A Web-based Decision Support Tool for Global and Supply Chain-linked Carbon Footprint Accounting

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Graduate School of Natural and Applied Sciences

by

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in partial fulfillment for the
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in

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I, Taha MOIZ, declare that this thesis titled, 'A Web-based Decision Support Tool for Global and Supply Chain-linked Carbon Footprint Accounting' and the work presented in it are my own. I confirm that:

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Date: 25 MAY 2017

"Great dreamers' dreams are never fulfilled, they are always transcended."

Alfred Lord Whitehead

A Web-based Decision Support Tool for Global and Supply Chain-linked Carbon Footprint Accounting

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Abstract

This thesis proposes a first web-based global carbon footprint accounting platform for world economies. As a response to steeply rising global carbon emissions, many nations decelerated to minimize their regional and global carbon emission in a recent United Nation's Conference on Climate change (COP21). In this regard, global multiregional input-output databases such as World Input-Output Database (WIOD), EXIOBASE, and EoRA become very critical databases to trace the regional and global greenhouse gas emissions of countries worldwide. Although these databases become very successful and critical for a consumption-based carbon footprint accounting, there is certain research need on developing an open source and web-based carbon footprint accounting model using these databases. This will increase the visibility of these tools and increase the application of consumption-based carbon footprint studies in multidisciplinary research fields including engineering and social sciences. As a response to this research gap, an open source web based carbon footprint accounting platform was developed. This platform is capable of analyzing the greenhouse contributions of each country with four different outputs such as scope based carbon footprint analysis, supply chain decomposition analysis, comparative country carbon footprint analysis, and time series carbon footprint analysis. The tool was constructed using the Ruby on Rails, with data accessed from the WIOD, and offers users to customize their inputs based on 40 countries and 35 economic sectors. In time this tool will include triple bottom-line supply chain analysis to fully map greenhouse emissions, energy consumption and socio-economic impacts, such as employment generation, economic value added and human health impacts.

Keywords: Decision support software, programming, data visualization, carbon footprint, global supply chains, life cycle sustainability assessment, multi region input-output analysis, global trade

Küresel ve Tedarik Zincirine Bağlı Karbon Ayak İzi Muhasebesi için Web Tabanlı Karar Destek Aracı

Taha Moiz

Öz

Bu araştırma dünya ekonomileri için ilk web tabanlı küresel karbon ayak izi hesaplama platformuna ilişkin olarak hazırlanmıştır. Büyük bir hızla yükselen küresel karbon salımlarına karşılık olarak birçok millet Birleşmiş Milletler Küresel Isınma Konferansında (COP21) bölgesel ve küresel karbon salınımlarını en aza indirgeyeceğini açıklamıştır. Bu bağlamda dünya girdi çıktı veritabanı (WIOD), EXIOBASE ve EoRA gibi küresel çok-bölgeli girdi çıktı veritabanları, dünya genelindeki ülkelerin yerel ve küresel sera gazı salınımlarının takip edilmesi açısından oldukça kritik hale gelmiştir. Her ne kadar bu veri tabanları tüketim tabanlı karbon ayak izi hesaplaması için oldukça başarılı ve kritik olsa da, bu veritabanlarını kullanan bir açık kaynaklı ve web tabanlı karbon ayak izi hesaplama modeli için hala ilave çalışmalara ihtiyaç duyulmaktadır. Böyle bir çalışma, söz konusu araçların görünürlüğünü arttıracağı gibi tüketim tabanlı karbon ayak izi çalışmalarının, endüstri ve sosyal bilimleri de içine alan çok disiplinli araştırma alanlarında uygulanmasını da artıracaktır. İşte bu araştırma boşluğuna cevap olarak açık kaynaklı web tabanlı karbon ayak izi hesaplama platformu geliştirilmiştir. Bu platform, her bir ülkenin sera gazı oluşumuna etkisini; kapsam tabanlı karbon ayak izi analizi, tedarik zinciri ayrışması analizi, karşılaştırmalı ülke karbon ayak izi analizi ve zaman serileri karbon ayak izi analizi gibi dört farklı sonuçta inceleme kapasitesine sahiptir. Bu araç WIOD sisteminden ulaşılan verilerle birlikte "Ruby on Rails" kullanılarak geliştirilmiş olup kullanıcılara girdilerini 40 ülke ve 35 ekonomik sektör temelinde uyarlama imkanı sunmaktadır. Zamanla bu araç sera gazı salınımlarının, enerji tüketiminin ve istihdam yaratma, ekonomik katma değer ve insan sağlığı gibi sosyo-ekonomik etkilerin tam bir haritasını çıkartmak için üçlü bir temel tedarik zinciri analizini içerecektir.

Anahtar Sözcükler: Karar destek yazılımı, programlama, veri görüntüleme, karbon ayakizi, küresel tedarik zincirleri, yaşam döngüsü sürdürülebilirlik değerlendirmesi, çok bölgeli girdi-çıktı analizi, küresel ticaret

To my parents and grandparents, for inspiring me.

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Abbreviations

WIOD	**W**orld **I**nput-**O**utput **D**atabase
GHGs	**G**reen**H**ouse **G**ases
CO_2	**C**arbon Di**o**xide
N_2O	**N**itrous **O**xide
CH_4	**M**ethane
COP 21	**C**onference of **P**arties **21**
UNFCCC	**U**nited **N**ations **F**ramework **C**onvention on **C**limate **C**hange
COP 15	**C**onference of **P**arties **15**
LCA	**L**ife **C**ycle **A**nalysis
P-LCA	**P**rocess-based **L**ife **C**ycle **A**nalysis
I-O	**I**nput-**O**utput
EIO-LCA	**E**conomic **I**nput-**O**utput **L**ife **C**ycle **A**nalysis
SRIO	**S**ingle **R**egion **I**nput-**O**utput
MRIO	**M**ulti **R**egion **I**nput-**O**utput
GRAM	**G**lobal **R**esource **A**ccounting **M**odel
GTAP	**G**lobal **T**rade **A**nalysis **P**roject
EXIOPOL	**Ex**ternality Data and **I**nput-**O**utput Tools for **Pol**icy Analysis
COICOP	**C**lassification of **I**ndividual **Co**nsumption by Purpose
ABS	**A**ustralian **B**ureau of **S**tatistics
OECD	**O**rganisation for **E**conomic **C**o-operation and **D**evelopment
IDE-JETRO	**I**nstitute of **D**eveloping **E**conomies, **J**apan **E**xternal **Tr**ade **O**rganization
SWD-EET	**S**tepwise **D**istribution of **E**misions **E**mbodied in **T**rade
ONS	**O**ffice for **N**ational **S**tatistics
ILO	**I**nternational **L**abour **O**rganization
EEBT	**E**misions **E**mbodied in **B**ilateral **T**rade

RoW	**R**est-of-the-**W**orld
NAS	**N**ational **A**ccounting **S**tatistics
MVC	**M**odel-**V**iew-**C**ontroller
G-CAT	**G**lobal **C**arbon **A**ccounting **T**ool
FBT	**F**ood, **B**everage and **T**obacco
CON	**C**onstruction
TTP	**T**extile and **T**extile **P**roducts
AHFF	**A**griculture, **H**unting, **F**orestry and **F**ishing
TBL	**T**riple-**B**ottom-**L**ine
SDGs	**S**ustainable Development Goals

Chapter 1

Introduction

1.1 Global Climate Change and Sustainable Development

Rapidly growing human population has created many detrimental problems, among those being global climate change [1]. Global warming is chiefly driven by emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). These GHGs contribute approximately 64%, 6% and 17% towards global warming respectively [2]. Of these GHG emissions, industrial sectors play the part of the largest contributors and in this age of consumerism, a sustainable world is not possible without sustainable and efficient manufacturing practices. It is important to note that in global practice it is (CO_2) analysis that is used to quantify the "carbon footprint" of activities, organizations, industries and populations, as the other gases are usually not carbon based and have limited data availability [3–6]. Wiedmann and Minx [3] also defined carbon footprint as "a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product."

It is numbers like these that have prompted world leaders to come together for forums like the Sustainable Innovation Forum 2015 or Conference of Parties 21 (COP 21) to develop policies to keep global climate change below 2°C [7]. The meeting is held under the authority of the United Nations with representation from 196 states ensuring worldwide support and action towards sustainable practices. The United Nations Framework Convention on Climate Change (UNFCCC or Framework Convention) is the parent treaty of the Kyoto Protocol of 1997. The UNFCCC with 196 parties and the Kyoto Protocol with 192 ratified parties aims to stabilize GHG emissions in the atmosphere to a level that will prevent dangerous human interference with the climate system [8]. The Kyoto Protocol required industrialized countries to limit GHG emissions for the years 2008-2012 to an average of approximately 5% below their 1990 emissions levels [9]. Seemingly simple enough, the accord fell in disarray when the United States of America, one of the leading emitters of GHG gases, did not ratify the treaty. Although the Kyoto Protocol targets were developed on a feasibility criteria, parties were unable to agree on implementation of the Kyoto agreement [10]. Subsequent meetings of the Conference of Parties in Lima, Warsaw, Doha, Durban, Copenhagen and several other countries, spanning two decades, envisioned modifications to get the parties to agree on implementation responsibilities of the Kyoto. Most notably in Copenhagen, 2009 (COP 15) the leaders of the parties agreed to limit global climate change to 2°C, the long term goal of the accord, and differentiated approaches for developed and developing countries. It also, for the first time, got the leading developing countries, Brazil, China, India, and South Africa, to report their GHG emissions on a global platform [11].

The COP21 (Paris, 2015) stands out from previous such conferences in that it will attempt to achieve a binding and universal agreement from all nations of the world. It has further tightened the global climate change limit to 1.5°C increase from pre-industrial era, along with financial support for nations to build more sustainable futures and taking actions to reduce emissions fast enough to reach the temperature goal. Nations are expected to submit updated individual climate plans named nationally determined contributions (NDCs) every five years. This will aim to increase their ambition in the long-term [8].

Of the 196 member states the area of focus is on the EU 27 countries and 13 major developed and developing countries around the world, primarily because these countries include some of the most developed and industrialized countries. Another reason to target these countries is because most of these are at the forefront towards greener and sustainable manufacturing with some of them even having previous agreements to reduce GHG emissions. The EU in 2015 has already committed to reducing GHG emissions by 40% compared to 1990 levels by 2030 and Germany, being the highest emitter of GHG in EU, has targeted 40% reduction by 2020 and 55% by 2030 compared to 1990 [12]. Even though Germany is likely to miss its target by one-fourth in 2020 [13], its ambition to address this issue shows Germany's commitment towards the issue of global climate change. The United Kingdom, being the second highest emitter of GHGs in the EU, passed in 2008 the world's first legally binding Climate Change Act targeting carbon emissions 80% below 1990 levels [14].

1.2 Novelty and Research Objectives

Pauliuk et al. [15] touched upon the need for collaborative open source software frameworks in the field of Industrial Ecology (IE). Their study led them to conclude that to improve productivity and quality of studies in Industrial Ecology an open source software for IE should be developed for the areas of Life Cycle Assessment (LCA), Input-Output (I-O) analysis and dynamic material or substance flow analysis. This paper aims to respond to the call by Pauliuk et al. [15] through the development of an online decision support tool to aid in determining the scope-based supply chain impacts of energy and carbon.

Since researchers in the field of carbon footprint analysis are usually not software engineers, they are not adept at building very optimal code hence reproducibility becomes difficult for their studies. The hallmark of IO and MRIO applications is that using the same data set other researchers should be able to achieve the same outputs as the original study. At the present, most IO studies are dedicated to single projects or studies and are coded on spreadsheets or on various programming languages. This poses challenges when these studies need to be replicated, either as is, or to be applied on developing countries.

In Chapter 2 of this paper it will be discussed that applications of MRIO are dominated by China, followed by the European Union. In fact when it comes to MRIO application only a few countries are represented, leaving the majority of countries to be grouped as Rest of the World (RoW). Thus MRIO studies with global coverage are few and far between. An open source tool will be beneficial to increase the efforts on studies conducted in RoW regions.

Keeping in line with the research gap in the literature and the need for open source tools expressed by Pauliuk et al., [15] an MRIO framework has been developed which is imposed onto a web-based decision support tool covering EU-27 countries and 13 major developed and developing countries as well as RoW. This framework covers several economic sectors and can be used to map scope-based shares of onsite activities, electricity and energy consumption and the overall supply chain carbon footprint of the manufacturing sectors of the countries. In time this tool is to be expanded to cover all regions of the world, including countries previously classified under RoW.

1.3 Thesis Outline

The rest of the chapters are organized as follows: Chapter 2 presents literature review with historical background and previous works. Chapter 3 details out the methodology carried out behind the execution of the Web-based tool. Chapter 4 provides a sample of the results obtained from the tool including analysis of the output. Finally, Chapter 5 gives the conclusion and points out the future work.

Chapter 2

Literature Review

2.1 Life Cycle Assessment and Input-Output Analysis

The actions and policies discussed in Chapter 1 shed some light on achieving low-carbon economies, there are more than a few methodologies that have been followed to measure and estimate GHG emissions associated with production activities. Input-output based life cycle assessment, process-based life cycle assessment (P-LCA), and hybrid LCA (a combination of P-LCA and input-output based LCA) have previously been employed, considerably for measuring process and product centered impacts to the environment [6, 16–21]. P-LCA utilizes a "cradle to grave" approach which includes raw material extraction, procession, production, transportation, use, and end-of-life, to analyze environmental impacts of products, this analysis has been done for fossil fuels in Turkey [22], boron [23], residential houses in the UK [24] and electricity generation in Mexico [25].

Despite the "cradle to grave" approach utilized by P-LCA, it has its limitations since it involves a certain number of processes without considering the entire supply chain of products, these and other limitations have been discussed extensively by De Benedetto & Klemeš [26] as well as the system boundary problem [16]. It is this factor which provides a noticeable advantage to using Input-Output (I-O) based models over P-LCA when working with industrial sectors and other large-scaled systems as I-O models provide an economy-wide analysis. Dong, Geng, Xi, & Fujita [27] have used a tiered hybrid LCA for carbon footprinting of industrial parks, and economic input-output life-cycle assessment

(EIO-LCA) has been used for analysis of a variety of areas, such as food manufacturing sectors [28], wind energy systems [29], triple bottom-line consumption [30–32] and other applications [33–38]. Other IO based LCA methods have also been used previously using hybrid triple bottom-line input-output LCA [39–45].

Single-region I-O (SRIO) models have been used previously for economy-wide level carbon footprint analysis of large-systems [46–48]. I-O based LCA models have also been utilized for analysis of GHG emissions and direct and indirect carbon footprints of supply chains of various industries [49–51], households [52] and goods trade [53–55] over the globe. These studies have been critical in concluding that to prevent underestimations in total carbon emissions of manufacturing supply chains, all supply chain contributors should be traced and evaluated. However, using I-O models for carbon footprint analysis have mostly been used for single country for a single year [56]. Keeping in line with I-O models, Multi Region Input-Output (MRIO) models advance over SRIO models as they help in estimation of carbon footprints at a global scale [39, 57–60]. Since contemporary supply chains are spread over multiple countries, emissions found in global trade are also reflected in multiple countries I-O tables [61, 62].

Global MRIO databases such as EoRA [63] World Input-Output Database (WIOD), Global Resource Accounting Model (GRAM), Global Trade Analysis Project (GTAP) [64], EUREAPA [65] and Externality Data and Input-Output Tools for Policy Analysis (EXIOPOL) [66] have been developed over the years to record global trade data [62, 67, 68]. WIOD has been used extensively for several sustainability evaluation studies, notably by Cansino, Roman, and Rueda-Cantuche [69] who utilized a WIOD-based model for testing of carbon footprint reduction policies of the Chinese government using combined input-output based econometric projection approach. Pascual-González, Guillén-Gosálbez, Mateo-Sanz, & Jiménez-Esteller [70] used a multivariate statistical analysis merged with WIOD MRIO tables to map environment impacts of developed countries catalogued into 5 categories and 69 indicators. Another study showed the versatility of the WIOD database by analyzing the geographical and factorial distribution of value addition in the global automotive production [71]. Lenzen, Wood and Wiedmann [72] conducted an uncertainty analysis to understand uncertainties in UK's CO_2 emissions embodied in trade. A first of its kind, such a study is important to understand errors and validation of data in MRIO data. Other MRIO databases have also been used in several other studies (e.g. EoRA, EXIOPOL, GTAP, GRAM) to holistically represent carbon footprint data in international trade. Analysis of carbon, water and ecological footprints [73, 74] along with carbon footprints assessments of household, consumption and production [75], international trade [76–78], and nations have been reviewed [79, 80].

One of the most critical elements when analyzing carbon footprints is to understand which scope contributes how much to the total emissions. The Greenhouse Gas Protocol classifies GHG emissions into three scopes based on where in the supply chain they can be located. Scope 1 emissions are those that sourced from within the industrial complex, for example, during production. Scope 2 emissions are classified as emissions from the generation of purchased electricity or heat, and scope 3 emissions cover sources which are not a direct part of the particular industry but occur from extraction or transportation of raw material and use of products and services [124]. For most industrial sectors, scope 3 emissions have the highest contribution as well as being likeliest to be overlooked. During analysis, segregation into scopes is an efficient way to ensure focus on the right areas when it comes to carbon reduction as scope 1 emissions are in the control of the specific industry and hence have an effect on scope 2 and scope 3 emissions.

Scope based carbon footprint investigations have previously been carried out for Turkish manufacturing sectors using trade-links between years 2000-2009 [103]. The results of the study paved way for further research by presenting the "carbon hotspots" of the manufacturing sectors included in the study. Carbon hotspots are the activities in a supply chain with a significant carbon footprint in the scope. The results concluded that there cannot be a single policy for all manufacturing sectors, as the scope division for each sector was unique, it prompts individual and focused attention towards each manufacturing sector. The aim of this work is to expand the work carried out previously for 40 countries and RoW. Similar studies have also been carried out on U.S. residential and commercial buildings, analyzing scope-based carbon footprint [125]. A hybrid Life Cycle Assessment (LCA) was used in this study to determine that scope 2 emissions are the largest contributors towards total carbon footprint of U.S. residential and commercial buildings.

The authors implemented a life stages based LCA approach, from construction to the end of use of buildings. It was determined that the major contributors of carbon footprint are on-site natural gas use, electricity consumption, commuting, construction sector supply chain and on-site petroleum use for residential and commercial buildings. Of all these

Table 2.1: A non-exhaustive list of MRIO studies 2009 onwards

Reference	Country	Impact Indicators	Database
(Druckman & Jackson, 2009) [81]	UK	CO_2	COICOP
(Lenzen, 2009) [82]	Australia (Victoria)	Water	ABS
(Nakano et al., 2009) [83]	41 countries/ regions	CO_2	OECD
(J. Minx et al., 2009) [47]	UK and three world regions	CO_2	
(Zhou & Kojima, 2009) [84]	9 Asian-Pacific countries and US	CO_2	IDE-JETRO/ GTAP
(Wiedmann et al., 2010) [85]	UK	CO_2	ONS
(Zhou & Imura, 2011) [86]	China	Ecological Footprint	IDE-JETRO
(B. Zhang, Chen, Xia, Xu, & Chen, 2013) [87]	China	Energy	China Statistical Yearbook
(Andrew & Peters, 2013) [64]	129 regions	GHG	GTAP
(Lenzen, Wood, & Wiedmann, 2014) [72]	UK	CO_2	ONS
(C. Zhang & Anadon, 2014) [88]	China	Water	Chinese Dataset
(Moran, McBain, Kanemoto, Lenzen, & Geschke, 2014) [89]	Congo, Kazakhstan, Rwanda, USA, Germany	Colton Footprint	EoRA
(Su & Ang, 2014) [90]	China	CO_2	IDE-JETRO
(McBain & Alsamawi, 2014) [91]	187 countries	Social Impacts	EoRA
(Ali Alsamawi, Murray, & Lenzen, 2014) [92]	187 countries	Employment Footprint	ILO
(K. Kanemoto, Moran, Lenzen, & Geschke, 2014) [93]	187 countries	CO_2	EoRA
(Stadler, Steen-Olsen, & Wood, 2014) [94]	RoW	Economic Structure	WIOD, EXIOBASE, GTAP
(R. Hoekstra, Edens, Zult, & Wilting, 2014) [95]	Netherlands	Environmental Footprint	WIOD, EoRA, Statistics Netherlands
(Moran & Wood, 2014) [96]		Comparison	EoRA, WIOD, EXIOBASE, GTAP
(Owen, Steen-Olsen, Barrett, Wiedmann, & Lenzen, 2014) [97]		Comparison	EoRA, GTAP, WIOD
(Okadera, Okamoto, Watanabe, & Chontanawat, 2014) [98]	China	Water Footprint	IDE-JETRO
(Tian, Chang, Lin, & Tanikawa, 2014) [99]	China	CO_2	State Information Center in China
(Zhongxiu & Yunfeng, 2014) [100]	40 Countries + RoW	CO_2	WIOD
(Müller, Klauenberg, & Wolfermann, 2015) [101]	Germany	Freight Transportation	EUROSTAT
(Duarte, Pinilla, & Serrano, 2015) [102]	Spain	Water Resources	WIOD
(Murat Kucukvar et al., 2015) [103]	Turkey	CO_2	WIOD
(Usubiaga & Acosta-Fernández, 2015) [104]	40 countries + RoW	CO_2	EXIOBASE
(Giljum, Bruckner, & Martinez, 2015) [105]	129 regions	Material Flow	GTAP
(Simas, Wood, & Hertwich, 2015) [106]	European Union	Labor, Energy, GHG	EXIOBASE
(Sanfélix, de la Rúa, Schmidt, Messagie, & Van Mierlo, 2016) [107]	40 countries + RoW	Li-ion batteries	WIOD
(Malik, Lenzen, & Geschke, 2016) [108]	Australia	Biofuel	ABS
(Liang et al.,2016) [109]	Russia	Timber Trade	WIOD
(Yu, Feng, Hubacek, & Sun, 2016) [110]	China	Agricultural Land Use	GTAP
(Steen-Olsen, Wood, & Hertwich, 2016) [111]	Norway	CO_2	EXIOBASE
(Jiang, Chen, Guan, Zhu, & Yang, 2016) [112]	China	CO_2	WIOD

Reference	Country	Impact Indicators	Database
(Ambrey & Daniels, 2016) [113]	Australia	CO_2 vs. well-being	EoRA
(Serrano, Guan, Duarte, & Paavola, 2016) [114]	EU 27	Water Resources	WIOD
(Ivanova et al., 2016) [115]	43 countries + 5 RoW	Material, water, land-use, GHG	EXIOBASE 2.2
(Eisenmenger et al., 2016) [116]	Austria	Material flow	WIOD, GTAP, EXIOBASE
(A. Tukker et al., 2016) [117]	EU 27	Carbon, water, land, material	EXIOBASE
(de la Rúa & Lechón, 2016) [118]	France	Socio-economy	WIOD
(Román, Cansino, & Rueda-Cantuche, 2016) [119]	Spain	Ozone	WIOD
(Murat Kucukvar, Cansev, Egilmez, Onat, & Samadi, 2016) [120]	Turkey	Energy, climate, manufacturing	WIOD
(Ali, 2017) [121]	EU & OECD	Carbon, water, land-use	WIOD
(Galli et al., 2017) [122]	15 Mediterranean countries	Ecological footprint	GTAP
(A. Alsamawi, Murray, Lenzen, & Reyes, 2017) [123]	187 regions	Human & economic harm	EoRA

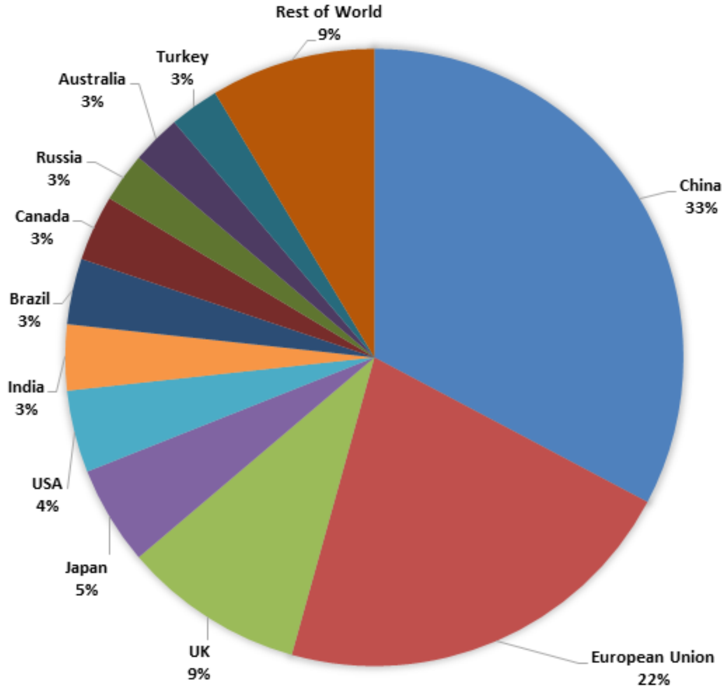

FIGURE 2.1: Country-wise applications of MRIO studies

components, the use phase of the life stage contributes 91% of the life cycle emissions. The authors also noted that the accuracy of results can be increased by further dividing the electricity and power sectors into the different sources of electricity produced used by the building, such as hydroelectric, fossil fuel, nuclear, solar, wind, and others. Another improvement to these results can be achieved by using dynamic modeling approach, since the global warming and carbon footprint model are dynamic in nature.

Considering there are several concrete actions for fulfilling a low-carbon economy, various approaches to approximate GHG emissions imbedded in production activities have been proposed. Hybrid Life Cycle Assessment (LCA) and Multi-region Input-Output (MRIO) based models appear in the literature to map the environment impacts of the processes. An MRIO model uses matrices covering countries and regions of trade flow. The model uses time series data of the flow of money between economic sectors, I-O tables. This method has been successfully used to analyze CO_2 emissions embodied in trade [78], a process called "stepwise distribution of emissions embodied in trade" (SWD-EET) was used for the purpose of studying how emissions embodied in trade become a part of a country's final demands. The paper defines that developing countries are net exporters of emissions while developed countries are net importers of emissions. Two I-O models were employed to measure the embodied emissions and "consumption-based" emissions. The emissions embodied in bilateral trade (EEBT) and multi-regional input-output (MRIO) approaches. The study shows large variation for some of the economies when the two different methods are used for estimation of 'consumption-based' emissions and trade balance emissions. The said variations are attributed to feedback effects via international trade.

Carbon footprint time series analysis has been constructed and applied on the UK by researchers as well [85]. They pointed out the core difference between MRIO and single region Input-Output analysis. Not-surprisingly, they found emissions occurring from imports are higher than exports in UK for years between 1991 and 2005. Researchers have reviewed articles that have applied MRIO analysis on carbon footprints of various countries. Research team divided their focus in terms of countries. However, ambiguity in MRIO Analysis has been underlined; one root cause is listed as number of experimental researches done in this area [80]. Cumulating different sectors is another reason for uncertainty in MRIO studies that results in undefined impact of aggregated sectors in single representation.

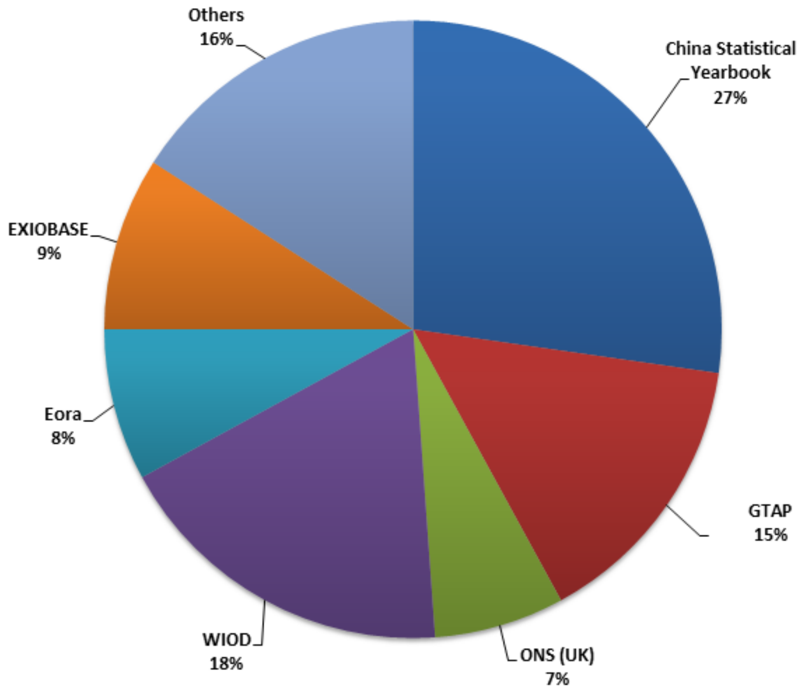

FIGURE 2.2: Databases used in MRIO applications

This thesis aims to present consumption-based approach in carbon footprint accounting framework as consumption-based approach estimates emissions of GHG embedded in international trade of several regions and nations. Traditional production-based approach differs from the contemporary consumption based approach as it is limited to territorial emissions since it does not involve direct or indirect carbon emissions of imports and exports [126].

Efforts were also made to analyze the worldwide usage of MRIO models based on country-wise applications, databases utilized and subject area of application. The Scopus Document Search database was used to find literature with the keyword "MRIO" [127]. Scopus not only allows access to the peer-reviewed literature but also performs analyses on the literature according to the keywords. The results and analyses in the rest of this chapter have been obtained with the help of the Scopus Document Search. A non-exhaustive list of MRIO based studies from 2009 onwards is presented in Table 2.1. Figure 2.1 shows that of the 113 applications of MRIO in countries around the globe, China dominates with a convincing 38 of 116 (33%) MRIO applications. Having the largest population and the highest growing economy, this logically makes sense. The European Union is second with 25 studies on MRIO's. However, one surprising outcome of research is that the United States lags far behind in applications of MRIO. Having one of the largest economies and being one of the main contributors of GHG emissions in the world, the US has only 5 studies dedicated to MRIO applications. Consistent with China's large number of MRIO based studies, the China Statistical Yearbook has been utilized 24 times (27%). The WIOD database, as visualized in Figure 2.2, has been used 16 times, GTAP has been used 13 times and databases such as EoRA and EXIOBASE were utilized for only 8% and 9% of the studies each. Several studies have used either the respective countries' own statistical database or several of the other open source databases available for public use. Some of these include countries like UK, Australia, France and Brazil.

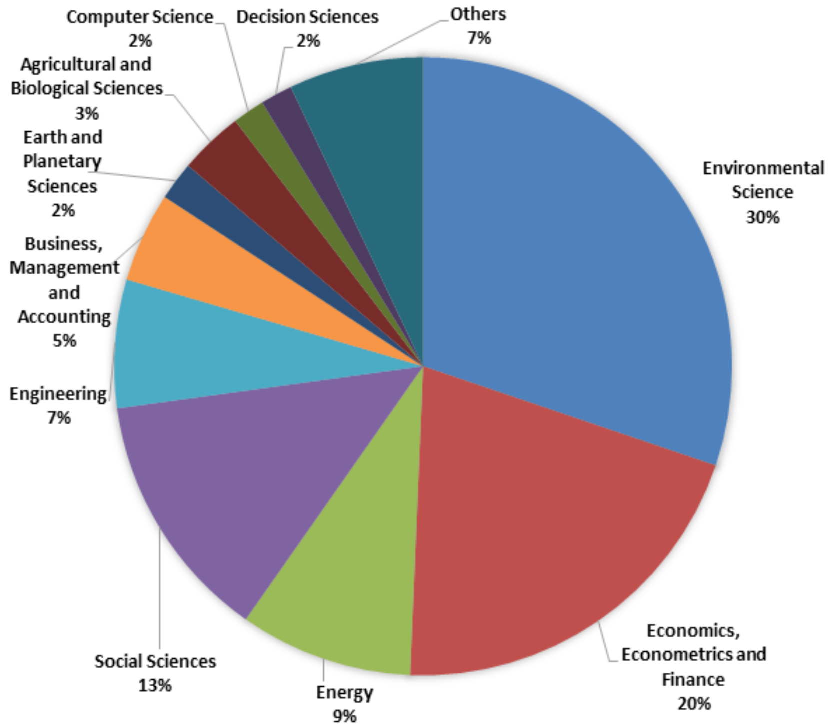

FIGURE 2.3: Subject-wise applications of MRIO studies

Finally Figure 2.3 describes that of the 289 studies implementing MRIO models, accessed during research, an overwhelming majority of 170 studies relate to Environmental Science, Economics and Energy. This lends further credence to the significance of MRIO models for analyzing international trade links, tracking GHG emissions and taking steps to improve the environment. MRIO models have also been applied to a host of other subject areas, including, but not limited to, Computer Science, Business, Management and Accounting, Agricultural and Biological Sciences, and Decision Sciences.

Chapter 3

Method

3.1 Introduction

MRIO models comprise of trade flow matrices that cover all the regions and countries in the particular model. Thus, global trade links among trading partners and international supply chains of world economies are tracked with the help of these matrices [128–130]. Typical MRIO frameworks consist of sector-wise imports and exports that are presented as monetary flows for each country. By merging all flows of imports and exports a reliable financial accounting framework is developed [62].

World Input-Output Database (WIOD) has been used in this work to extract monetary flows between the 40 major world economies. The WIOD database falls under the 7th framework program and is supported by the European Commission. It carries time-series I-O tables from 1995 to 2013 for 27 EU countries and 13 other major countries with 35 distinct industries and 59 products [61]. Supply and Use tables (SUT) are utilized at basic prices along with the assumption of fixed product sales. This assumption entails that each product conforms to its own particular sales structure regardless of which industry it is produced in. The National Accounts Statistics (NAS) is the source for all tables present in the WIOD and encompass mainly publicly available data. MRIO analysis essentially supplies a set of multipliers illustrating the total environmental impacts based on per dollar economic output, hence it measures a global multiregional environmental footprint of supply chains [80]. Once the MRIO model is formed, carbon footprints can be estimated by multiplying the output of each sector by its carbon impact per million dollar ($M) of economic output.

3.2 Ruby on Rails

The modern programming environment offers several diversified programming languages and scripts. However, not all of them support programming for front-end web framework. A high-level programming language, Ruby, was selected for the development of the Global Carbon Accounting tool (G-CAT) and the most widely used rapid web framework for Ruby, Ruby on Rails, was preferred and utilized for back-end Web framework of the project [131].

3.2.1 Ruby on Rails Applications Review

Developed in 1993 by Matsumoto, Ruby allows for fully object-oriented, simple exception handling and straightforward syntactic [132]. Through its agile-reliable working structure, various industries such as 3D modeling, robotics, business and telephony have utilized Ruby to produce outstanding results [133]. Numerous applications have been served to the research community specifically. As an example, BioRuby software is a featured development by Bioinformatics society [134], whereas Ruby-Helix was used to generate helical image analysis of biological filaments [135]. Mspire is another Ruby based memory-efficient software library and a further advancement for Bioinformatics [136].

3.2.2 Logic of Rails

The Web framework of Ruby on Rails is segregated into two distinct parts, front-end and back-end. The part of the framework where the user interacts with, by manipulating the input data options for which they seek outputs, is the front-end of the Web framework. The front-end also includes the display of results or outputs. At the back-end, there are an overwhelming number of operations that are processed of which the end-user does not need to interact with. In term of Rails, a Model-View-Controller (MVC) methodology is implemented. In MVC, the user uses the Controller, in this case the Controller being the inputs required for this tool. The Controller in turn manipulates the Model to run according to the specified inputs and the Model updates the View of the user to display the results and outputs corresponding to the inputs. Thus, the Model is at the back-end of the framework and the View and Controller are at the front-end.

3.3 Tool Mechanism

In this section, the main processes involved in the MRIO tool are explained in greater depth. Application of MRlO analysis into the Web based platform requires further application steps, some of which are not involved in the theoretical phase. Hence, the steps below include all necessary steps to transform an Input Output formulation to web framework and to obtain results. Main steps can be summarized as;

i Request (User)

ii Parse Matching Data (Filtering) environment

iii Calculation (Leontief's)

iv Results (Total Impact, Scope, Global Mapping Perspectives)

It is noteworthy to mention that, distinct from further efforts done in this area, this Web-based tool aims to represent the required data with modern depictions by incorporating Google Charts API [137]. The mechanism behind the current framework is as depicted in Figure. 3.1.

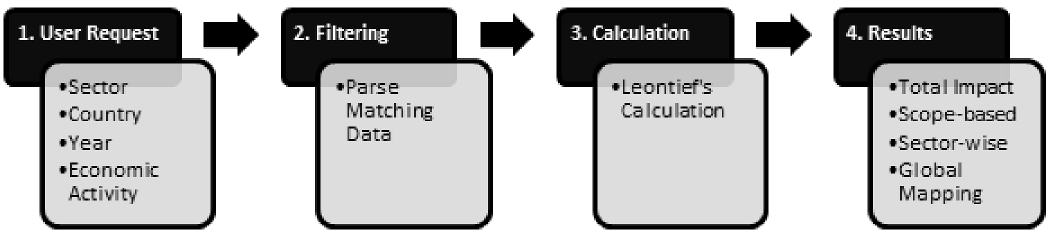

Figure 3.1: Framework of Web-Based MRIO Tool

3.3.1 Request Phase

Request phase starts with interaction of researcher with the MRIO tool. The web tool can accessed at: `http://s3-lab.sehir.edu.tr/gcat.html`. Request is completed in 6 sequential steps.

Step 1: The request phase starts with the user selecting the year for which they want to run the model, as is shown in Figure 3.2. Due to the use of the WIOD database, the Global Carbon Accounting tool (G-CAT) enables users to select a year from 2000-2009.

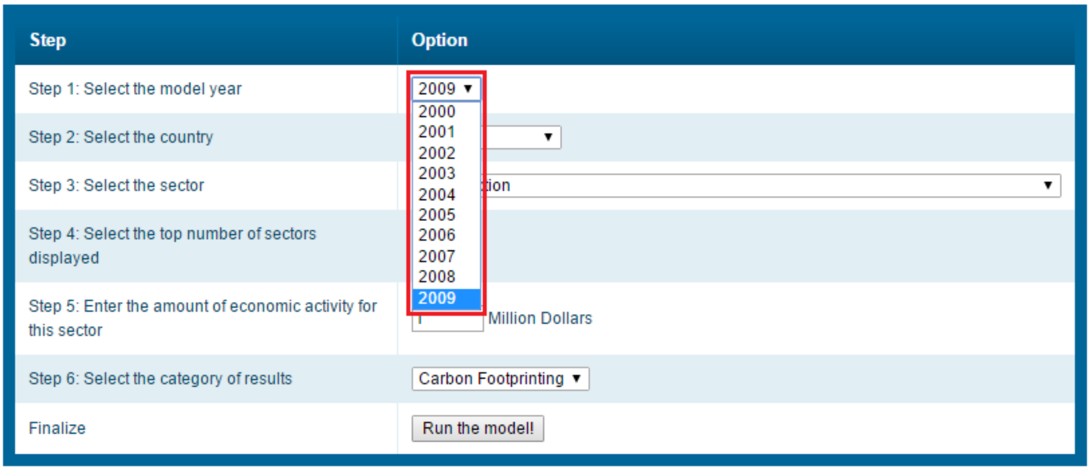

FIGURE 3.2: Step 1: Select the Model Year

Step 2: As shown in Figure 3.3, in the second step users can select the requested country from a list of 40 countries and Rest-of-World to make Input-Output formulations on.

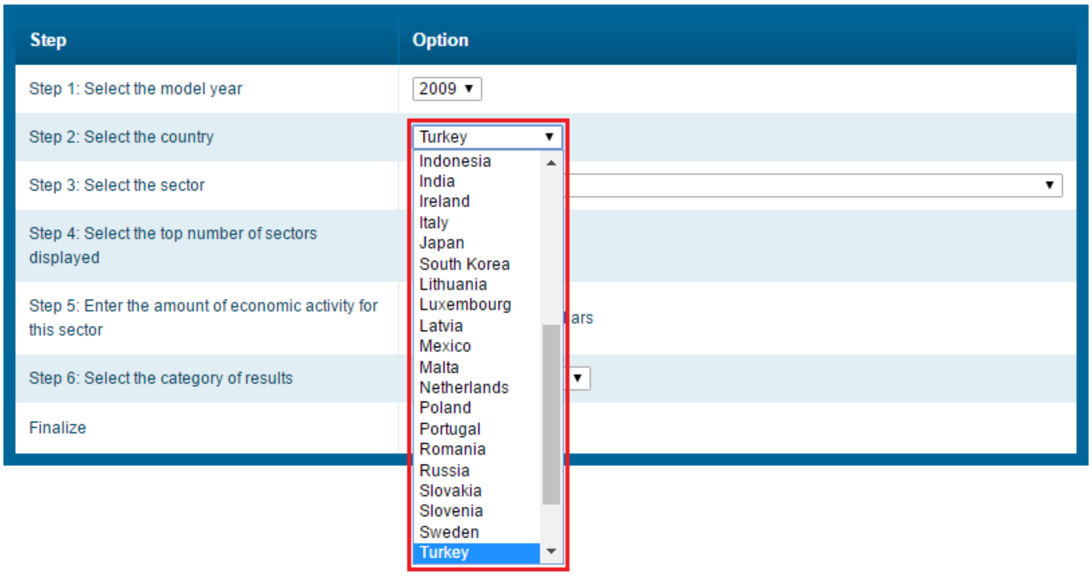

FIGURE 3.3: Step 2: Select the Country

Step 3: As the G-CAT supports the 35 industrial sectors as per the WIOD database, users should specify one industrial sector from the list of sectors displayed in an inclusive list. A screen-shot of this step can be seen in Figure 3.4.

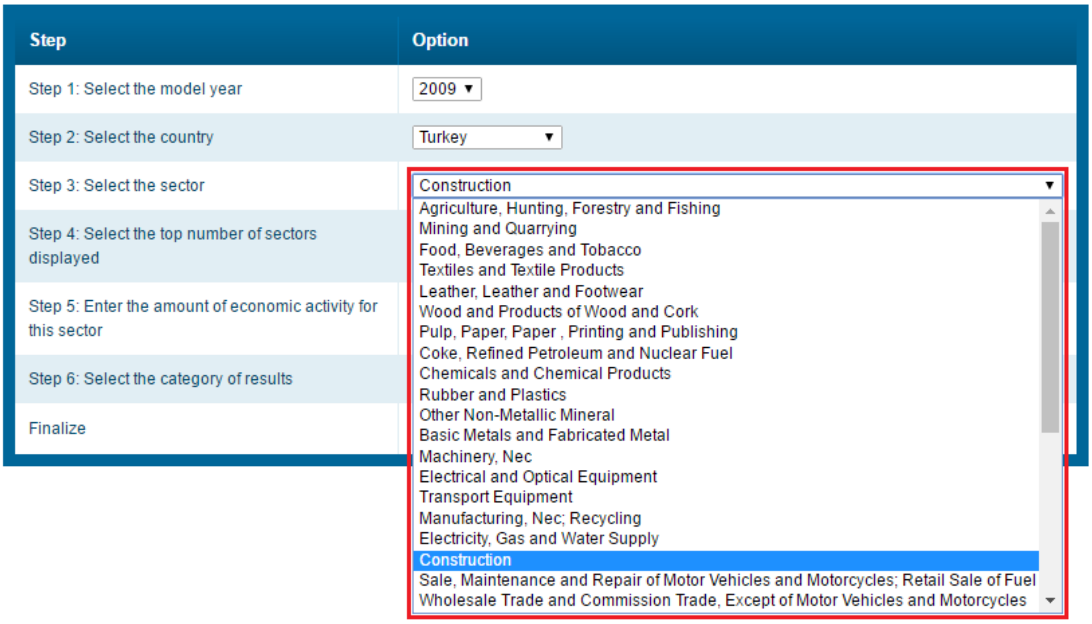

FIGURE 3.4: Step 3: Select the Sector

Step 4: The results of the G-CAT includes a table of the top contributing sectors for the specified year, country and sector. Hence, as shown in Fig. 3.5, in this step, users can select how many sectors the tool should display in the results table. Options include top 10, top 25 and top 50. Top 25 is set as the default.

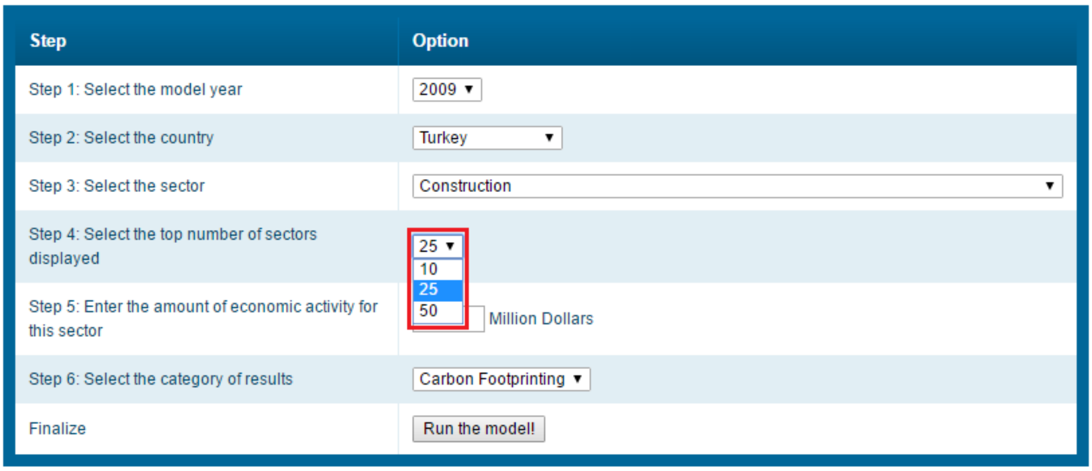

FIGURE 3.5: Step 4: Select the Number of Sectors to display

Step 5: After selecting the unique parameters as per their need, users might also customize the amount of economic activity related to the processes of the chosen sector.

The input is entered in the text box for Step 5 (Fig. 3.6) and its units are Million USD. The overall amount of carbon emissions is directly proportional to the economic activity.

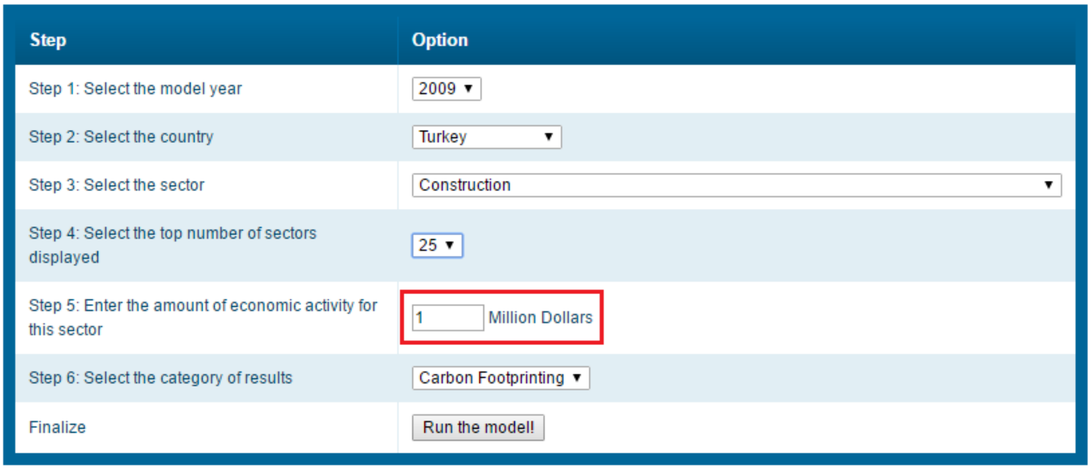

FIGURE 3.6: Step 5: Enter the amount of economic activity

Step 6: The final step allows the users to select which impact indicator to use in the calculations. At present, it includes only Carbon Footprint.

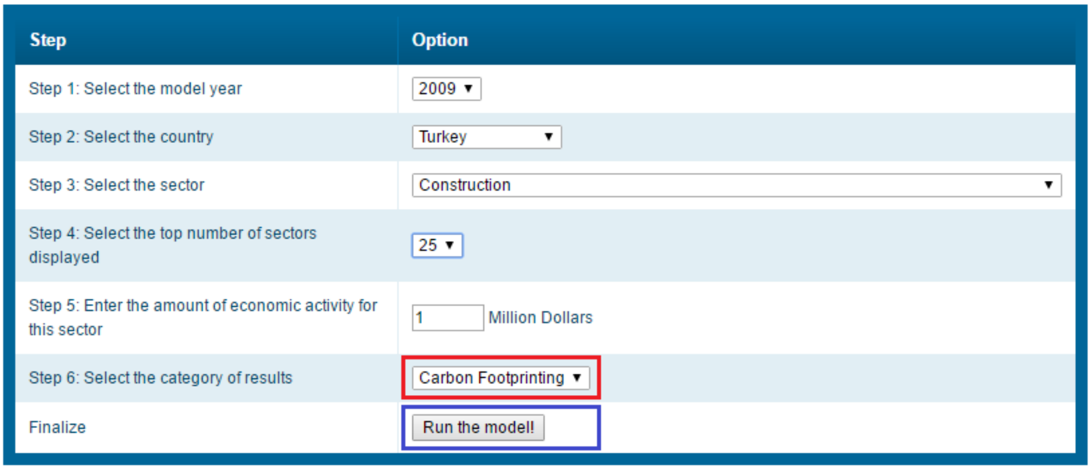

FIGURE 3.7: Step 6: Select the indicator and run the model

After the customization of steps according to request, users can run the MRIO model to execute Input-Output analysis. With "Run the model!" command (Fig. 3.7), users will be presented the results after after server completes calculations.

3.3.2 Parse Matching Data (Filtering)

The second phase of the G-CAT tool is parsing the data complying with the request. The tool searches WIOD's database to compile information for relevant data. The database is comprised of two matrices. The first is a static matrix, representing binary relation of 35 sectors for each of the 41 countries and regions with a 1435 x 1435 matrix. Static matrix is not affected by economic activity of request. The second matrix is initially a zero vector that stands for economic activity of request and is then shaped by the input amount. Upon request, this vector may be customized with various amounts for multi countries and sectors or just change the single value of zero vector.

3.3.3 Calculation Phase

Leontief's calculation has clarified the way of dependency studies of economy with its basic input-output formulation [138]. As the studies evolved on this topic, IO analysis has been widely utilized especially on carbon emission calculations and it has been found by researchers that inputs of processes have versatile impacts on various entities such as national trades, supply chains and organizations [79]. G-CAT makes matrix computations just after gathering relevant information according to customized request. After calculations are finalized, the third and final matrix is obtained which enlightens the IO analysis with its results in the final phase. Final matrix is a vector representing each sector for each country.

3.3.4 Results Phase

G-CAT provides researchers the ability to investigate their results in depth with 3 different perspectives; total impact, global mapping and scope perspectives. Total impact perspective is key for displaying results with floating numerical and sorting in ascending order. This perspective could also be customized by the user to display the top 10, 25 or 50 sectors whereas it is set to top 25 sectors by default. As well as displaying top affected sectors and connected countries, global mapping perspective presents trendy visuals of the results with the help of Google. Scope perspective is another form of understanding the results visually on G-CAT. This helps user understand the contribution of carbon emissions with respect to which scope they originate from. A detailed analysis on the results output of the tool is provided in Chapter 5.

Chapter 4

Results

The Global Carbon Accounting Tool (G-CAT) has been built to deliver results covering various interpretations. It gives a simple tabulated result of the output as well as four interactive charts depicting results to allow for easier understanding of carbon footprint impacts. The first of these charts is a Production versus Consumption based Analysis, showing the contributions of direct and indirect impacts for the selected sector. Direct impacts are specific to the sector and country selected, indirect impacts are further segregated into country-based and global impacts. Indirect impacts based on the country of selection include emissions arising from all other sectors within the country apart from the sector of selection. Global indirect impacts encompass emissions from all other sectors and from all other countries barring the country and sector of selection. The second output chart is a bar chart of Impact by Country depicting the carbon footprint contributions of the top 10 countries as per the input country and sector. The Sector Breakdown for Supply Chain Components pie chart is the third graphical output obtained from the G-CAT. This chart shows contributions of the selected sector, the Transport sectors, Trade sectors and all other sectors combined. The last graphical output complies with the novelty of this tool as it gives a Scope-based Analysis for the selected country and sector, showing the emissions divided for each of the 3 scopes. Scope 1 being the emissions pertaining to the particular input sector for the input country, Scope 2 being the emissions from the Electricity, Gas and Water Supply sector of the input country and Scope 3 consisting of emissions amounting from all other sectors and countries except for those classified under Scope 1 and 2.

For the purpose of illustrating the usage of the G-CAT, a selection of countries including Brazil, China, Germany, India, Turkey and, USA were used to derive results for Food, Beverage and Tobacco (FBT), Construction (CON) and, Textile and Textile Products (TTP) sectors. The economic activity input was taken as 1 Million USD for all iterations. An additional feature of the tool is depicted in the results as Time Series Analysis to help illustrate the trend of greenhouse gas emissions of the sample countries. Such an output is not directly obtained from the G-CAT.

4.1 Tabulated Results

The first output of the G-CAT is the results table. According to the number of top sectors selected in the Request Phase, it gives as much or as little information. Table 4.1 shows the top 25 sectors for Turkish Food, Beverage and Tobacco production for year 2009. The table lists the sectors in descending order of emission contribution. However, all contributions after the top 25 sectors are grouped together as 'All Other Sectors' and appear at the bottom, above the total. The highest contributing sectors are the Agriculture, Hunting, Forestry and Fishing (AHFF) and FBT, 238.71 and 136.22 million tons of CO_2 equivalent, respectively, both emanating from Turkey. The table also serves as an aid to assess to what extent a country's supply chain is internal or external. As per the evidence in the 'Country' column, there are almost as many internal contributing sectors as there are external in the top 25 for the FBT emissions in Turkey. This leads to the supposition that Turkey's supply chain for Food, Beverage and Tobacco (FBT) is a balance of internal and external trade.

4.2 Production versus Consumption-based Analysis

The Production versus Consumption chart displays the cumulative carbon footprint impacts categorized by direct and indirect impacts for Food, Beverage and Tobacco (FBT) and Construction (CON) sectors. Direct impacts are specific to the sector and country selected while indirect impacts are segregated into country-based and global impacts. Indirect impacts based on the country of selection include emissions arising from all other sectors within the country apart from the sector of selection. Global indirect impacts

Table 4.1: Tabulated top 25 sectors in the supply chain for Turkish Food, Beverage and Tobacco production

	Country	Sector	Mt of CO_2 Equivalent
1	Turkey	Agriculture, Hunting, Forestry and Fishing	238.71
2	Turkey	Food, Beverages and Tobacco	136.22
3	Rest of World	Agriculture, Hunting, Forestry and Fishing	82.75
4	Turkey	Electricity, Gas and Water Supply	69.55
5	Turkey	Other Non-Metallic Mineral	19.09
6	United States	Agriculture, Hunting, Forestry and Fishing	17.58
7	Turkey	Water Transport	13.04
8	Brazil	Agriculture, Hunting, Forestry and Fishing	8.82
9	Turkey	Inland Transport	7.39
10	Turkey	Coke, Refined Petroleum and Nuclear Fuel	6.97
11	Turkey	Other Community, Social and Personal Services	6.85
12	Russia	Agriculture, Hunting, Forestry and Fishing	6.58
13	Indonesia	Agriculture, Hunting, Forestry and Fishing	5.58
14	Rest of World	Electricity, Gas and Water Supply	5.45
15	Russia	Electricity, Gas and Water Supply	4.88
16	Bulgaria	Agriculture, Hunting, Forestry and Fishing	4.5
17	Turkey	Rubber and Plastics	4.26
18	Turkey	Chemicals and Chemical Products	4.21
19	China	Electricity, Gas and Water Supply	4.02
20	India	Agriculture, Hunting, Forestry and Fishing	3.84
21	Germany	Agriculture, Hunting, Forestry and Fishing	3.65
22	Turkey	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	3.25
23	Turkey	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	2.96
24	Turkey	Mining and Quarrying	2.81
25	China	Agriculture, Hunting, Forestry and Fishing	2.65
	Other	All Other Sectors	81.38
	Total	All Sectors	746.98

encompass emissions from all other sectors and from all other countries barring the country and sector of selection. Therefore, the direct impacts correspond to the production phase of the supply chain of the product, whereas the indirect impacts correspond to the consumption phase of the supply chain. It is important to note that consumption includes both supply and distribution aspects of the supply chain.

Direct Impacts pertaining to the countries in the sample aid to explain the extent to which Food, Beverage and Tobacco is directly produced in the region under study. Brazil and India are agriculture conducive countries, hence the large shares of regional Indirect Impact. However, Brazil's agricultural produce is not proportionally utilized for Food, Beverage and Tobacco production, a conclusion drawn from seeing that only 2% of Brazil's emissions are from Direct Impacts. Conversely, India has the highest percentage of emissions resulting from Direct Impacts, at 24%. For the sample countries in this study, Brazil has the largest contribution of regional Indirect Impacts in its supply chain of Food, Beverage and Tobacco (FBT), with 93% of all emissions amounting to it (Figure 4.1). Overall, the regional Indirect Impacts for this sector are dominant for all the sample countries. Germany, is the only country where global Indirect Impacts exceed regional Indirect Impacts, suggesting that Germany's supply chain is inclined more towards external trade. The figure also serves to correct the earlier assumption drawn from Table 2 about Turkey's supply chain structure being balanced between internal and external trade. Since the combined direct and regional indirect impacts constitute 70% of Turkish emissions, it is likely that there are further contributors to the regional Indirect Impact that are not in the top 25.

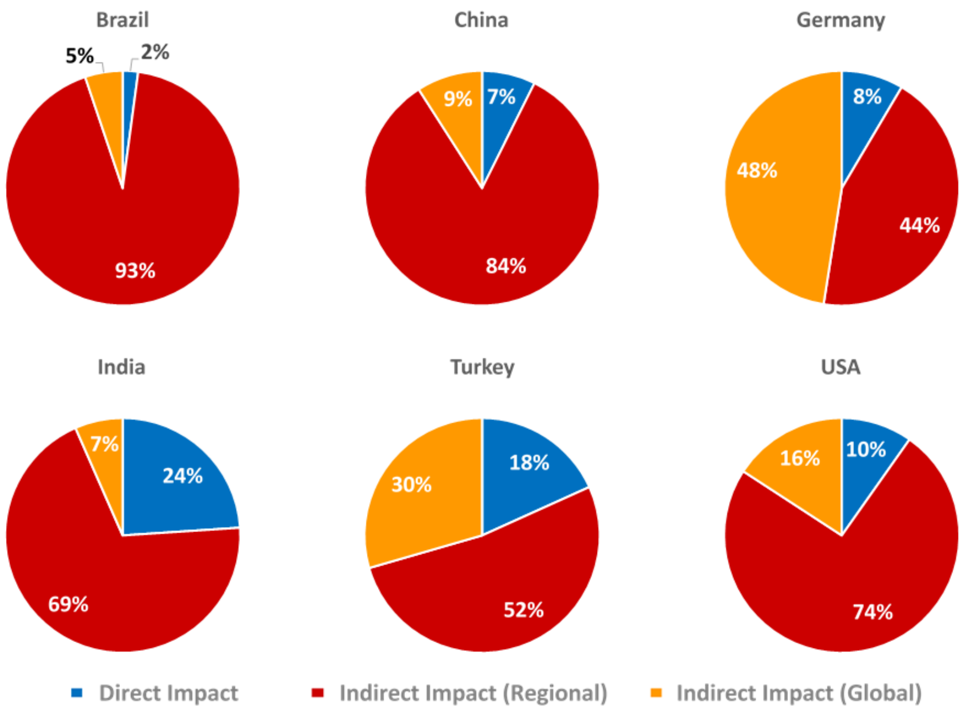

Figure 4.1: Production vs Consumption-based Analysis for Food, Beverages and Tobacco sector

A comparison between direct and indirect impacts can also be made by changing the sector under observation from Food, Beverage and Tobacco (FBT) to Construction (CON). Figure 4.2 illustrates the contrast between the distribution of the impacts for the two sectors. Most notably, Turkey has the highest percentage contribution of Direct Impacts at 25%, whereas India has a Direct Impact share of only 3%. While a simple comparison between sectors as different as Food, Beverage and Tobacco (FBT) and Construction (CON) does not reveal a lot of information, by comparing the differences in Production versus Construction emissions of Construction sector, some probing analyses can be made. India, China and Turkey are all currently investing large amounts of money in infrastructure development; however, the G-CAT shows us that for India and China, the Construction related greenhouse gas emissions are dominated by indirect impacts. In fact, while the same can be said for all six countries in the sample, it is only glaringly obvious in the case of India and China, where Indirect impacts account for 97% of all carbon emissions for 2009.

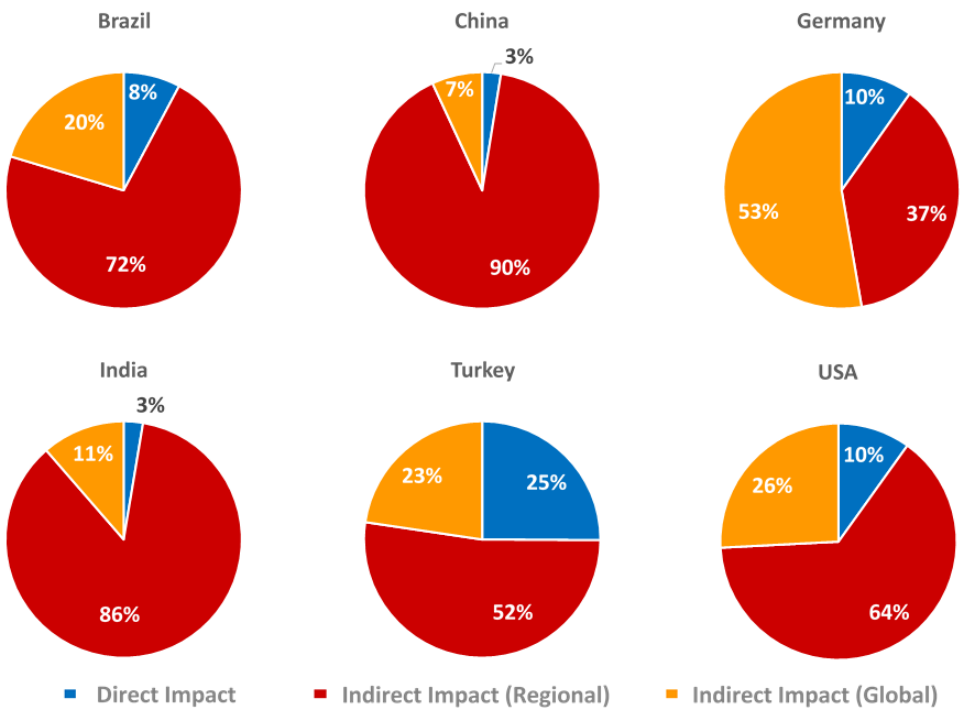

FIGURE 4.2: Production vs Consumption-based Analysis for Construction sector

4.3 Impact by Country

The G-CAT visually represents the top 10 countries that contribute to carbon emissions for each selected sector. This chart serves to show the distribution of emissions at a glance. For the countries in the sample, each country is the largest contributor for the Food, Beverage and Tobacco (FBT) sector. Since, for each country in the sample, the combination of Direct and regional Indirect Impacts for this sector are greater than 50%, the bar for each corresponding country is the largest as per Figure 4.3. The remaining 9 countries of the top 10 are ranking in order of decreasing contributions to emissions.

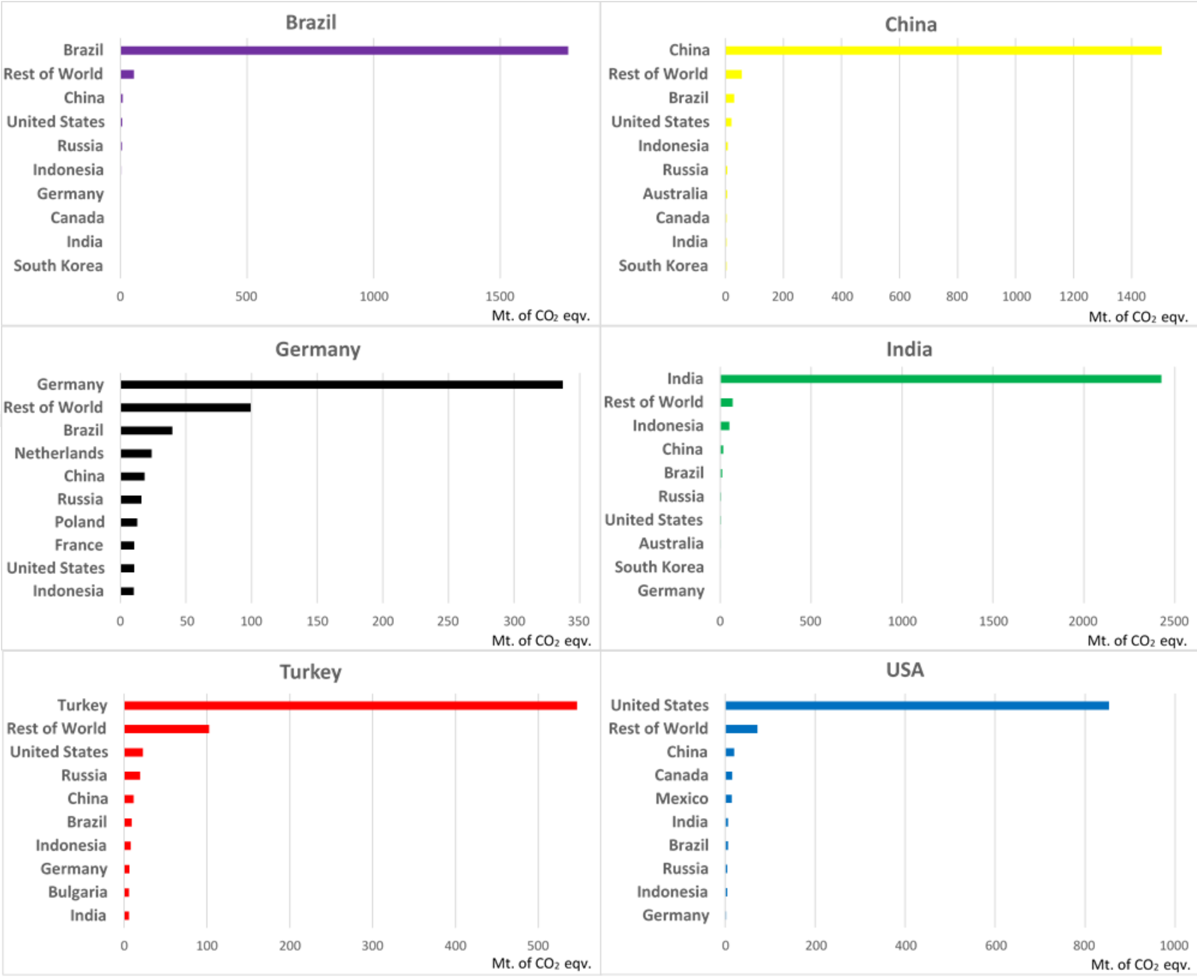

FIGURE 4.3: Impact by country for Food, Beverage and Tobacco sector (X-axis shows Million tons of CO_2 emissions)

4.4 Sector Breakdown for Supply Chain Components

Considering only the Direct and regional Indirect contributions, the sector breakdown for the internal supply chain can be examined from the tool. This output provides a simple comparison of the emissions of the selected sector with sectors related to Transport, Trade and all other sectors besides these. The sample countries have low contributions from Transport and Trade sectors, between zero to 5%, depending on the country (Figure 4.4). The sector under examination, in this case Food, Beverage and Tobacco (FBT), has at most 26% contribution among the countries in the sample. These relations serve to also highlight the scope-based distributions for the supply chain emissions, further discussed in section 4.5.

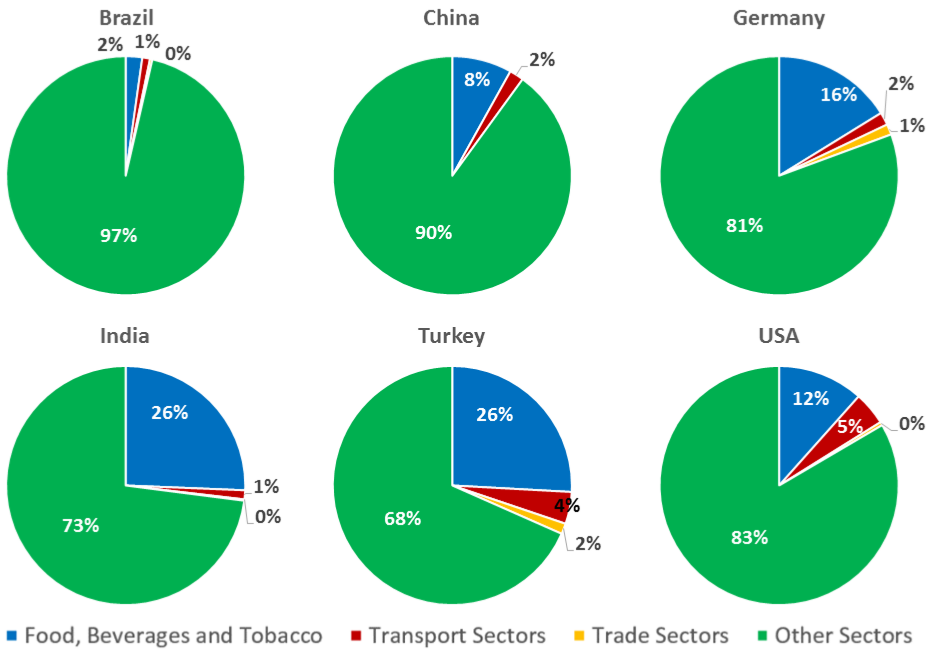

FIGURE 4.4: Sector breakdown for Supply Chain components for Food, Beverages and Tobacco sector

4.5 Scope Analysis

The last output provided by the G-CAT is the scope analysis for the sector and country selected. This analysis breaks down all the carbon emissions in to scope 1, scope 2 and scope 3. These scopes are divided based on the carbon footprint accounting standard. Scope 1 GHG emissions arise from on-sire combustion of fossil fuels. Scope 2 emissions arise from purchased electricity, heat and/or steam, while scope 3 emissions account for all upstream GHG emissions in the supply chain such as those related to production of raw materials, service inputs and transportation, etc [103].

Figure 4.5 visualizes the scope-based impacts of the 6 countries in our sample for Food, Beverage and Tobacco (FBT) sector for year 2009. While scope 3 emissions remain the highest across the 6 countries, scope 1 contributions fluctuate according to the production values of each country. Brazil has the overall largest scope 3 contribution of 98% and 2% scope 1 emissions. This unusual distribution can be credited to higher contribution of Agriculture, Hunting, Forestry and Fishing (AHFF) sector and lower FBT production.

Another anomaly apparent in the distributions of the remaining five countries is that only for Turkey is the scope 2 emission lower than scope 1 emission. Typically, scope 1 emissions have a larger contribution than scope 2 emissions across sectors, whereas scope 3 dominates the GHG emissions [103].

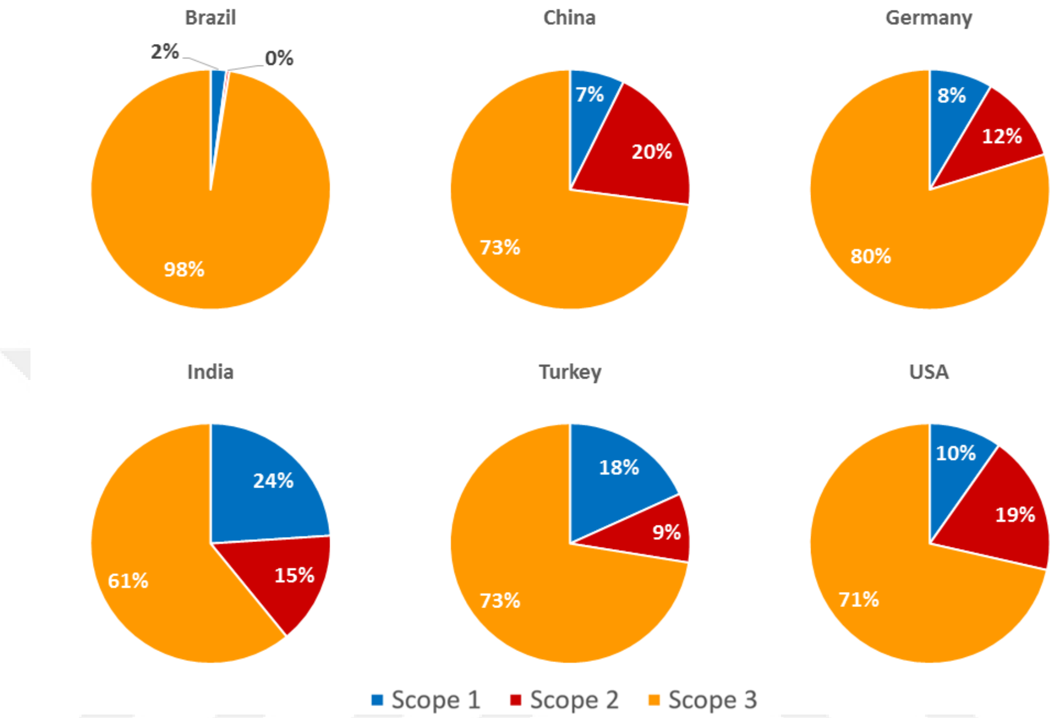

FIGURE 4.5: Scope Analysis for Food, Beverage and Tobacco sector

4.6 Time Series Analysis

The final analysis done on the sample of 6 countries selected for examination is a time series analysis. This analysis, although, is not a direct output of the G-CAT, it is included in this study to demonstrate the capability of the model to calculate results from year 2000 to 2009. Three sectors were chosen for this analysis, Food, Beverage and Tobacco (FBT), Construction (CON) and, Textile and Textile Products (TTP). Figure 4.6 shows that over the years, total carbon emissions for each of these sectors has reduced significantly, even though, there was a spike of increased carbon emission after the turn of the century.

As a general trend, as consumption of manufactured goods has increased since the year 2000, for the case of the sample countries and sectors, the overall emissions of GHG have decreased. This perhaps indicates the success of the various policies and stringent measures taken since the Kyoto Protocol to curb greenhouse gas emissions around the globe. Brazil, India and China are countries with the fastest growing economies and together with USA are some of the largest contributors to global carbon emissions. These countries have shown a total decrease of between 40-50% across the three sectors in the sample, in a span of 10 years. Another observation made from Figure 4.6 is the difference in the emissions between developed and developing countries, particularly for Food, Beverage and Tobacco (FBT).

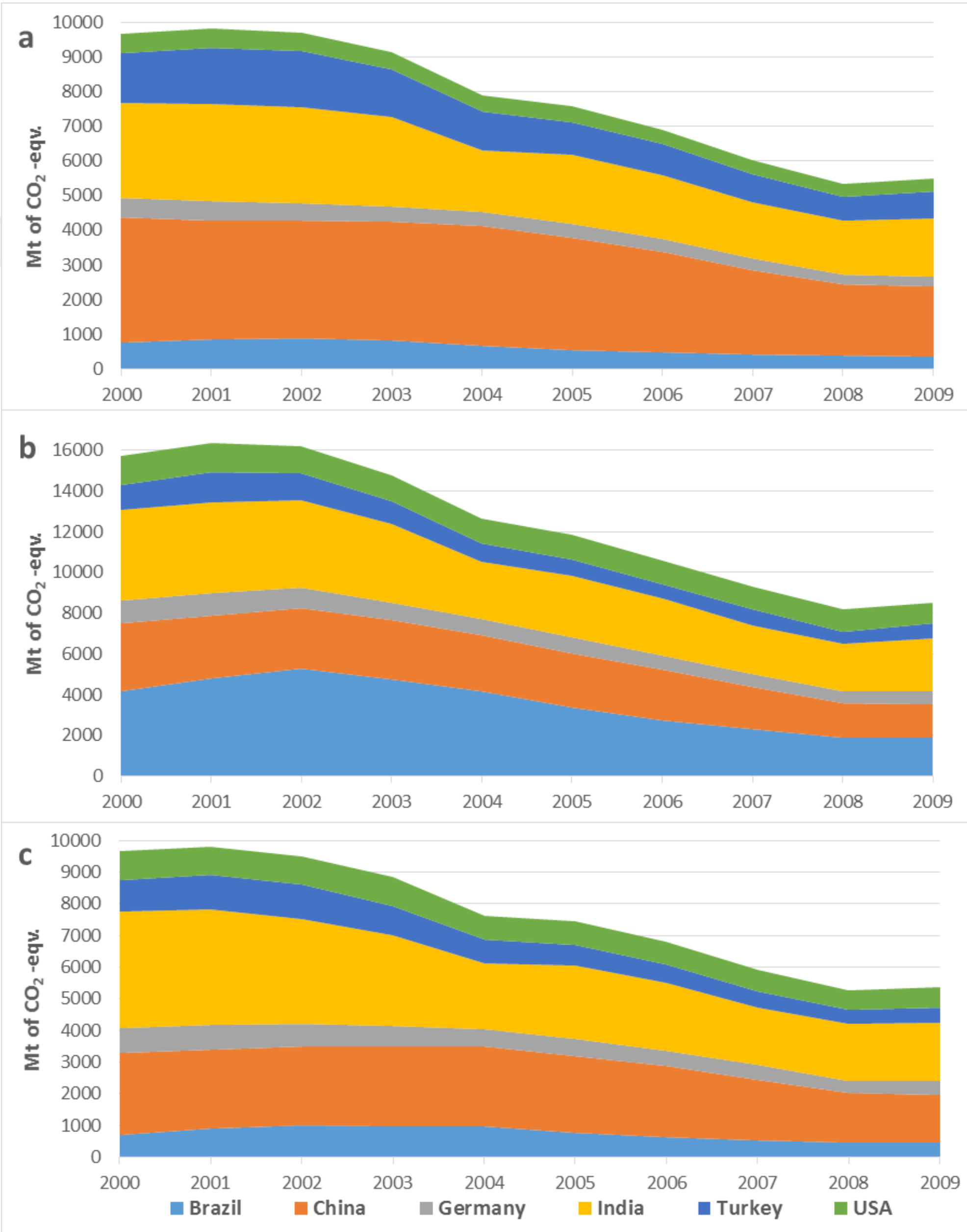

FIGURE 4.6: Time series analysis of CO_2 emissions of sectors (a) Construction (b) Food, Beverage and Tobacco (c) Textile and Textile Products

Chapter 5

Conclusion

This work is critical towards tracing global and regional greenhouse gas emissions of countries worldwide. Due to rapidly rising global carbon emissions in the previous few decades, many countries have embarked upon decreasing their regional and global carbon emissions. Considering the importance and the interest of the world in curbing GHG emissions and detrimental climate change, it begs a need to analyze the carbon footprint of the most industrialized countries in the world. Hence, the target was to map and analyze scope-based emissions of 40 countries and regions, as well as develop an online web-based decision support tool to aid in visualizing these emissions.

The literature review suggests that other researchers have attempted to implement MRIO, SRIO modeling techniques for analyzing carbon footprints on the back of global MRIO databases such as WIOD, EXIOBASE and EoRA. Although the work in the literature has mostly been confined to limited regions and countries. The target was to create a MRIO global, scope-based carbon footprint accounting platform using WIOD database. This platform would best serve its purpose as an online tool capable of showing four analyses of the results of the input. These analyses include Production versus Consumption-based emissions comparison, sector-wise breakdown of emissions, country-wise breakdown of supply chain emissions and scope-based analysis. Thus, the Global-Carbon Accounting Tool (G-CAT) has been developed which uses the WIOD database and Leontief's input-output methodology to transform the input parameters to investigate supply chain-based carbon emissions for the 40 countries and rest of the world.

Another unique aspect of this tool is that it is capable of allowing a time series analysis of results as the tool works for data from year 2000 to year 2009.

The tool in its online platform is aided by Ruby on Rails. The back-end of the framework is where the mathematical operations are processed to generate the results and the front-end is the interactive section of the framework. Users view and control the front-end of the Web framework and input the parameters for year, country, sector and economic activity, plus an additional input of number of sectors to display in the output. This user request is followed by parsing of matching data and processing of Leontief's calculation on the input parameters. The results are subsequently displayed to the user in the form of a results table and four interactive charts built on the Google Charts application-programming interface.

The results displayed by the G-CAT include a table listing the top countries and sectors responsible for the emissions of the particular country and sector selected in the input as well as four interactive graphs. The first of these is a Production versus Consumption graph that shows the supply chain distribution of the carbon emissions in relation to direct and indirect impacts. In this case, direct impacts correspond to the Production aspect of the supply chain and indirect impacts are segregated into regional and global impacts corresponding to the Consumption facet of the supply chain. The second result shows the global distribution of the GHG emissions for the selected sector and country. This bar graph serves not only to visualize which countries contribute to emissions for the chosen sector but also how much each country contributes to the whole. The third result is a sector breakdown in to supply chain components of transport and trade. This graph helps to understand the distribution of carbon emissions across the different component of the supply chain. Lastly, the scope analysis completes the result graph, showing the spread of carbon emissions divided into the scopes they originate from. Scope 1 emissions correspond to on-site fossil fuel emissions, scope 2 emissions are associated with emissions arising from purchased electricity, heat and/or steam and scope 3 emissions encompass all upstream carbon emissions excluding those associated to scopes 1 and 2. Using scope-based analysis makes it simpler to pinpoint which industries policy makers should target for the most beneficial reduction in carbon emissions.

To illustrate the use of the G-CAT, six countries were used to obtain results for the sectors of FBT, CON, and TTP from year 2000 to 2009, with economic activity taken as USD

1 Million. The countries selected represent a mix of developed and developing countries spanning 4 continents. The results obtained from the G-CAT for these countries help to ask key questions about the impact global trade has on the GHG emissions of industrial sectors. For example, for the FBT sector, in the case of Germany and Turkey, there is a balance between GHG emission contributions pertaining to internal and external trade (Fig. 4.1). Whereas, Brazil and India have supply chains that are more internal, with very few emissions arising from global sectors. These relations are further evidenced in Fig. 4.3, where it can be seen which regions comprise of the top 10 external contributors of CO_2 for the country.

A wider breadth of thinking is required to comprehend the supply chain operations beyond the conventional objective of minimizing total cost and maximizing total supply chain profits. There is a need for an equilibrium between economic, social and ecological corollaries of supply chain operations and this equilibrium is crucial in accomplishing sustainable development goals. In supply chain terms the impacts of economy, society and environment are described as Triple Bottom-Line (TBL) impacts and in order to create policies for industrial activities that are economically feasible, socially beneficial and environmentally favorable, a deeper understanding of the link between these three aspects is requisite [120, 139]. As was recently concluded by Allen, Metternicht and Wiedmann, in their review of models covering Sustainable Development Goals (SDGs), only 1 model of 80 is capable to analyzing variables related to all 17 SDGs [140]. Since the spread of the SDGs covers economy, society and environment, a need has arisen for the development of a global MRIO analysis framework capable of analyzing TBL sustainability performance of supply chains at a global and regional scale. The Environmental Footprints Explorer offers a web platform comparing MRIO GHG analysis between databases of WIOD, GTAP, EXIOBASE and EoRA, creating potential for a time series capable TBL platform [141]. Work along these lines will result in a complete and comprehensive output view for industries in the developed world allowing an easier way to understand where the world is wasting energy and which areas are critical, not just for carbon reduction, but also holistically for economic and social well-being.

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