully integrated the onsite and supply chain-linked impacts in various environmental and ecological impact categories. Another researcher, who has been active in the application of these techniques is Kucukvar, has successfully applied the methodology to a number of interesting applications including land use and construction waste. For example, Kucukvar et al. (2014) presented an application of the IO model to several U.S. land use sectors, including cropland, forest land, fishery land, etc. to provide a comprehensive triple-bottom-line (TBL) sustainability assessment model looking at these land uses and trace the supply chains of these sectors that link them to the demand originates from the U.S.. They also provide insights for policies on land management. In another paper, Kucukvar et al., (2016) studied the impact of energy sector on both regional and global supply chains. The authors argue that by considering regional/global supply chains, stake holders can capture the true impact of the energy sector on sustainability policies more accurately. Yet another piece by (Kucukvar et al., 2016) consider the application of LCA to construction waste recycling. The researchers build a multi-criteria optimization model to propose sustainable waste management strategies. They apply the IO model to quantify the environmental impacts of the waste and consider all 3 options- recycling, landfill and incineration as a means of disposing waste. In another recent work, Park et al.,(2015) apply the IO life cycle approach to the analysis of 276 U.S. manufacturing sectors and 4 transportation modes, and study the environmental impact associated with these modes of transportation. The results show that the food manufacturing sector has the greatest environmental impact. In another article, ecologically-based life cycle assessment model (ECO LCA) is applied to agricultural and food production sectors in the U.S. (Park et al., 2016). They adopt the Ecologically-based life cycle assessment tool to show that grain farming, dairy food, and animal production-related sectors have the largest impact on both environmental and ecological impact categories and further they impact human health, the ecosystem and resources. Most of these works focus on single year impacts, which may lack the critical insights that can only be obtained from multi-period (in other words, time series) analysis.

2.2 Motivation and Organization of the research

Studies that utilize input output extended life cycle assessment methods generally provide a comprehensive understanding about the environmental and socio-economic impacts at the

regional, national or global scale. However, in most of the studies, single year (e.g. Egilmez et al., 2013, 2014) or short term (e.g. Kucukvar et al., 2015) periods are considered as the horizontal time dimension of the assessment. GHGs and specially CO2 emissions stay in the atmosphere for longer periods of time which requires a specific attention and requires us to consider the following question: What is the stock behavior of CO_2 emissions? In system dynamics, scientists bring attention of researchers to the behavior of stocks instead of rates. In this context, rate is typically considered as the annual change of a variable, whereas the stock is the cumulative impact over time. In this study, we incorporate the change in CO_2 emissions' stock (cumulative) over a longer period of time (1970-2011). To be able to account for the entire account of carbon footprint impacts, input-output (I-O) analysis is employed. The reason is that I-O LCA is the most comprehensive LCA method as it accounts for onsite as well as the supply chain impacts (Egilmez et al., 2015). We apply the life cycle-based *time series* carbon footprint assessment model to 276 manufacturing industries of the U.S economy over a multiyear period. This study focuses on highlighting CO_2 emissions stock of U.S. manufacturing industries by integrating input output-based life cycle assessment and data analytics techniques.

3. Methodology

An integrated methodology with 3 steps is developed to tackle the problem. First, I-O LCA models are developed for the years between 1970 and 2011 by using the national input output tables and environmental impact multiplier datasets. Second, the life cycle inventory (LCI) data are obtained by integrating the economic output data of 276 U.S. manufacturing industries in each I-O LCA model for each year and the carbon footprint results are obtained. Third, the resulting data are analyzed by using visual and statistical data analytics methods. Following sections explain the I-O LCA model, time series analysis, and data collection steps.

3.1. Input Output-Life Cycle Assessment (IO-LCA)

IO-LCA is known as a top-down approach that is based on integration of environmental impact indicators, monetary flows, and interdependencies between the economic sectors that form the macro-economic structure of a country (Suh et al. 2004; Tatari and Kucukvar, 2011). Input output-based life cycle assessment frameworks have been widely used in literature which typically addresses large scale socio economic and environmental assessment problems (Kucukvar et al., 2014). IO-LCA approach integrates the environmental impact multipliers with the economic input output tables of a regional, national, or global economy to quantify the environmental impacts of the economic transactions considering direct and indirect (supply chain) impacts. According to the

notation of the EIO analysis, sector level direct requirements are represented by the A matrix, which presents the dollar value of inputs required from each and every sector in a macro-economic system to produce one dollar of output for each sector. Hence, the total output of a sector with a final demand, *f*, is computed as shown in Eq. 1. (Miller and Blair 2009):

$$x_i = [(I_i - A_i)^{-1}] f_i \quad (1)$$

In equation 1, x_i is the total industry output vector for year *i*, I_i represents the diagonal identity matrix for year *i*, and f_i refers to the final demand vector representing the change in a final demand of desired sector for year *i*. Also, the bracketed term $[(I_i - A_i)^{-1}]$ represents the total requirement matrix, which is also called as the Leontief inverse (Leontief, 1970). The Leontief inverse indicates the sum of direct and indirect purchases required to produce a dollar of output from an industry in a regional, national or global economy (BEA, 2012). After the total economic output calculation (x_i) has been established, the total environmental impacts, termed as r_i, (direct and indirect) can be calculated by multiplying the economic output of each industrial sector by the multiplier matrix. Thus, a vector of total environmental outputs can be expressed as (Miller and Blair 2009):

$$r_i = E_{dir(i)} x_i = E_{dir(i)} [(I_i - A_i)^{-1}] f_i \quad (2)$$

where r_i is the total environmental pressure vector for year *i*, calculated by multiplication of $E_{dir(i)}$ and total economic output vector. $E_{dir(i)}$ is a diagonal matrix indicates the direct environmental impacts per dollar of output vector for year *i*. Recent applications of the aforementioned single region IO-LCA framework for U.S. manufacturing sectors can be found in the literature such as (Egilmez et al., 2013; Kucukvar et al., 2015; Park et al., 2015; Park et al., 2016).

3.2. Time Series Analysis

Even though building IO-LCA model for a specific year is critical to study the impacts across the supply chains, the behavior of carbon stock can only be evaluated over time. Time series IO-LCA models can provide critical quantitative insights related to the rate (annual carbon emissions) and stock (cumulative carbon emissions). Therefore, a time series analysis is conducted for the years 1970 to 2011, where the input output and environmental impact (CO_2 equivalent – kton) multiplier datasets were available for the U.S. economy (Lenzen et al., 2012). The objective is to trace the trend of CO_2 emissions, in other words the cumulative stock in comparison to the growth trend in GDP (See Figure1). The GDP growth of the U.S. has been tremendously increasing as a result of industrial growth and the expansion of global trade. Most of the input-output-based LCA studies

focus on the environmental and/or socio-economic impacts for a specific year and the time series behavior has not been addressed significantly in the literature.

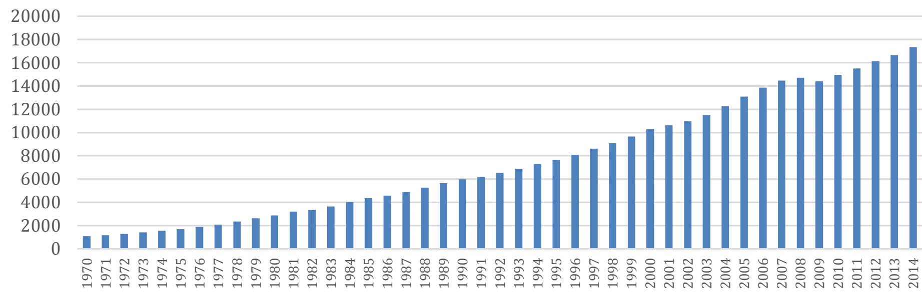

Fig. 1. U.S. Gross Domestic Production ($B USD) between 1970-2014 (BEA, 2015)

3.3. Data

Economic output, total requirement and CO2-equivalent multiplier datasets for the U.S. economy is extracted from EURA-MRIO database (Lenzen et al., 2012; 2013). According to the database, the U.S. economic structure is formulated as 429 industries based on NAICS classification system, where theoretically an industry has 428 supply chain industries. The units of measurement for indicators used are as follows: 1) economic output dataset: $M, 2) total requirement dataset: unit-less, and 3) CO_2 equivalent multiplier dataset: k-ton CO_2-equivalent/$M.

The U.S. economic structure consists of a total of 276 manufacturing industries out of 429 economic sectors. For ease of representation, manufacturing industries are grouped into 53 major manufacturing industries and shown with acronyms given in Table 1. The classification is made according to NAICS coding and classification system (U.S. Census, 2011). The analysis is conducted around two major variables: total economic output and carbon footprint. The total economic output can be termed as the total economic activity occurs in the economy as a result of the specific economic production of U.S. manufacturing. So, the total economic output includes the direct (onsite) production activities and the supply chain (supporting industries of U.S. manufacturing) impacts. The carbon footprint is the estimated total carbon emissions in metric ton CO2-equivalent associated with the economic activities.

Table 1. U.S. Manufacturing **s**ectors and abbreviations

Sectoral code	Sector name	Acronym
1	Aerospace product and parts manufacturing	APPM
2	Agricultural chemical manufacturing	ACM
3	Agriculture, construction, and mining machinery manufacturing	ACMM
4	Apparel manufacturing	AM
5	Architectural and structural metals manufacturing	ASMM
6	Audio, video, and communications equipment manufacturing	AVCM
7	Basic chemical manufacturing	BCM
8	Beverage manufacturing	BM
9	Boiler, tank, and shipping container manufacturing	BTSM
10	Commercial and service industry machinery manufacturing	CSIM
11	Computer and peripheral equipment manufacturing	CPEM
12	Converted paper product manufacturing	CPPM
13	Cutlery and handtool manufacturing	CHM
14	Electric lighting equipment manufacturing	ELEM
15	Electrical equipment manufacturing	EEM
16	Electronic instrument manufacturing	EIM
17	Engine, turbine, and power transmission equipment manufacturing	ETPEM
18	Food manufacturing	FM
19	Forging and stamping	FS
20	Foundries	FOUND
21	Furniture and related product manufacturing	FRPM
22	Household appliance manufacturing	HAM
23	HVAC and commercial refrigeration equipment manufacturing	HVAC
24	Industrial machinery manufacturing	IMM
25	Iron and steel mills and manufacturing from purchased steel	ISMM
26	Leather and allied product manufacturing	LAPM
27	Manufacturing and reproducing magnetic and optical media	MRMO
28	Medical equipment and supplies manufacturing	MESM
29	Metalworking machinery manufacturing	MMM
30	Motor vehicle body, trailer, and parts manufacturing	MTPM
31	Motor vehicle manufacturing	MVM
32	Nonferrous metal production and processing	NMPP
33	Nonmetallic mineral product manufacturing	NMPM
34	Ordnance and accessories manufacturing	OAM
35	Other chemical product and preparation manufacturing	OCPM
36	Other electrical equipment and component manufacturing	OECM
37	Other fabricated metal product manufacturing	OFMM
38	Other general purpose machinery manufacturing	OGPM
39	Other miscellaneous manufacturing	OMM
40	Other transportation equipment manufacturing	OTEM
41	Paint, coating, and adhesive manufacturing	PCAM
42	Petroleum and coal products manufacturing	PCPM
43	Pharmaceutical and medicine manufacturing	PMM
44	Plastics and rubber products manufacturing	PRPM
45	Printing and related support activities	PRSA
46	Pulp, paper, and paperboard mills	PPPM
47	Resin, rubber, and artificial fibers manufacturing	RRAF
48	Semiconductor and other electronic component manufacturing	SECM
49	Soap, cleaning compound, and toiletry manufacturing	SCCT
50	Textile mills	TM
51	Textile product mills	TPM
52	Tobacco manufacturing	TOBM
53	Wood product manufacturing	WPM

4. Results

We present the results in five sub-sections. In the first sub-section, we focus on the total economic output variable and time series analysis is highlighted. The second sub-section presents findings related to the carbon footprint considering the annual (flow rate) and stock (cumulative) behavior of these results. The third sub-section overviews the time series behavior of carbon footprint intensity, termed as metric ton CO_2-equivalent per million dollar economic activity. The fourth section focuses on the time series behavior of top 10 carbon intensive industries in terms of total carbon footprint share among all of the economic sectors. And, the fifth sub-section concludes the results section with a detailed supply chain decomposition analysis.

4.1. Time Series Analysis of Total Economic Output (TEO) in $M

The time series analysis of total economic output is presented in Figures 2 and 3. In Figure 2, the annual total economic activity is plotted, which presents a steady increase over time, with an exception in 2008 due to the Mortgage crisis. In terms of annual total economic activity, U.S. manufacturing experienced an average of 8% growth rate per year. And, in 2011, the annual flow rate reached a level 20 times that in 1970. In terms of the stock behavior, the increasing rate of annual activity caused a rapid growth in the cumulative output. The cumulative behavior of economic activity is vital for the EIO-LCA model since the carbon footprint impacts are also estimated cumulatively based on the economic outputs. In Figure 3, the stock behavior indicates a dominating increase when compared with the rate behavior over time.

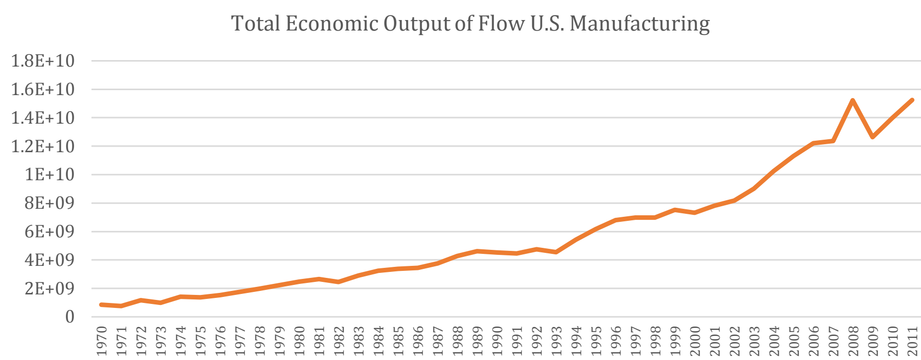

Fig. 2. Economic Output Flow

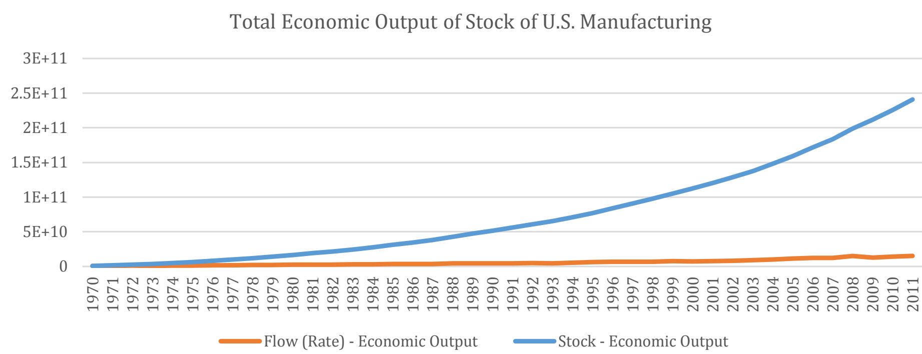

Fig. 3. Economic Output Stock

4.2. Time Series Analysis of Carbon Footprint Flow and Stock

In this section, the time series analysis aspects of economic output versus carbon footprint is analyzed and highlighted in detail. The section has 2 components: carbon footprint flow and carbon footprint stock. The flow section looks at the annual rate changes over the time in terms of economic activity and carbon footprint. On the other hand, the stock section considers cumulative behavior of carbon footprint and economic output. Since carbon emissions stuck in the atmosphere for longer period of times, the stock behavior of carbon footprint trend is also critical.

4.2.1. Carbon Footprint Flow (Rate)

The total economic output (TEO) and total carbon footprint for the U.S. manufacturing sectors from 1970 to 2011 are presented in Figure 4, and the percentage change of TEO and CO_2 are also presented in Figure 3. During the period from 1970 to 2011, there was a substantial growth of the total TEO of the U.S. manufacturing sectors from $ 759.46 million dollars to $ 15,247.67 million dollars. The average total TEO was found to be $5,734.90 million dollars; the cumulative TEO was found to be$ 240,865.64 million dollars from 1970 to 2011. In terms of carbon footprint, unlike the change of TEO, there was no significant growth in the carbon footprint of the U.S. manufacturing sectors from 1970(14,042 Mt CO_2) to 2011 (15,080 Mt CO_2). The average carbon footprint during 30 years period was found to be 13,989 Mt CO_{2}-eqv; the cumulative CO_2 was found to be 573,538 Mt CO_{2}-eqv. So, this trend implies, that the same level of carbon footprint is being produced while the economic activity is rapidly growing. That's why the carbon footprint stock keeps increasing over time. Assume that the total atmospheric emissions in the ecosystem is like a bathtub, the carbon sequestration capacity of the earth is the drain and the incoming emissions as a result of economic activity can be considered as the faucet. The level of water in the bath tub will keep

increasing over time due to non-decreasing inflow of carbon footprint production and non-increasing outflow of carbon footprint sequestration. The annual rate behavior is also depicted in Figure 5. The percent rates are calculated by taking the average of each 5 year time period.

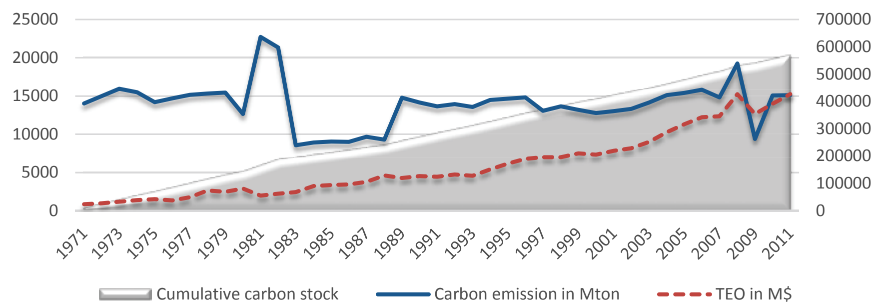

Fig. 4. Change in carbon footprint flow (annual rate) and TEO during the period 1970-2011.

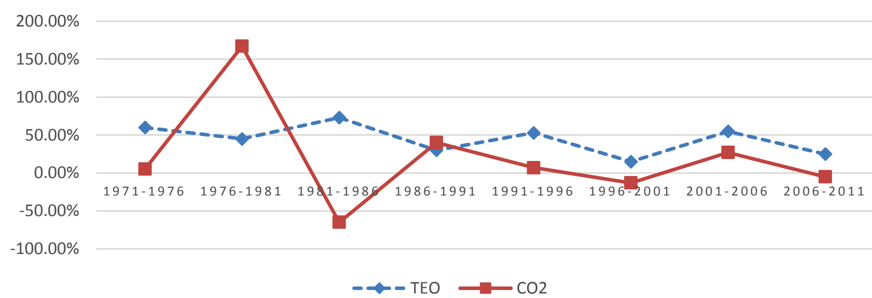

Fig. 5. Percent change in carbon emissions and TEO flow during the period 1970-2011

4.2.2. Carbon Footprint Stock

The cumulative carbon footprint impacts of 53 manufacturing sectors from 1970 to 2011 was further decomposed into onsite (direct) and supply chain (indirect) carbon footprint (Figure 6). Even though the carbon emissions flow (annual) rate is observed as steady, the stock has experienced a steady increase over time with 10.5% increase in carbon footprint (CFP) stock annual and 40 times shift from 1970 to 2011 based on 1970 levels.

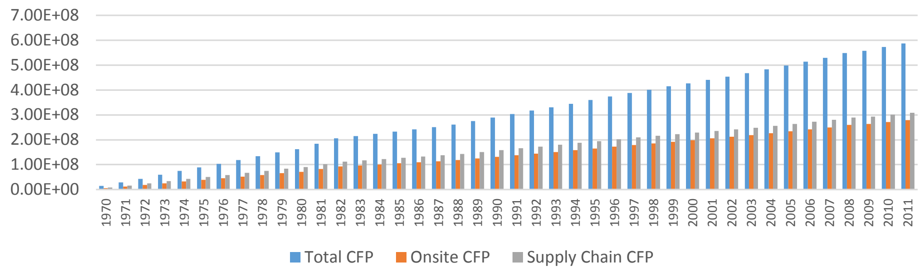

Fig. 6. Overall trend of U.S. manufacturing carbon footprint (1970-2011)

In addition, the decomposition of onsite and supply chain carbon footprint impacts are presented with column % share graph in Figure 7. The results indicated that on the average, onsite CFP accounts for 47% of total CO2 emission from 1970 to 2011, which means that carbon footprint of U.S manufacturing mainly contributed by their supply chain sectors during the time period of analysis. Particularly, onsite impact was dominant during the periods of 1981, 1982, and 2008, which could be attributed to the economic crises, and decrease in overall economic activity.

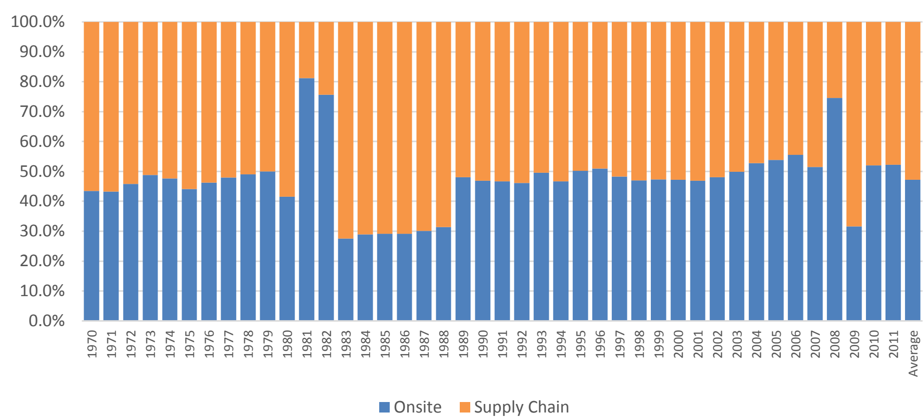

Fig. 7. Carbon emission from onsite and supply chains (1970-2011)

4.3. Carbon Footprint Intensity

The change of carbon emission intensities (metric ton CO_2-equivalent emissions per $M economic activity) for onsite and supply chains for the 41 year period are presented in Figure 8. Results indicate that the U.S. manufacturing sectors have experienced a significant decrease in CO_2

intensity between 1970 and 2011. The average total CO_2 intensity was found to be 0.0048 Mt per $M of TEO. In 1970, U.S. manufacturing sector's CO_2 intensity was 0.008 Mt/ $M which has decreased by about 95% (down to 0.001 metric ton/ $M TEO). During the period from 1981 to 1983, it increased by about 70%, and then switch to a decreasing trajectory once again. The results may stem from that the U.S showed a tremendous increase in TEO, but less increase in CO_2 emission, which means an overall improvement in carbon efficiency. The onsite and supply chain CO_2 intensities were found to be 0.008 Mt per $M and 0.01 Mt per $M TEO, which has also decreased by about 94% (0.00048 Mt per $M TEO) and 95% (0.0005 Mt per Million dollars TEO), respectively. From the decomposition analysis, CO_2 in supply chain (0.0026 Mt per Million dollars TEO) was little higher than that of CO_2 intensity from onsite (0.0022 Mt per Million dollars TEO). It is evident that CO_2 intensities decreased significantly. However, the total carbon footprint stock (depicted in Figure 6) has not decreased, in fact, it increased over 40 times that of 1970 levels. The trend of total economic output versus carbon intensity of U.S. manufacturing is also plotted in Figure 9. This graph also reveals the ugly truth: carbon intensities significantly decreased as a result of technological advancements, however the total economic output kept increasing as a result of increasing consumption, which yields substantial growth in carbon footprint stock.

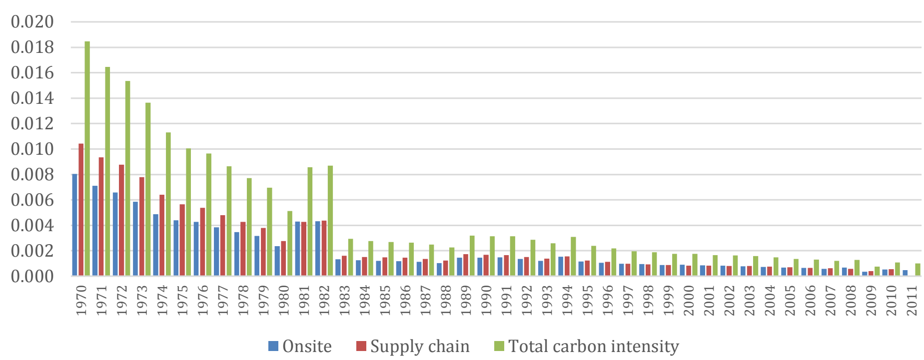

Fig 8. Carbon intensity from onsite and supply chain (per unit of output (Mt CO2-eqv. Per $K TEO)

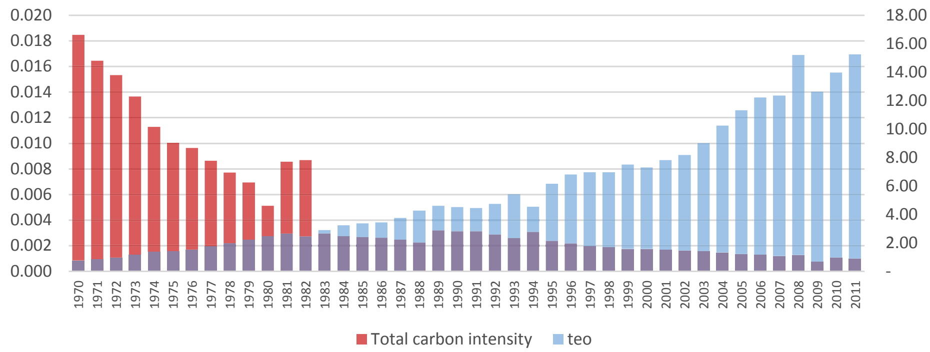

Fig. 9. Total carbon intensity vs. total economic output ($ billion USD)

Moreover, as shown in Table 2, CO_2 intensities from both onsite and supply chain sectors were decomposed by manufacturing industry. Total onsite carbon intensity represents the CO_2 embodied in the onsite economic output (just the specific industry's economic output). On the other hand, total supply chain CO_2 intensity represents the CO_2 emitted during the supply chain activities of each sector. By comparing the sectoral onsite and supply chain related CO_2 intensities, U.S. manufacturing sectors showed a similar results to direct and indirect CO_2 emissions.

It is also observed that substantial differences exist between the CO_2 intensities of the 53 manufacturing sectors in the U.S. The average CO_2 intensity was 4.174 Mt per Million dollars TEO. In terms of specific industry-based results, the Petroleum and coal products manufacturing (PCPM) sector was found to have the highest intensity (11.066 Mt per Million dollars TEO), which also showed high contribution to supply chain CO_2 intensity (5.593 Mt per Million dollars TEO). This can be explained by the fact that PCPM sector is the main supplier of petroleum and coal products for other manufacturing sectors – the predominant nonrenewable energy sources. The second CO_2 emission intensive sector was Agricultural chemical manufacturing (ACM), whose embodied CO_2 emission intensity was 9.465 Mt per Million dollars TEO followed by Basic chemical manufacturing (BCM) (9.095 Mt per Million dollars TEO), which also showed high contribution to both direct and indirect CO2 emission intensity. Chemical products of these sectors is usually high energy-intensive product because of high utilization of machinery, and high demand for chemical product exist for other sectors. Notably, except fifteen sectors of U.S. manufacturing sectors including Iron and steel mills and manufacturing from purchased steel (ISMM), Forging and stamping (FS), Household appliance manufacturing (HAM), and Tobacco manufacturing (TOBM), etc; U.S.

manufacturing sector's embodied CO_2 intensity are dominated by emission intensity from supply chain sector.

Table 2. Overall carbon intensity by manufacturing sector

Sector	Onsite	Supply Chain	Total	Sector	Onsite	Supply Chain	Total
PCPM	5.473	5.593	11.066	CSIM	1.646	1.615	3.261
ACM	4.498	4.966	9.465	FRPM	1.705	1.554	3.259
BCM	4.284	4.810	9.095	SCCT	1.555	1.644	3.199
FM	3.545	3.956	7.501	FOUND	1.557	1.612	3.170
LAPM	2.773	4.364	7.136	OGPM	1.510	1.628	3.138
RRAF	3.453	3.590	7.043	CHM	1.478	1.645	3.123
ISMM	3.447	3.283	6.730	MTPM	1.523	1.547	3.070
NMPM	3.193	3.365	6.558	ASMM	1.526	1.516	3.041
NMPP	3.008	3.132	6.140	OAM	1.621	1.407	3.028
TM	2.980	3.033	6.013	ACMM	1.520	1.497	3.017
PPPM	2.595	2.824	5.419	MMM	1.537	1.463	3.001
PCAM	2.529	2.614	5.143	MVM	1.537	1.449	2.986
OCPM	2.425	2.598	5.024	HVAC	1.472	1.486	2.958
TPM	2.290	2.345	4.635	OTEM	1.469	1.478	2.947
PRPM	2.160	2.231	4.392	OFMM	1.423	1.450	2.873
WPM	2.161	2.186	4.347	IMM	1.358	1.505	2.864
BM	2.110	2.112	4.222	ELEM	1.422	1.420	2.842
FS	2.076	2.074	4.150	ETPEM	1.366	1.423	2.789
BTSM	2.067	2.073	4.140	CPEM	1.251	1.371	2.621
CPPM	1.948	2.030	3.978	SECM	1.257	1.345	2.601
EEM	1.912	1.964	3.877	AVCM	1.314	1.198	2.512
AM	1.906	1.968	3.873	PRSA	1.198	1.274	2.472
HAM	2.045	1.811	3.856	EIM	1.224	1.188	2.411
TOBM	1.852	1.847	3.699	APPM	1.141	1.148	2.290
OECM	1.608	1.869	3.477	PMM	1.097	1.159	2.257
OMM	1.603	1.687	3.290	MESM	1.028	0.943	1.971
MRMO	1.666	1.618	3.284				
Average	***2.044***	***2.130***	***4.174***	***Total***	***108.343***	***112.909***	***221.252***

4.4. Top 10 most emitting manufacturing industries

In the previous section, the time series trend of economic output and carbon footprint of U.S. manufacturing sectors, and CO_2 emission intensities were provided. This section provides a detailed overview of carbon emissions from a sectoral point of view. Area charts given in Figures 10 and 11 present the CO_2 emission contribution of the top ten emitting U.S. manufacturing sectors and its change over time decomposed into onsite, and supply chain CO_2 percentage share, and Fig 12 shows the overall percentage share of CO_2 emission of top ten sectors; bar graph represents the

percentage share of CO_2 emission for each manufacturing sector; line graph represents the cumulative CO_2 emission of top ten sectors.

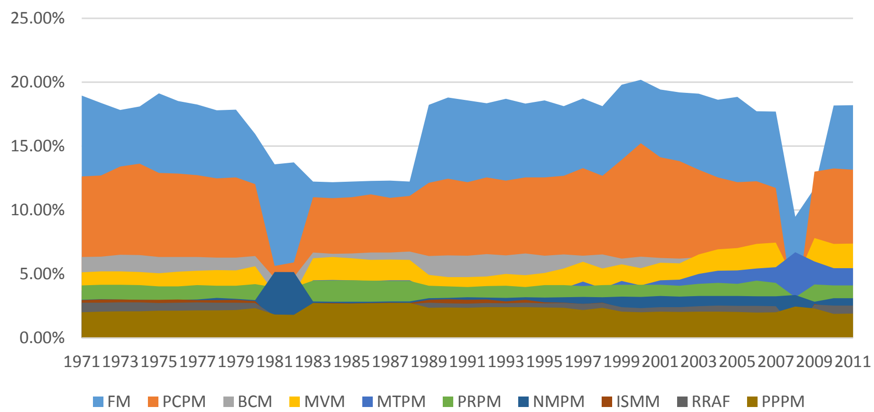

Fig. 10. Percent share of direct carbon footprint share of top 10 U.S. mfg. sectors

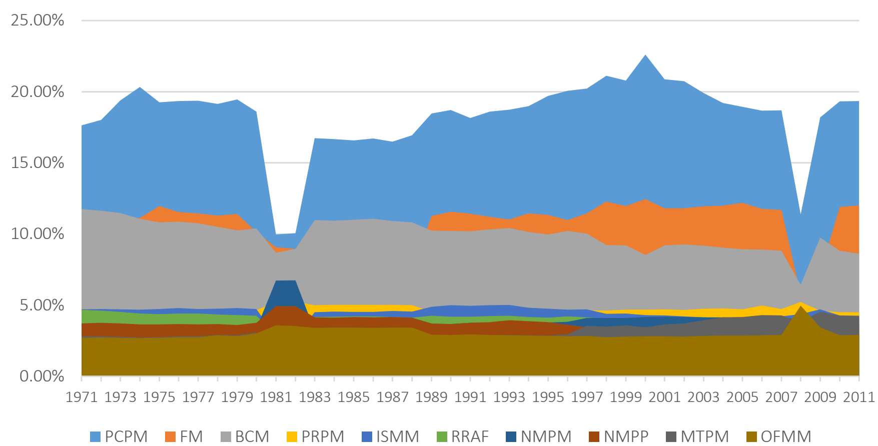

Fig. 11 Percent share of indirect (supply chain) carbon footprint share of top 10 U.S. mfg. sectors

Figure 11 presents the change of overall percentage share of CO_2 emission of supply chain. There was increasing trend of CO_2 emission from PCPM (0.10%), FM (0.03), PRPM (0.02%), NMPM (0.26%), MTPM (0.50%), and OFMM (0.07%) sectors. PCPM sector was dominant on CO_2 emission

over 30 years of period of time among top ten sectors. On the other hand, BCM (0.27%), ISMM (0.09%), RRAF (0.18%), nonmetallic mineral product manufacturing (NMPP) (0.11%) sectors' CO_2 emission was decreased. PCPM was found to be the dominant sector in terms of indirect CO_2 emission over the 30 years period; the average percentage share of CO_2 emission was found to be 18.2% (in Figure7.b) ranging from 9.96% (in 1981) to 22.61% (in 2000), followed by FM (10.7%) ranging from 5.80% (in 2008) to 12.45% (in 2000), BCM (10.0%) ranging from 6.45% (in 2008) to 11.76% (in 1970).

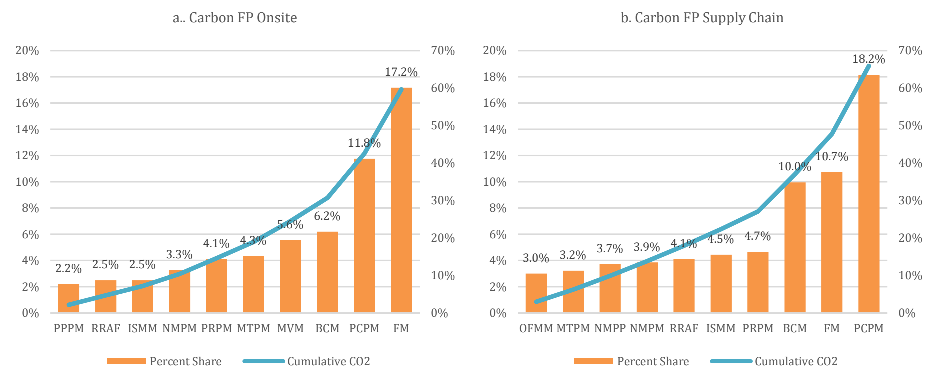

Fig 12. Overall percentage carbon footprint shares of top 10 mfg. sectors (onsite vs. supply chains)

Top ten manufacturing sectors with high contribution of CO_2 emission on average, were considered for each decomposition. As for the onsite during the 30 years period, top ten sectors, showed about 59.7% of cumulative CO_2 emission as shown in Figure 12 a. Among the ten sectors, Food manufacturing (FM) sector was found to have the largest percentage share of CO2 emissions; the average percentage share of CO2 emission was found to be 17.2% (in Figure 12.a) ranging from 9.49% (in 2008) to 20.19% (in 2000). CO_2 emission from Petroleum and coal products manufacturing (PCPM) sector took second place, accounting for 11.8% of CO_2 emission share ranging from 1.49% (in 2008) 15.24% (in 2000). As for the change pattern of CO_2 emission from onsite, FM had a notable decrease between 1980 and 1988 and between 2007 and 2008 which showed decrease in overall CO_2 emission from 1970 to 2011 accounting for 0.04%. With FM sector, Iron and steel mills and manufacturing from purchased steel (ISMM) (0.21%), Resin, rubber, and artificial fibers manufacturing (RRAF) (0.08%), and Pulp, paper, and paperboard mills (PPPM) (0.06%), Plastics and rubber products manufacturing (PRPM) (0.002%) sectors also showed overall decrease in CO_2 emission. On the other hand, the other five manufacturing sectors showed

an increase of CO_2 emissions, Petroleum and coal products manufacturing (PCPM) (0.04%), Basic chemical manufacturing (BCM) (0.01%), Motor vehicle manufacturing (MVM) (0.43%), Motor vehicle body, trailer, and parts manufacturing (MTPM) (0.48%), and Nonmetallic mineral product manufacturing (NMPM) (0.04%) showed increasing trend of onsite CO_2 emission for 30 years period.

4.5 Supply Chain Decomposition Analysis

To gain an understanding of how various sectors contribute to onsite and supply chain carbon footprints, let's take a look at the food manufacturing (FM) industry. This industry sector uses inputs from various other sectors such as poultry processing, agricultural chemical manufacturing, fertilizer industries etc. Table 3 provides a detailed supply chain decomposition. The results are presented in terms of onsite and supply chain carbon footprint of the top 10 sectors based on total carbon footprint contribution. As a second step to this analysis, the top 5 sectors by carbon footprint are provided. The results indicate that Petroleum refineries (PR) industry are the dominant sector based on direct carbon footprint, in that 99.29% of carbon footprint is from onsite and only 0.71% was from its supply chain. Within the top 5 sectors in its supply chain, indirect carbon emission was mainly caused by Other basic Organic Chemical Manufacturing (OOCM), which showed the second largest contributor to carbon emission and direct carbon emission accounted of approximately 56.23% of the total embodied carbon emission.

It terms of upstream/downstream carbon emission contributions, the Petroleum refinery industry contributed the largest share accounting for 37.19% of total indirect carbon emission followed by petrochemical manufacturing (PM) (2.03%). Among other contributors the plastics material and resin manufacturing, (PMRM) contributed 1.84%, all other basic inorganic chemical manufacturing (ABICM) (0.31%), and all other chemical product and preparation manufacturing (ACPPM) (0.26%). Among the top ten sub U.S. manufacturing sectors, two industries including pesticide and other agricultural chemical manufacturing, and all other basic inorganic chemical manufacturing industries were found to be significant contributor to upstream/downstream supply chain carbon emission accounting for 85.48% and 98.56%, respectively. For these sectors, a large part of carbon emission in supply chain was dominated by the sectors of petroleum refineries and other basic organic chemical manufacturing industries.

<INSERT TABLE 3>

Indirect CO_2 is emitted from offsite activities that is occurred by burning fossil fuel at the power plants and other industrial facilities to produce pesticide and chemical product are very significant

supply chain activities. Direct CO_2 are produced by onsite activities that burns fuel to generate electricity and heat, material and resource through the industrial process or machinery. Indeed, power plants (e.g. chemical, steel) and refinery facilities are the major industrial sectors that cause direct/indirect greenhouse gasses (GHGs) in the U.S. are the main barriers for reaching and realizing the sustainable development goals. Therefore, it should be noted that utilizing energy efficient processes and alternative biomass, e.g. solar, hydro-and wind power during production and supply chain must be emphasized to minimize either onsite and supply chain related carbon emissions (Kucukvar et al., 2015).

5. Discussion

Supply chain management practices have been implemented from sustainability perspective and due to the successful implementation of these strategies, reductions in operational costs and environmental impacts are achieved. This success is indicated by the substantial reduction in the carbon intensity (See Figure 8). However, the total carbon footprint impact has not been reduced due to enormous growth in total economic output of manufacturing industries, which is being triggered by increase in overall demand/consumption. The increasing trend in economic output and household consumption are the top drivers of non-decreasing GHG emissions stock. According to the fifth assessment report for climate change prepared by Intergovernmental Panel on Climate Change states that "*cumulative* emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond", which significantly stresses the importance of looking at the stock of GHG emissions rather than the rate (IPCC, 2014). According to this study, the last four decades' cumulative GHG emissions results indicate that food manufacturing, petroleum products manufacturing, power generation, and basic chemical product manufacturing industries are the top drivers of GHG emissions thus climate change in the supply chains. The food, energy, and chemical products-related consumption is increasing more rapidly compared to the technological innovation achieved towards more environmentally sound manufacturing processes in these industries. This finding was also mentioned in the EPA's 2014 adaptation plan. EPA states that "scientific evidence demonstrates that the climate is changing at an increasingly rapid rate, outside the range to which society has adapted in the past". This signifies the innovation in both production and the consumption aspects of the issue. Another recent study also indicate that "Ambitious climate policy requires strong public support" according to a public survey performed in China (Bernauer et al., 2016). Although some governments, business organizations, and societies are striving to make the world a more sustainable place, due to various reasons the success of U.S. towards stabilizing the GHG emissions is still out of reach.

Public inclusion for effective policy making, collective thinking and actions are among the most important steps that all stakeholders should highly be urged to implement since most of the industries found guilty (in other words "responsible") for the majority of the GHG emissions stock are highly tied with the final consumers. A recent piece of research found evidence that though the majority of U.S. population perceives climate change as an important problem for our common future, it still ranks behind economy, war, and terrorism. This also signifies the failure of science and scientists ability to communicate the importance of climate change across the stakeholders, governments, societies, business and nonprofit organizations (Sterman, 2011). Technological advancements should not deceive us in terms of reaching the sustainable development goals, because they will not be enough (*as evidenced by this piece of research)*, to change the increasing growth into a decreasing trend in GHG emissions due to environmentally unconscious and economically-focused increasing consumption patterns which are increasing environmentally unconscious supply and thus manufacturing.

In terms of policy making, in the very least, a national perspective, the best a global perspective needs to be integrated into *all* the decision making frameworks for sustainable development. The reason for a holistic understanding is the need for inclusion of all partners such as government, corporates and business organizations, non-profit organizations and society as a whole in action plans. Separated policies or individualist short-term approaches can make incremental improvements at best, whereas the planet need a *paradigm shift*. It's evident that industrial sectors such as fertilizer manufacturing, chemical product-plants, and nonrenewable energy production (specifically petroleum refineries) are primarily responsible for the carbon footprint stock. Instead of wait-and-see policy making (Sterman, 2011) we should be proactively implementing regulatory and incentive-based policy to limit and ultimately reduce GHGs.

In fact, we are as humans are responsible for all the damage that are being made to the planet and the environment. If the societies are not persuasive or educated to be persuasive enough for a paradigm shift, we can expect things to get much worse (Sterman, 2011). From a producers' perspective, business organizations need to account for their supply chain-linked carbon footprint impacts instead of just onsite emissions, so that green supplier selection will not just be a popular topic in literature but rather a critical component of businesses decision making. In an open and liberal economy, there needs to be an economic reason for the producer or a consumer to go to a more environmentally friendly, more sustainable option for a product or service.

6. Conclusion, limitations and future work

In this study, carbon footprint assessment of U.S. manufacturing was undertaken. The carbon footprint assessment was performed by developing Input-Output LCA models for the period 1970 through 2011. Several aspects of carbon footprint assessment were considered, namely: time series, stock vs. flow analysis, carbon footprint intensity analysis, on-site vs. supply chain impacts, and supply chain decomposition. We developed a time series EIO-LCA model to estimate the carbon footprint stock and flow of U.S. manufacturing industries considering onsite and supply chain impacts as a whole. The time series assessment of economic activity indicates a positive growth during the study period. In parallel with the economic output, the carbon footprint trend showed a steady increase over the course of the same time period in terms of cumulative (stock) carbon footprint. In contrast, carbon intensity of manufacturing activities has dropped significantly (by over 90%) in the last four decades, which can be attributed to technological advancements. Even though technology and the way goods are produced has changed and improved tremendously, the consumption (thus production) had gone up significantly. In return, the total carbon footprint associated with manufacturing activities has increased steeply and continues to increase.

The salient result of this research is that only focusing on technological advancement when dealing with environmental issues does not provide ample and significant solutions for the climate change and global warming. Economic structure of countries needs to be aligned with environmental impacts. Carbon footprint is still an externality when it comes to strategic decision making for a country or company. Unless the externalities are not internalized into the economic system (e.g. carbon taxing) strategically, the way we produce and consume will not change. The increasing stock trend of carbon footprint cannot be shifted to a decreasing trend unless the overall carbon footprint increase can be shifted to a net decrease.

We made several assumptions in order to carry out the analysis in this study and they can be relaxed in the future. For example, due to using a single region EIO-LCA model, we assume that U.S. manufacturing imports are domestically consumed. Also, carbon sequestration impact is not considered since this paper aims to investigate the amount of carbon footprint produced by the U.S. manufacturing and its supply chains. In order to overcome the aforementioned limitations, the future directions of current study should include; 1) the case of multi-region EIO-LCA models, 2) the integration of uncertainty (stochastic modeling) and decision support frameworks such as sustainability performance assessment, eco-efficiency analysis to benchmark manufacturing sectors carbon footprint based environmental performance, and 3) integrating the midpoint and endpoint impacts along with EIO-LCA model to estimate the human-life and eco-system level account of carbon footprint impacts.

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