



Article A Comparative Time-Series Investigation of China and U.S. Manufacturing Industries' Global Supply-Chain-Linked Economic, Mid and End-Point Environmental Impacts

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Abstract: Manufacturing activities of China and the U.S. account for a substantial portion of the global manufacturing output and environmental sustainability impacts. The two countries' economies account for one third of the global economic output. Their supply chains are critically linked with and serve most of the production and service industries across the globe. Recent global trends in manufacturing necessitate a study that comparatively analyzes the two countries' manufacturing industries from an economic and environmental perspective. In this paper, U.S. and China manufacturing industries were investigated to analyze the economic and mid and endpoint environmental impacts over a 20-year study period. The literature is abundant with single period and single country focused works, and this study contributes to the state-of-art by extending the temporal dimension to 20 years and spatial focus to the global economy (40 countries and rest of the world). In terms of the methodology, Multi-region input-output (MRIO) models were built using the World Input-Output Database (WIOD) as the primary database, global input-output tables, environmental impact and economic output multipliers, and manufacturing industries' final demand. Twenty MRIO models, each comprised of 40 major economies and the rest of the world (ROW), were built to cover the global trade linkages, which yielded the global supply chain linked cradle-to-gate life cycle inventory (LCI) of economic outputs and environmental impacts. The environmental LCI was extended to midpoint (Global Warming Potential (GWP) and Ozone Depletion Potential (ODP)) and endpoint (human health and ecosystem) impact dimensions by ReCipe framework. Lastly, the relative impact of a unit change in Leontief inverse, final demand and Green House Gas (GHG) emission multipliers on the total economic output and environmental impacts were explored with structural decomposition analysis (SDA). Results indicated that both countries' manufacturing industries experienced positive economic output growth, in which China was more dominant in recent years. Both countries' manufacturing industries' midpoint and endpoint impacts were found to be steeply rising despite the negative growth observed in emissions intensities. The amount of GHG emissions and related midpoint (global warming and ozone depletion) and endpoint (damage to ecosystems and human life) impacts seemed to be quickly worsening in China compared to the USA.

Keywords: input-output analysis; multi-region; sustainability; midpoint; endpoint; structural decomposition

1. Introduction

Manufacturing plays a substantial role in every economy due to its multiplier effect on sustainable economic growth. The gross output of U.S. manufacturing in 2013 was \$5.9 trillion, which was equivalent to 35.4% of the U.S. GDP in 2013 [1]. Thus, manufacturing has



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). been one of the most critical sectors in terms of employment and contribution to gross domestic production (GDP) in the U.S. In the context of environmental pressures, greenhouse gasses are among the primarily crucial impact categories. An Intergovernmental Panel on Climate Change report (2014) states that 65% of global GHG emissions are attributed to fossil fuel use due primarily to industrial processes. Another 11% is attributed to the direct and indirect emissions releases related to deforestation and other land use such as decay in biomass. While methane (CH₄) contributes to 16% of the total, nitrous oxide has a share of 6%. Moreover, according to the same report, the U.S. is the second-largest carbon dioxide (CO₂) emitter with 15%, after China with 30%. These statistics clearly indicate that it is important to comparatively study and assess the economic output and associated environmental impacts of the manufacturing industries in the U.S. and China, which together constitutes roughly half of the manufacturing-related carbon emissions worldwide.

Previous environmental impact assessment studies related to sustainable manufacturing research focused on conducting life cycle assessment (LCA) to build life cycle inventory (LCI). These studies' scope measures the inventory of the total energy use, raw material use, air and water emissions, as well as the total solid waste produced from the cradle-tograve (grave being the ultimate disposal) [2]. However, it is crucial to take a further step and study the ripple impacts of GHG emissions and resource extraction inventory on the earth and society, which are called midpoint and endpoint impacts. Midpoint impacts are typically termed as impact pathways at the intermediate position, such as ozone depletion potentials. In contrast, endpoint impacts are damage indicators at the level of the ultimate societal or ecological concerns about human health damage [3]. Endpoint measures make it easier to interpret and communicate the importance of sustainable development more effectively with academic and non-academic audiences.

Additionally, most of the works' focuses typically cover single or a few years of study period; however, longer period time-series analysis is critical to assist with future policymaking and have a comprehensive understanding of the trend of such impacts over time. This study's primary objective is to comparatively assess the economic and environmental (midpoint and endpoint) impacts of the U.S. and China's manufacturing industries for the period between 1994 and 2014. This study's secondary objective is to conduct a structural decomposition analysis (SDA) for both countries on the emission intensity, final demand, and economic output categories to understand the primary drivers of the overall environmental impacts of the study period.

2. Literature Review

The literature is abundant with works that address the environmental sustainability impact assessment of industrial processes. Among the environmental impact assessment techniques, life cycle assessment (LCA) is the predominant approach that is typically used to trace the environmental impacts that occur throughout the life cycle of products [4]. This assessment incorporates all the stages of a product life cycle, including raw material extraction, distribution, consumption, and disposal [5,6]. Curran [7] states that LCA can be used as a tool to compare products that have the same functionality or products that undergo a modification to change the product to make it more "environmentally friendly."

Although it could be practical to study a product life cycle, it is important to address and estimate the economic, social, and environmental impacts on larger scales such as city, region, country, or global economy. To be able to cope with environmental assessment studies that focus on regional or national economies, input-output economic tables are integratively used with environmental impact multipliers, which are the basis of input-output analysis (IOA) [8,9]. IOA studies could be subdivided into two, namely: single region IOA and multi-region IOA (in other words, multi-region input-output (MRIO)). Single region IOA focuses on assessing sustainability impacts on a single region (e.g., country, city, state, etc.), which holds domestic technology assumption. On the other hand, MRIO approaches more comprehensively take into account the international monetary flows. The World Resource Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) established the accounting standards to trace GHG emissions in the onsite and supply chain tiers of industries. MRIO has been used in the economy and environmental sustainability literature for various purposes. For instance, Zhang & Anadon [10] developed an MRIO model to evaluate the rate and structure of virtual water trade and consumption-based water footprint in China. Moreover, Kagawa el al. [11] used MRIO to assess the waste embedded in final consumption. Wiedmann et al. [8] used MRIO to conduct a time-series analysis of the UK's carbon footprint. Zhang et al. [12] used MRIO to investigate the energy embedded in China's foreign exports. Moreover, Zhang et al. [14] used MRIO to investigate the water withdrawals by the industries in China and demand-driven industrial water consumption integrated into the final demand and interregional trade. Bortone et al. [15] applied optimization approach for polluted groundwater treatment in a case of permeable reactive barriers.

In a recent work, Turkish manufacturing industries' carbon footprint was assessed with MRIO [4]. The researchers found that the highest carbon footprint share was electricity, gas, and water supply among the Turkish manufacturing sectors. MRIO models were developed to assess Turkish and 27 European food manufacturing industries' carbon and energy footprint. In another recent work, Abbood [16] studied the U.S. manufacturing carbon and energy footprint impacts by using stochastic MRIO models. The study results indicated that 81.7% of the carbon footprint was from U.S. manufacturing and regarding energy, U.S. manufacturing was 84%. However, this work's limitations include: (1) the focus was only on the life cycle inventory (LCI), but the midpoint and endpoint impacts were not addressed; (2) the study period was the years 2000–2009; (3) carbon footprint impacts were studied aggregately, not in detail.

Although LCA studies (whether process LCA or IOA is used) provide results of life cycle inventory (LCI), it is also crucial to study the ripple effects of these inventory results on the planet, termed as life cycle impact assessment (LCIA). Recent reports state that the primary driver of global warming is the human expansion of the "greenhouse effect" [17]. According to NASA [18], the greenhouse effect is the increase in temperature that results from the trapping of Earth's heat radiating towards space by the atmosphere. These impacts are categorized as midpoint and endpoint impacts. Moreover, the main difference between midpoint and endpoint impacts could be understood by the respective different stages in the cause and effect chain when calculating the effect. For example, one of the midpoint impact of N₂O emissions, which refers to looking at the end of the cause-effect chain, is the damage to human health due to ozone depletion. In other words, N₂O emissions will eventually damage human health through ozone depletion [18,19].

Throughout the years, various LCIA methodologies were developed. Pizzol et al., [20] used and compared eight methods, Stepwise 2006, Impact 2002b, EDIP 2003, Eco-indicator 99, CML 2001, TRACI 2, ReCiPe and USEtox, to assess the ecotoxicological impact of metals. The authors found out that the ecotoxicological impacts of metals vary based on the LCIA method employed. In a similar study by Pizzol et al. [21], nine different LCIA methodologies (EPS 2000 was added to the eight methods above) were compared to assess metals' impact on human health. The authors found out that there is no agreement between the results of different methods. This study uses the ReCiPe methodology for LCIA assessment due to its suitability in merging with LCI results, because a single value of mid and endpoint impact can be evaluated, standardized, and weighted by ReCipe approach. Table 1 shows a summary of the literature studying impact assessment from life cycle perspective.

Source	Problem Focus –	Env. Impact Focus		Mathad(a)
		Midpoint	Endpoint	
Pizzol et al. [20]	Impact of metal on human health	Yes	Yes	Comparing LCIA methods
Pizzol et al. [21]	Impact of metal on ecosystem	Yes	Yes	Comparing LCIA methods
Lopsik [22]	Wastewater	Yes	Yes	Process-LCA + RECIPE
Slagstad & Bratteø [23]	Water and wastewater system	Yes	No	Process-LCA + RECIPE Midpoint
Oliveira et al. [24]	LCA of electricity storage systems for grid application	Yes	Yes	Process-LCA + RECIPE
Ioannou-Ttofa, Foteinis, Chatzisymeon, & Fatta-Kassinos [25]	LCA of membrane bioreactor treatment process	Yes	Yes	Process LCA, IPCC 2013, RECIPE
Lamnatou & Chemisana [26]	Constructin	No (other method)	Yes	Process-LCA + IPCC 2012 midpoint RECIPE endpoint
Belboom, Digneffe, Renzoni, Germain, & Léonard [27]	municipal solid waste management	Yes	No	Process-LCA + RECIPE
Chatzisymeon, Foteinis, Mantzavinos, & Tsoutsos [28]	Olive mill wastewater treatment	Yes	Yes	Process-LCA + RECIPE
Benetto et al. [29]	LCA of heat production from grape marc pellets	Yes	Yes	P-LCA + RECIPE
Pan, Lin, Snyder, Ma, & Chiang [30]	Energy	Yes	Yes	P-LCA + RECIPE
Adam, Quaranta, & Loyaux-Lawniczak [31]	Terrestrial and aquatic ecotoxicity assessment of chromium	Yes	No	P-LCA + RECIPE midpoint
Dong & Ng [32]	Construction	Yes	Yes	P-LCA + RECIPE
Samani, Mendes, Leal, Miranda Guedes, & Correia [33]	Sustainability Assessment of Advanced Materials for Novel Housing Solutions	No	Yes	P-LCA + RECIPE
Repele & Bazbauers [34]	Building material (bricks)	Yes	No	P-LCA + RECIPE
Park, Egilmez, & Kucukvar [6]	U.S. mamufacturing, ecosystem level, single region, impact assessment	Yes	Yes	ECO-LCA + RECIPE
Park, Egilmez, & Kucukvar [35]	Supply chain plus onsite (direct) agricultural activities' midpoint impact characterization in the US	Yes	Yes	IO-LCA + RECIPE midpoint
Selicati, Cardinale, and Dassisti [36]	interoperability of exergy and Life Cycle Thinking in assessing manufacturing sustainability	Yes	Yes	Review of literature

 Table 1. Summary of the Selected Relevant Literature in Mid and EndPoint Impact Assessment.

From Table 1, it can be seen that RECIPE and Ecologically-based LCA (a single region IO-LCA approach [6]) were adopted frequently in various problems in the literature. A recent review of hybrid approaches [36] indicated that the mid and endpoint impact assessment is necessary to couple the results of LCA studies in manufacturing industries' sustainability assessment to have a holistic understanding from the entire life cycle of activities. For instance, the manufacutring e-waste disposal is a huge issue in China as 70% of world's e-waste is collected in Guiyu, China, where about 25% of this was recycled. [37] Some of these wastes end up in landfill, which could impact ground water systems. For instance, boron concentrations in groundwater treatment were assessed using a monitoring approach which is considered as a process of LCA [38]. Prior to this study, the closest works include [39,40], where manufacturing and agricultural production activities were investigated on a single study period (1 year) and considering a single region (U.S. economic system). The limitation of the current literature is that the data used is outdated (belongs to 2002) and single-year studies are based on the 2005 ECO-LCA model. In addition, keeping a single region scope (U.S. economy only) lacks the estimation of potential impacts at the global trade level. To the best of our knowledge, a comparative midpoint and endpoint impact assessment of the U.S. and China's manufacturing as a time-series investigation has not been proposed. Thus, the goals of this research are as follows: (1) Build longitudinal multi region input-output (MRIO) models to study the economic output of China and U.S. manufacturing activities considering their onsite and supply chain (domestic and global) related economic outputs over the longest possible period according to WIOD database, (2) Calculate the greenhouse gas emissions (GHGs) life cycle inventories, (3) Estimate the midpoint and endpoint impacts of the U.S. and China's manufacturing activities by integrating the life cycle inventory and RECIPE framework, (4) Conduct a structural decomposition analysis to understand the sensitivity of inputoutput models' parameters on the life cycle inventory, mid and endpoint impacts for both economies. The rest of the paper is organized as follows: Section 3 deals with the methodology, Section 4 with results, Section 5 with discussion, and Section 6 concludes.

3. Methodology

The scientific questions proposed in this study are as follows. (1) How did the economic versus environmental impacts (life cycle inventory of GHGs, mid and end point impacts) of Chinese and U.S. manufacturing industries change over the study period? (2) How has the stock (cumulative) and flow (annual rate) of GHG emissions evolved? (3) How sensitive are the environmental and economic outputs for each country to the change in interindustry supply chain linkages (total requirement matrix), change in final (consumer) demand, and change in environmental impact intensities (impact per dollar of output)? Figure 1 demonstrates the proposed hierarchical methodology in this study. There are 4 phases, namely: data collection and preparation, developing MRIO models for the study period between 1995 and 2014, conducting midpoint and endpoint impact assessment with ReCiPe, and lastly, conducting structural decomposition analysis (SDA). The input-output and final demand data of 40 major countries and the Rest of the World (RoW) were collected by using the World Input-Output Database (WIOD) [41]. In the second phase, multi-regional input-output (MRIO) models were developed to be used to quantify the total economic output and the three GHG emissions types. MRIO models were designed to cover the period between 1995 and 2014. The third step was using ReCiPe framework [39,40], which primarily uses the MRIO life cycle inventory results as input parameters to estimate the midpoint and endpoint impacts, termed as the LCIA. Finally, structural decomposition analysis (SDA) was employed to investigate the effect of the economic output changes, GHG emissions multipliers, and the final demand.



Figure 1. Summary of the Methods.

3.1. Data Collection

Data used to build MRIO models were obtained from the World Input-Output Database (WIOD) [41]. The data consists of economic input-output tables (flow matrix), final demand, and environmental impact (GHG emissions) multipliers for all countries and all industries (41 × 35 = 1435 rows). WIOD provides economic input-output data for 40 major countries and the rest of the world (RoW). Country and industry codes and classifications are kept as it was provided in the WIOD sources. To assess the midpoint and the endpoint impacts of GHG emissions, the results of LCI were used to characterize the midpoint and endpoint impacts. The characterization factors have three different cultural perspectives, namely: (1) Individualist (20 years), (2) Hierarchist (100 years), (3) and Egalitarian (1000 years). The 3 aforementioned perspectives could represent issues like time perspective or appropriate management, or future innovation and improvements. Repele & Bazbauers [34] suggest using a hierarchical perspective. Thus, the hierarchical aspect is chosen in this study.

3.2. MRIO Framework

MRIO models developed in this study comprised of the flow matrices for all the 41 countries (this covers national and international economic flows). In contrast to a single region input-output model, MRIO models enable researchers to trace the economic and environmental impacts both at the national and global scale, which can uncover the links between various sectors, as well as the economic relationship between different regions of the global economy [42–44]. It is important to note that the 41 countries (40 countries and 41st country being the rest of the world) make up the global supply chain network of all industries (each country's economy is made up of 35 industries). Thus, both domestic and global supply chain flows are traced with the MRIO framework. Equation (1) shows the quantification of the GHG emissions inventory:

$$E_{GHG-T_{ij}} = C_{GHG_{ij}} \left(I - A^{CR_{ij}} \right)^{-1} f_{ij}$$

$$R = 1, 2, 3 \dots .41, \ i = 1, 2, 3 \dots .35, \ j = 1, 2, 3 \dots .41, \ C = 1, 2, 3 \dots .41.$$
(1)

where E_{GHG-T} is the total GHG emissions vector and C_{GHG} is carbon emissions per milliondollar economic activity for each sector of 41 regions (*R*) as a diagonal matrix. *i* is the identity matrix, A^{CR}_{ij} matrix is the technical coeffect matrix. A^{CR}_{ij} contains interindustry requirements for all the 35 sectors of all the 41 regions. A^{CR}_{ij} presents the inputs of sector *i* from country *C* to industry *j* in country *R*, and f_{ij} is the final demand. The term $(I - A^{CR_{ij}})^{-1}$ is called the Leontief inverse [44], which is also termed with L in the literature [9]. In 2016, 97% of U.S. GHG emissions came from CO₂, N₂O, and CH₄. Thus, these three GHGs were considered as the LCI categories. This study does not consider the use of other substances such as environmental indicators and phenomena such as competitive adsorption, chloride desorption or mercury speciation.

In terms of studying supply chain impacts, a decomposition analysis was performed by investigating the onsite and supply chain impacts at the domestic and global scales. Equations (2) and (3) depict the calculation of onsite (E_{GHG-O}) and supply chain E_{GHG-SC} impacts for industry i in country j, respectively [9]. The domestic versus global supply chain impacts were traced by calculating the supply chain impact estimated in the home country (*j*) and the difference between the total supply chain impact $\sum_{j=1}^{41} \sum_{i=1}^{35} E_{GHG-SC_{ij}}$ and the impact occurred in home country.

$$E_{GHG-O_{ij}} = C_{GHG_{ij}} A^{CR_{ij}} f_{ij}$$
⁽²⁾

$$E_{GHG-SC_{ii}} = E_{GHG-T_{ii}} - E_{GHG-O_{ii}}$$
(3)

3.3. RECIPE Framework

LCIA could be performed by multiplying the results of LCI by the midpoint and endpoint characterization factors (CF). Thus, the midpoint impacts of GHG emissions inventory is calculated using Equation (4).

$$GWP = \sum E_{GHG_m} * CF_{E,GWP_m} \tag{4}$$

where *GWP* is global warming potential from GHG and its unit is kg CO₂ equivalents; E_{GHG_m} is total emissions of GHG_m ; CF_{E,GWP_m} is the characterization factors obtained from Huijbregts et al. [41], and it converts emissions of GHG_m to global warming potential (GWP), where m represents the GHG emission type investigated (m = 1,2, and 3, CO₂, N₂O, and CH₄, accordingly).

Equation (5) illustrates the calculation of ozone depletion protentional.

$$ODP = \sum E_{GHG_n} * CF_{E,ODP_n} \tag{5}$$

where *ODP* is ozone depletion potential from GHG in kg CFC-11 equivalents; E_{GHG_n} is total emissions of GHG_n ; CF_{E,ODP_n} is the characterization factor that converts emissions of GHG_n to ozone depletion potential, where m represents the number of GHG investigated; for ozone depletion, n = 1 since only N₂O has ozone depletion midpoint impact, thus CO₂ and CH₄ were not considered.

The two types of end point impacts studied in this study were damage to human health and damage to the ecosystem. Damage to human health is premature death and sickness disability, including irrigation caused by the emissions of GHG by the manufacturing industries. Damage to human health is measured as disability-adjusted life years (DALY) and its unit could be understood as one lost year of healthy life. Damage to human health in this study comes from GWP and ODP midpoint impacts. The second type of damage is damage to the ecosystem. Damage to the ecosystem is defined as the loss of species due to environmental load, and its measured by species per year (Species.year). Species.year's unit indicates that there is roughly one extinction per million species each year. Damage to the ecosystem is assumed to be the sum of GWP's damage to terrestrial species and the damage of GWP to freshwater fish.

The endpoint impact is calculated by multiplying midpoint impact by endpoint characterization factors, as illustrated in the Equation (6).

$$HH = GWP * CF_{GWP,HH} + ODP * CF_{ODP,HH}$$
(6)

HH is the damage to human health in DALY; $CF_{GWP,HH}$ is GWP to HH characterization factor; $CF_{ODP,HH}$ is ODP to HH characterization factor. Finally, the mathematical formulation for damage to ecosystem is presented in Equation (7).

$$ES = GWP * CF_{GWP,ES}$$
⁽⁷⁾

where *ES* is damage to the ecosystem, measured as species.year, and $CF_{GWP,ES}$ is *GWP* to ES characterization factor.

The flow chart below, Figure 2, shows the midpoint and endpoint impact of the three investigated GHGs.



Figure 2. LCI and LCIA flowchart [37].

Figure 3 illustrates the calculation of midpoint impact from the multiplication of LCI results with the characterization factors, as well as the estimation of endpoint impacts from the multiplication of midpoint impacts by the endpoint characterization factors. We note that these comprehensive midpoint and endpoint impacts on human health and ecosystems span various individual impacts such as ground water pollution, waste disposal management, etc.



Figure 3. Mid and endpoint Impact characterization factors [37].

3.4. Structural Decomposition Analysis

Rose & Chen [45] define structural decomposition analysis (SDA) as an "analysis of economic change utilizing a set of comparative static changes in key parameters in an input-output table". SDA investigates the driving factor that over time changes the total output. For example, if SDA is applied to Equation (1), it can examine how the change in C_{GHG} , $A^{CR_{ij}}$, and f_i will drive the change in GHG emissions. To formulate the equations of

SDA on Equation (1), for simplicity E_{GHG} is set as X, $(I - A^{CR_{ij}})^{-1}$ as L, C_{GHG} as c, and f_i as f, thus Equation (1) is modified to:

$$X = cLf \tag{8}$$

There are three terms in Equation (6), and considering two different years, y_{i+1} and y_i , i = 1995, 1996,..., 2013. The number of decomposition equations describing the change in output is determined by taking the factorial of the number of terms in Equation (8), equal to 3! = 6. Therefore, six decomposing equations that represent the change in **X** are derived. Equations (9)–(14) illustrate the decomposition equations of change in GHG emissions.

$$\Delta X = c_{vi+1} \Delta L f_{vi+1} + c_{vi+1} L_i \Delta f + \Delta c L_i f_{vi}$$
(9)

$$\Delta X = c_{yi+1} \Delta L f_{yi+1} + c_{yi} L_i \Delta f + \Delta c L_i f_{yi+1}$$
(10)

$$\Delta X = c_{yi+1} \Delta L f_{yi} + c_{yi+1} L_{i+1} \Delta f + \Delta c L_i f_{yi}$$
(11)

$$\Delta X = c_{yi} \Delta L f_{yi} + c_{yi+1} L_{i+1} \Delta f + \Delta c L_{i+1} f_{yi}$$
(12)

$$\Delta X = c_{yi} \Delta L f_{yi+1} + c_{yi} L_i \Delta f + \Delta c L i + f_{yi+1}$$
(13)

$$\Delta X = c_{yi} \Delta L f_{yi} + c_{yi} L_{i+1} \Delta f + \Delta c L_{i+1} f_{yi+1}$$
(14)

The effect of the change in the Leontief matrix can be calculated by taking the mean for the six first terms in the six decomposing equations. However, Dietzenbacher & Los [46] state that maximums, minimums and standard deviations of each term could also be considered. In this study, the change in emissions for each term was calculated by taking the mean for the terms.

4. Results

4.1. Results of LCI

4.1.1. Economic Output

The results of the time-series analysis of U.S. manufacturing economic output is shown in Figure 4a. From the figure, U.S. economic output has an increasing trend until the financial crisis in 2008. Due to the crisis, U.S. total economic output has dropped by approximately one billion dollars due to the U.S. manufacturing economic output decline in 2008. The economic output fell from 5485 billion dollars to 4590 billion dollars. From 2010 to 2011, U.S. economic output yielded the highest increase of around one billion. The U.S. had the highest economic output of 6560 billion dollars in 2014. U.S. manufacturing domestic onsite economic output remains proportionate to the total global economic output. The percentage share of the U.S. manufacturing domestic (onsite) output ranges between 64% and 69% of total global economic output. Early years have a higher percentage share in comparison to recent years. Moreover, U.S. manufacturing's domestic economic output ranges from 81% to 89% (see Figure 4a). The early years had a higher percentage share of economic output, and the recent ones have a lower one. Based on these findings, it could be concluded that the increase of total global economic output resulted in a higher percentage of global supply chains' economic output in recent years rather than the domestic (onsite + domestic supply chains) economic output.





b (China)



Figure 4. Manufacturing industries' global economic output (% share) U.S. (a) China (b).

Similarly, China's economic output results from the years 1995 to 2014 are shown in Figure 4b. China's total economic output increased throughout the 20 years. However, similar to the U.S., the highest increase in total economic output was between the years 2010 and 2011. The overall increase in China's economic output between the years 2010 and 2011 was 1.78 billion dollars. China had the highest economic output of 11,892 billion dollars in 2014. China's manufacturing domestic onsite percent share ranged from 71% to 79% of total economic output between 1995 and 2014. In comparison to the early years, China's domestic percentage share decreased in recent years while its global output increased.

4.1.2. Global, Domestic, and Onsite Greenhouse Gas Emissions

Figure 5a shows the total GHG emissions for U.S. manufacturing between the years 1995 and 2014. The GHG emissions seemed to be increasing from year to year except during the financial crisis in 2009. In comparison to 2008, in 2009 the GHG emissions dropped by 163 million metric tons of CO_2 equivalent. From Figure 5a, it can be seen that the GHG emissions in 2010 are relatively high in comparison to the total global economic output of 2010. U.S. manufacturing domestic onsite GHG emissions range from 41% to 54% of the total GHG emissions (onsite + domestic supply chain + global supply chain), while the domestic GHG emissions ranged from 71% to 84%.



(a) U.S. GHG emissions



(**b**) China GHG Emissions

Figure 5. Manufacturing industries GHG emissions. (MMT CO₂ eqv.) (a) U.S., (b) China.

In comparison, China's total GHG emissions are illustrated in Figure 5b. From the figure, China's GHG emissions had a slight drop in GHG emissions in the years 1997, 1998, 1999, and 2000. However, starting in 2001, the GHG emissions of China's manufacturing have experienced a continuous increase. Moreover, manufacturing domestic onsite percentage share and the domestic supply chains' percentage shares decreased in recent years. However, global supply chain-linked emissions increased. Since 2008, about 4 trillion yuan has been invested in manufacturing industries to boost domestic consumption and economy, which resulted in increasing GHG emissions from metal and non-ferrous metal production. The twelfth five-year plan was issued for energy conservation and GHG emission reduction, which reduced the rate of GHG emission from onsite and domestic supply chain activities since 2012 [47].

4.2. LCIA Results

4.2.1. Midpoint Impacts (GWP, ODP)

The impacts of U.S. manufacturing on global warming is shown in Figure 6a. For the years before the U.S. economic crisis, the GWP did not seem to create severe fluctuations across the years. However, an increasing trend exists for the years after the economic crisis in 2008. Although the GHG emissions of 2010 were lower than the ones in 2011, the GWP of 2010 was higher than in 2011. This is because the amount of CH₄ emissions in 2010 was

higher than the CO2 and CH4 GWP characterization factor, which is 34 times larger than the CO_2 characterization factor. Similarly, the GWP results of China's manufacturing on global warming are depicted in Figure 6b. Since 2002, it is evident that China's manufacturing industries' GWP impact is on a continuous rise, compared to a less steep rise observed in the U.S. manufacturing graph in Figure 6b.



402/ GWP 2072 2126 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 Years Global Supply Chain Domestic Supply Chain Manufacturing Domestic On-Site 2 per. Mov. Avg. (Global Supply Chain)



Figure 6. Manufacturing industries' GWP (global (M kg CO₂ eq). (a) U.S., (b) China.

Figure 7a shows the trend of ozone depletion impacts of U.S. manufacturing. There is an inherent fluctuation, continuous until 2009, which seems to have a relatively small range. However, in 2010, a crucial amount of drop was observed in the ozone depletion potential, and after 2010, the ozone depletion potential was on an increasing trend. The GHG emissions of 2012 were found to be more substantial than in 2011. However, the ODP of 2012 was found to be relatively lower than in 2011. This could be attributed to the share of N_2O emissions in 2011 being higher than it was in 2012. Similarly, the ODP impact of China's manufacturing industry was shown in Figure 7b. The ODP results of China seem



to be relatively aligned with the GWP results of China. The ODP of China manufacturing

was found to be on a continuously increasing trend starting from 2003 to 2014.





Figure 7. Manufacturing industries' ODP (HND kg CFC-11 eq). (a) U.S., (b) China.

4.2.2. EndPoint Impacts (Damage to Human Health, Damage to Ecosystem)

U.S. manufacturing's damage to human health results are shown in Figure 8a. It can be concluded that damage to human health increased drastically after 2010. However, for China (See Figure 8b), the damage has been on the rise since 2003. The results of the U.S. and China's manufacturing industries' impacts on the ecosystem are shown in Figure 9a,b, respectively. Similar to the results of human health impact, the impact of U.S. manufacturing increases after 2010, while for China, the impact is on a continuous rise since 2003. When we compare the actual estimated damage, the ratio of China to U.S. jumped from 1.9 (1212/637) in 1995 to 3.3 (2777/833) in 2014. This clearly indicates the significant and serious increase in Chinese manufacturing impact on human health in 1995, while it jumped to 3.3 times in 2014. Furthermore, in this comparison, it is also hard to see a decrease in damage to human health in U.S. manufacturing either.



(a) U.S. Damage to Human Health

Figure 8. Manufacturing industries' damage to human health (HND DALY) (a) U.S., (b) China.

When we compare the damage to ecosystem ratio of China to U.S., the ratio was 1.9 in 1995, and jumped to 3.15 in 2014 according to the Figure 9a,b. Unfortunately, the damage estimations to the ecosystem were non-decreasing in both countries and in China it has gotten significantly higher especially in the last 5 years of study period. In both countries, onsite manufacturing activities dominate the endpoint impacts, which was followed by the global supply chains.

4.3. Structural Decomposition Analysis (SDA)

SDA results were summarized based on the change in Leontief inverse, final demand, and GHG emissions multipliers.

4.3.1. Leontief Inverse (L = $(I-A)^{-1}$) (Effect of Interindustry Demand)

Figure 10 shows the effect of interindustry demand on difference in the total GHG emissions between the U.S. and China during 1995–2011. In the Figure, the blue color code represents an increase and the orange color code indicates a decrease. The value of the difference remained above zero for most of the period except for the U.S. during 1995–1999. From the chart, Chinese manufacturing industries emitted more GHG emissions than U.S.

manufacturing industries. The GHG emissions difference failed to follow a constant trend before 2002 in China but grew faster after 2002. The trend is different from the U.S. in that period, as there was a sudden decrease in the GHG emissions in 2002, and started to increase again thereafter. This is because the GHG emissions in the Chinese manufacturing industry were much larger than those of the U.S. manufacturing industry since 2008 as a result of rapid economic growth and demand shift from global markets. The cause for this finding is that the economic output in China was fairly larger than that of the U.S during 2008–2014, considering the financial crisis in the U.S. in 2008 and its aftermath. According to the results in Figure 4, the domestic supply chain in China was 1.13–1.81 times that of the U.S. during 2008–2014. Since 1995, China has seen rapid economic growth, resulting in more domestic supply chain activities within the country. On the other hand, the U.S. has been the largest developed country in the world for some time.



(a) U.S. Damage to Ecosystem





Figure 9. Manufacturing industries' damage to ecosystem (species. year). (a) U.S., (b) China.



Figure 10. Effect of change in Leontief's inverse on the total economic output of U.S. (a) vs. China (b).

In Figure 10a, the effect of change of interindustry demand in the U.S. on the total GHG emissions is depicted. In the Figure, the blue color code represents an increase and the orange color code indicates a decrease. The chart shows that the total economic output drops significantly in 2001–2002 and 2008–2009. Similarly, Figure 10b shows the effect of change of interindustry demand in China on the total GHG emissions. Overall, the effect of China's interindustry demand is to instigate an increasing trend over the study period, compared to more severe fluctuations in the interindustry demand of the U.S.

4.3.2. Effect of Final Demand

The effect of the change in final demand on the total GHG emissions of the U.S. and China is shown in Figure 11a,b, respectively. In the U.S., the effect of final demand on the GHG emissions is on a continuous rise, apart from some slight drops in 2000–2001, 2001–2002 and substantial decline in 2008–2009, which could be mainly attributed to the financial crisis. A similar effect is observed in China, as well. In Figure 11b, the impact of the change in final demand on the GHG emissions of China increases rapidly between 1995 and 2014. In general, China tends to produce higher GHG emissions than the U.S. This finding is mainly because the final consumption in Chinese industries was generally higher than that of the U.S. industries. Since 1995, China's economy has been rapidly growing,

while U.S. has already developed. Our analysis indicates that the effect of final demand on the economy between China and U.S. was huge during the examined time period. We can easily conclude that the final demand increase in both countries significantly linked with the GHG emissions. It seems suitable to compare our study with that of Zhao's [48]. Our result is similar to theirs in how their study identifies the total demand as a driving factor of GHG emission in manufacturing industries in both the U.S. and China.



Figure 11. Effect of change in final demand (f) on GHG emissions of U.S. (a) vs. China (b) mfg.

4.3.3. GHG Emissions Coefficients

Figure 12a shows the SDA results of GHG emissions' coefficients for the U.S. Similarly, Figure 12b shows the change in China's GHG emissions intensity over study period. Unlike the final demand, the GHG emissions coefficients decreased across the years; this clearly indicates that the GHG emission intensity of both countries' manufacturing activities are on a decreasing trend. These facts reveal that the effect of the GHG emission coefficient is more minor than final demand. The drop in GHG emissions per output unit in manufacturing activity could shift towards manufacturing industries that are less dependent on fossil fuel energy.



Figure 12. Effect of change in emission coefficients on total GHG emissions Of the U.S. (a) vs. China (b) Mfg.

5. Discussion

The final demand was a key factor in the non-decreasing GHG emission stock in both the U.S. and China. However, rising human consumption patterns have still been an essential and primary driver of environmental impacts at the mid and endpoint. Both U.S. and Chinese manufacturing economic output causes the vast majority of the environmental impacts at the host country, while the rest of the world (ROW) stands out as being significantly impacted. GHG emissions per million-dollar economic output have been decreasing, which could be attributed to technological advancements in manufacturing processes. Considering our research results, there are several potential policy suggestions from an economic and environmental impact perspective.

Economic output: Manufacturing industries have the highest multiplier effect on an economy, ranging from 5 to 15 jobs created due to a manufacturing job. This multiplier impact is highly necessary and important for sustainably growing economies and meeting society and consumers' expectations and needs at large. While providing these significant contributions to the economy, due to high linkage with nonrenewable energy consumption, manufacturing industries are among the primary causes of environmental pollution, global warming, and ecosystem level resource depletion. Therefore, analyzing the extent of the economic and environmental impacts of manufacturing industries' sustainability performance is crucial for establishing a viable sustainable development agenda for the world. In this context, U.S. and Chinese manufacturing accounts for a substantial portion of the global industrial output (around 45% in United Nations Statistics Division 2018 Report). China has been on a substantial growth trend in both manufacturing and non-manufacturing activities and passed the U.S. manufacturing output after the 2010s [49].

Considering the changes in both Chinese and U.S. manufacturing-related economic output in recent decades, it was necessary to conduct a time-series analysis of both from economic, environmental, and ecosystem level perspectives).

Energy and Emissions: Both U.S. and Chinese manufacturing industries were found to have great potential for reducing carbon emissions. Onsite emissions accounted for significantly larger shares than emissions related to the global and domestic supply chains. Electricity, gas, and water supply; coke, refined petroleum and nuclear fuel; mining and quarrying; basic metals and fabricated metal; and chemicals and chemical products industries were still the primary drivers of environmental impacts investigated, while simultaneously contributing to the host country's economy substantially. This indicates that both manufacturing economies are not experiencing sustainable growth, which means the mid and endpoint environmental impacts of production processes are steadily increasing.

These findings suggest that policy-making for a change in renewable energy dependency of manufacturing activities is crucial as fossil fuel-based energy is still the leading cause of GHG emissions, and thus mid and end point impacts. Thus, radical transformations are necessary and required in energy policy and global energy outlook. It is important to note that both countries' manufacturing-related emissions intensity has been decreasing; however, both final demand and manufacturing output continues to rise and offsets the potential benefits of lower emissions intensities. Manufacturing activities are becoming less energy intense, as the emissions multipliers are decreasing. However, this positive change does not substantially decrease the total emissions stock and mid and endpoint impacts, as they were both found to be experiencing positive growth. While that the U.S. has the largest economy, the scale of China's economy and international trade have been substantially growing; both countries have significant global roles, and the bilateral relationship between the two countries will be an important determinant of the carbon footprint and economic output [50]. The trade restriction between the U.S. and China would significantly impact the world's GHG emissions. The implemented China and U.S. trade restriction reduces overall energy consumption and final consumption of both sides, contributing to long term GHG emissions reduction. Mainly, concerning trade restriction, energy consumption and most of the manufacturing industries' GHG emissions will decrease significantly [49]. Thus, the trade restrictions would increase the dependency on non-fossil fuels in China and the U.S, where modest efforts in environmental improvement are not enough to mitigate climate change. Therefore, a strong mitigation policy is necessary. It is difficult to benefit the economy and environment simultaneously. For example, in the case of effects on the rare earth minerals market, the trade war could mean disaster for many countries' environments, such as Vietnam, Brazil, and Russia, which have rich deposits of rare minerals, as the U.S. will increase the sourcing from these countries instead of China. Emission reductions induced by trade restrictions would stop the collaborative practice to fight against global climate change.

Mid and Endpoint Impacts: Our findings indicate that the extent of worsening is more serious in China compared to the U.S. in both midpoint and endpoint impact categories. Damage to human health and damage to ecosystem indicators show a significant increase in China compared to U.S., while both countries' overall impacts are on a positively growing trend. From the LCIA modeling perspectives, the literature [35] have compared the territorial differences between the LCIA system's boundaries and its significance for environmental policy decisions of compiling a supply chain-linked life cycle emission inventory of various countries and regions. Therefore, it is beneficial to study the linkage of supply chain-linked emissions among industrial sectors in the U.S. and China. Emissions results could be interpreted differently because environmental policy decision-makers could measure both direct and indirect effects from, e.g., fuel category indirect and total requirements. For example, decision-makers need to impel onsite cleaner production for mid and endpoint impact of Electricity, Gas, and Water Supply. In that case, the breakdown information of fuel or energy consumption in the entire supply chain is required to seek significant contributors by energy-producing sectors, e.g., reducing CO_2 in refined petroleum and nuclear fuel. If decision-makers want to evaluate the indirect effect in the chemicals and chemical products industries' supply chain, life cycle emission intensity by direct input coefficient is useful for comparing with process-based life cycle emission factors. If they want to look for crucial factors of mid and endpoint impact of emissions induced by final demand, emission intensity by total input that is calculated from the ReCipe method is going to be more relevant. As the U.S. and China are increasing household consumption and service requirements, life cycle emissions in both countries will play a more critical role in the global supply chains.

6. Conclusions, Limitations, and Future Work

This study aimed to investigate the life cycle inventory, midpoint, and endpoint impacts of the selected GHG emissions caused by U.S. and Chinese manufacturing industries in the last two decades, from a global trade perspective. An integrated methodology that consists of MRIO and ReCipe approaches was proposed and implemented to reach this overarching goal. The analysis focused on 40 major countries and considered the rest of the world as the 41st country. Each country was represented with 35 primary services, construction, energy, manufacturing, etc., industries based on the WIOD database notation and classification. The selected GHG emissions were CO₂, N₂O, and CH₄. A total of 20 MRIO models were developed, which were used to estimate the GHG emissions inventory (LCI). Then, LCI was merged with the ReCiPe to estimate the midpoint and endpoint impact of the U.S. and China's manufacturing industries. The study period was between 1995 and 2014. In the final phase of the methodology, structural decomposition analysis (SDA) was implemented to assess the change in the selected components of the MRIO model such as emissions to air (E2A) multipliers, final demand, and Leontief's inverse on the total GHG emissions. Our finding showed that both manufacturing industries in the U.S. and China had positive economic growth during the study period. There was significant growth of midpoint and endpoint impact for both countries even though both countries experienced negative growth in GHG emissions intensities.

Among the limitations, the study period does not include the most recent data (latest data year is 2014) due to working with the WIOD database. As more recent input-output tables become available on the WIOD database, this analysis should be revisited and reinvestigated. Input-output-based sustainability assessment models provide a holistic understanding about the industries' domestic and global onsite and supply chain activities. However, they are not focused on individual manufacturing processes, which is another limitation of this framework. Moreover, this study has the following extensions, and they are left as future work. Current work investigated the manufacturing industries of the U.S. and China. A similar approach could be used for the service or other industries. Additionally, this study examined U.S. and Chinese manufacturing; however, a similar approach could include other countries' manufacturing industries. This study investigated the U.S. and China's manufacturing separately for a fair comparison. However, it would be important to study the U.S. and China's manufacturing impacts together in the same model, which could be further compared with this study's findings. Also, finally, ecoefficiency analysis on the results of midpoint and endpoint impacts could be carried out by considering the economic output and environmental impacts. Therefore, Principal Component Analysis and Data Envelopment Analysis (DEA) methods could be employed over a longitudinal study period.

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