A MULTI-SCALE MULTI-REGIONAL ASSESSMENT OF EMBODIED CO_2 EMISSIONS IN CHINA’S CONSTRUCTION SECTOR

OGUNGBILE ADEDAYO JOHNSON

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A Multi-Scale Multi-Regional Assessment of Embodied CO_2 Emissions in China's Construction Sector

OGUNGBILE, Adedayo Johnson

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CERTIFICATE OF ORIGINALITY

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DEDICATION

To God, Adejoke, and Aderinsola.

ABSTRACT

While the conversation around climate change and its environmental consequences is a hot topic worldwide, China's contribution to reducing and increasing GHGs remained a subject of importance. The focus of emissions studies in China's construction sector, considered a significant stakeholder in GHGs emissions generation in the country, is concentrated around the operational phase use of the industry. By implication, many studies aggregated at sectoral and provincial levels of the sector are methodologically inept in investigating the direct CO_2 emissions and determining the hidden linkages of CO_2 emissions embodied in trans-sectoral and inter-provincial trades with the entire economic structure.

The literature review identified the gaps in CO_2 emission accounting in China's construction industry. The study was designed to bridge the gaps identified and significantly accrued to methodological improvements in CO_2 emission accounting in the sector. Therefore, the study aimed to quantify the direct and indirect embodied CO_2 emissions in China's construction sector at the national, regional, and provincial levels to determine the aggregated hidden linkages of CO_2 emissions embodied in trans-sectoral and inter-provincial upstream trades of the industry. In achieving the aim of the research, three objectives were set to guide the study, including: (1) to quantify the direct CO_2 emissions embodied in China's construction sectors (National and regional levels) and (2) to investigate embodied CO_2 emissions linkages from a sectoral and provincial perspective and (3) to investigate the driving forces of embodied CO_2 emissions interactions among provincial construction sectors from a multi-regional perspective.

Two separate datasets were used in the study. The first data set was used to quantify the direct CO_2 emissions from construction project activities at regional and national aggregation levels. The data included fossil fuel, electricity consumption and economic data of the sector between 1997 and 2015. The second data set included the construction sector's annual CO_2 emissions and China's economic data in input-output tables for 2012, 2015, and 2017. A hybrid framework was developed for quantifying the direct CO_2 emissions in the sector, while an environmental extended hybrid multi-regional input-output (MRIO) tables were constructed for Hypothetical Extraction Method (HEM), Structural Decomposition Analysis (SDA), and Logarithmic Mean Divisia Index I

(LMDI-I) methodologies to determine the hidden linkages and driving forces of CO_2 emissions in China's construction sector.

The study identified the industry's gradual shift from coal as the primary energy source, with over 30% of direct CO_2 emissions generated in the Northeast region of China. The study shows a correlation between direct CO_2 emissions, construction materials and annual construction outputs. The Chinese construction sector's hidden total CO_2 emissions linkages increased from 1,499 $MtCO_2$ in 2012 to 2,000 $MtCO_2$ in 2017. The construction sector in China was determined to have more CO_2 emissions in the forward linkages than in backward linkages, indicating the industry is a net exporter of CO_2 emissions to satisfy final demands in other economic sectors. The study identified construction sectors in Gansu, Xingjian, Ningxia, and Inner Mongolia as the most crucial provinces with hidden CO_2 emissions linkages.

Finally, the four driving forces of CO_2 emissions assessed in the study showed significant addition and reduction drives in the sector's production-based CO_2 emissions. The SDA and LMDI-I analysis results showed that final demand, Leontief structure, and final demand structure effects contributed 964.30, 338.47, and 20.22 $MtCO_2$, respectively. However, direct carbon emission intensity caused a CO_2 emissions reduction of 117 $MtCO_2$. The study identified Henan, Shanghai, Jiangsu, Liaoning, and Jilin provinces as having the most critical CO_2 emissions change contributions in 2015 and 2017.

The study proposed a dynamic and systemic assessment for quantifying CO_2 emissions embodied in the construction industry's upstream and downstream activities and interactions within the entire national economic structure. The assessment system can give an early predictive CO_2 emissions indication to policymakers and other stakeholders within the industry on the sources and destinations of embodied CO_2 emissions within the construction sector. The study presented a simplified methodology for detecting hidden linkages and identifying driving forces of CO_2 emissions in provincial and regional interactions. In addition, the methodology and developed models are practical foundations for further examinations and studies on construction-related CO_2 emissions and interaction with other economic sectors. The study concludes with policy suggestions, limitations, and future research directions, one of which is the complete decomposition of different driving forces contributing to CO_2 emissions changes in the construction industry, not included in this study.

Keywords: embodied CO_2 emissions; multi-regional input-output analysis; hidden emission linkages; HEM; SDA; driving forces analysis

LIST OF PUBLICATIONS AND ACHIEVEMENTS DURING THE STUDY

This section contains academic publications, achievements, and endeavors during the study period between January 2019 and April 2022.

Refereed Journal Papers (*Published*)

1. **Ogungbile, A. J.,** Shen, G. Q., Wuni, I. Y., Xue, J., & Hong, J. (2021). A Hybrid Framework for Direct CO2 Emissions Quantification in China's Construction Sector. International Journal of Environmental Research and Public Health, 18(22), 11965. doi.org/10.3390/ijerph182211965.
2. **Ogungbile, A. J.,** Shen, G. Q. P., Xue, J., & Alabi, T. M. (2021). A Hypothetical Extraction Method Decomposition of Intersectoral and Interprovincial CO2 Emission Linkages of China's Construction Industry. Sustainability, 13(24), 13917. doi.org/10.3390/su132413917.
3. Wuni, I. Y., Shen, G. Q., **Ogungbile, A. J.**, & Ayitey, J. Z. (2021). Four-pronged decision support framework for implementing industrialized construction projects. Construction Innovation, ahead-of-print(ahead-of-print). doi:10.1108/CI-11-2020-0184.
4. Xue, J., Shen, G. Q., Deng, X., **Ogungbile, A. J.,** & Chu, X., (2022). Evolution modeling of stakeholder performance on relationship management in the dynamic and complex environments of megaprojects. Engineering, Construction and Architectural Management.
5. Tobi Michael Alabi, Favour D. Agbajor, Zaiyue Yang, Lin Lu, **Adedayo Johnson Ogungbile** (2022). Strategic potential of multi-energy system towards carbon neutrality: A forward-looking overview, Energy and Built Environment.

Academic Events Attendance and Participation

1. Presented at the Professional Services Advancement Support Scheme (PASS) Workshop Series. Exporting Industrialized Construction under the Belt and Road Initiative: Nigeria, a Market yet Untapped. March 17th, 2020.

2. Participated in the Centre of Leadership Development in Built Environment Sustainability programme with students from selected Universities in Hong Kong and the United States of America between May 2020 and May 2021. Awarded with the second-best team project titled "Urban Scale Passive Solar Control Modeling for Retrofitting of Park Island Estate, Ma-Wan, Hong Kong".

3. Participated and presented at the Environmental Advocacy for the Greater Bay Area moot court Organized by the Hong Kong America Centre (HKAC) with Support from the Environment and Conservation Fund at City University, Hong Kong. November 2nd, 2019.

4. Participated and presented at the Climate Change Simulation of the COP 25 at City University, Hong Kong. November 23rd, 2019.

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LIST OF ABBREVIATIONS

CEADs – Carbon Emissions Accounts and Datasets
HEM – Hypothetical Extraction Method
MRIO – Multi-Regional Input-Output
IDA – Index Decomposition Analysis
SDA – Structural Decomposition Analysis
SPA - Structural Path Analysis
LCA – Life-Cycle Analysis
SDG – Sustainable Development Goal
GHGs – Greenhouse Gases
WTO – World Trade Organization
EU – European Union
BRICS – Brazil, Russia, India, China, South Africa
IEA – International Energy Agency
IPCC – Intergovernmental Panel on Climate Change
UN – United Nations
SCE – Standard Coal Equivalent
WIOD – Word Input-Output Database
SRIO – Single Regional Input-Output
LMDI– Logarithmic Mean Divisia Index Methods
GDP – Gross Domestic Product
BRI – Belt and Road Initiative
GHGs – Green House Gases
CH_4 – Methane
$N_2$0 – Nitrous oxide
HFCs - Hydrofluorocarbons
PFCs – Perfluorocarbons
SF6 – Sulphur hexafluoride
NDRC – National Development and Reforms Commission
UNFCCC – United Nations Framework Convention on Climate Change
BASIC– China, Brazil, India, and South Africa

UNEP - United Nations Environmental Program
CMM – Classical Multiplier Method
KLEM – Capital–Labour–Energy–Materials
EEIOA – Environmentally Extended Input-Output Analysis
SAM – Structural Accounting Matrix
LPG – Liquefied Petroleum Gas
NC – National Communication
MEIC – Multi-resolution Emission Inventory for China
CEIC – Census and Economic Information Center
MFE – Mixed Forward Linkages
NBE – Net Backward Linkages
MBE – Mixed Backward Linkages
NFE – Net Forward Linkages
FE – Forward Effects
BE – Backward Effects
TE – Total Effects
NT – Net Transfer
FDSE – Final Demand Structure Effect
FDE - Final Demand Effect
LSE - Leontief Structure Effect
DCEIE – Direct Carbon Emissions Intensity Effect
OECD – Organization for Economic Co-operation and Development
EXIOPOL – Environmentally Extended Input-Output Policy Analysis
ADB-MRIO – Asian Development Bank Multi-Regional Input-Output
WIOD – World Input-Output Database
NBS – National Bureau of Statistics
CPA – Critical Placement Analysis
GWP – Global Warming Power

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

Over the last two decades, climate change issues have been paramount in global discussions. In 2016, the United Nations set climate change as the thirteenth of the seventeen goals of the Sustainable Development Goals (SDG) (UN, 2017). The American Metrological Society estimated CO_2 production to be 408.8 parts per million (ppm) in the present century, representing 46% above the average concentration in the last two centuries with 280ppm (American Meteorological Society, 2020). The 350ppm safe level is well exceeded (Ebi et al., 2021). In recent decades, China has led global emissions indicators with its developmental growth and economic boom Sun, Ding, and Yang (2017). The upward trend in CO_2 production worldwide, coupled with the visible biological degradations, could be related to reasons combating climate change has become an essential task in global discussions. In 2011, China suffered climate woes such as recurrent droughts and floods, resulting in heavy casualties and economic losses (Liu, Wang, Xu, Liu, & Luther, 2018). Many and more of these disasters globally are significant effects of climate change.

From 1990 to 2010, China's greenhouse gas (GHG) emissions increased by 174%, with a projection made that at the present rate of CO_2 emissions, China's emissions are expected to grow three times above the world's average (Liu, Hao, et al., 2016; Liu, Geng, et al., 2016). Many past studies attributed the projected increase in China's GHG emissions to the continued use of coal as the primary source of power generation. Data retrieved from the National Bureau of Statistics revealed that most of the energy generation in China is dependent on coal production (Lin & Xu, 2020). Sun et al. (2017) stated that coal contributes almost 70% of China's energy consumption. The dependence on coal as the primary energy source is representative of many economic sectors in China, including the fast-growing construction industry.

The construction industry in China experienced an enormous boom after China's admittance to the World Trade Organization (WTO) in 2001 (Liu et al., 2018). According to Liu et al. (2018), in 2009, the construction sector in China contributed between 28.5% and 38.6% to the final economic output of the country. The joining of the WTO related to an increase in domestic production (intermediate trade) and foreign trade (exportation) in the construction sector. In addition to the rise in international trade, the construction industry grew from being one of the less productive sectors of China's economy to becoming the largest exporting sector of the economy in 2015 (Hong, Zhang, Shen, Zhang, & Feng, 2017). Chen, Ni, Xia, and Zhong (2019b) suggested that the increasing trend in China's carbon emissions results from the increase in the export scale of China, especially to the EU, BRICS countries, and the rest of the world.

Also, rising from the impact of the 2008 global economic recession, China increased its exportation activities and became the largest CO_2 emitter globally (Pu, Fu, Zhang, & Shao, 2018). The International Energy Agency (IEA) data indicated that the cement industry contributes 5% to the global carbon emissions making the construction industry and its processes one of the largest international carbon-emitting sectors, with an approximate 25% contribution (Wu, Song, Zhu, & Chang, 2019). According to Hong, Shen, Feng, Lau, and Mao (2015), more than half of the world's cement production originates from China. Inductively, China's CO_2 emissions could be mostly related to emanating from the construction industry's products and raw materials.

Many studies analyzing China's construction industry's emission contribution to global stock have focused on construction-related activities. Hong et al. (2015) noted the importance of not limiting construction emissions investigations to construction-related activities and the need to have a holistic examination of pre-and post-construction-related activities. Generally, studies of building embodied energy and other environmental impacts are rare in China, primarily because of barriers to obtaining quantitative data for analysis (Chang, Ries, & Wang, 2010). Therefore, it is essential to investigate the embodied emissions originating from China's construction industry involving the direct and indirect sources, from on-site construction activities to upstream sources of the sector's supply chain. Results from such studies would facilitate the amelioration of CO_2 discharge from the construction industry and serve as a guide in understanding the sources, nature of the emissions, and the development of improved industry-related policies.

In most construction emissions articles in China, quantification focused mainly on the national level. Hong (2016) lamented the unfortunate neglect of environmental pollution embedded in regional and interregional trades in China's construction sector. Furthermore, in building emissions studies, CO_2 emissions have been extensively studied at the project level; the influences of sectoral and regional consumption and production interactions are often missing. Sectoral CO_2 emissions could result from two sources: Production-based and consumption-based emissions. Chen, Wu, Geng, and Yu (2017) defined CO_2 emissions based on the sources as "a combination of production-based sectoral emissions of a single sector, which is the on-set emissions that occur in the sector, and consumption-based sectoral emissions (or embodied emissions). According to Chen et al. (2017), embodied emissions are the sum of direct on-spot emissions attributed to the products going to final demand in the sector and the emissions embodied in the intermediate goods and services delivered from other sectors". Liu et al. (2018) opined that 90% of energy consumption in the construction industry accrues from intermediate demand in the construction process.

In contrast, the final demand partly determines the production requirement of the sector. The final demand is the products consumed by end-users, indicating the last stage of the industry's production chain. In this study, embodied CO_2 emissions are the total emissions emanating from the consumed energy during the whole life of construction activity, from the extraction of raw materials and natural resources processing to manufacturing, transport, operational project stage, occupation, and demolition. Therefore, this study employs multi-regional input-output (MRIO) models to holistically investigate intra- and inter-sectoral emissions interactions within the Chinese construction industry at national and provincial levels while also quantifying the emissions resulting from the direct use of material and equipment on construction sites.

The study aims at quantifying the direct and indirect CO_2 embodied emissions in China's construction sector at the national, regional, and provincial levels within a multi-regional system for assessing embodied CO_2 emissions in the industry. In achieving the aim of the study, the quantification of direct CO_2 emissions from the construction sector of China will be investigated at national and regional levels considering provincial discrepancies. Also, an MRIO model was constructed to investigate the intra- and inter-sectoral hidden linkages and the economic networks amongst the construction industry and other economic sectors in various provinces and regions in China. The constructed MRIO model was analysed using a Hypothetical Extraction Method (HEM) to determine the sector's hidden emissions linkages. Furthermore, the study adopted a structural decomposition analysis (SDA) technique to determine the driving forces of CO_2 emissions transmissions in the production-based supply chain of the upstream construction sectors. Finally, a multi-regional CO_2 emissions assessment system in the Chinese construction sector was developed by integrating a process-based direct CO_2 emission intensity module, a regional-based sectoral CO_2 emission linkages module, and a structural decomposition analysis module. The developed framework for assessing CO_2

emissions in the Chinese construction sector will provide an excellent guide to track the industry's emission performance, formulate industry-specific policies to address the industry's contribution to climate change and realize a cleaner and sustainable built environment.

1.2 Problem Statement

Over the years, the Intergovernmental Panel on Climate Change (IPCC) reported alarming dangers that loom on humankind and the environment because of anthropogenic climate change (IPCC, 2006, 2007, 2017). Many of the risks forecasted have occurred and keep intensifying due to weather immoderations, such as extreme drought, hurricanes, flooding, and increased global heat. IPCC (2007) described CO_2 emissions as having the most significant contribution to global climate change, with China being the most critical contributor to global CO_2 emissions. In 2014, National Development and Reform Commission (NDRC) report estimated the CO_2 emissions from China at 10,300 $MtCO_2$ in 2013. The report further predicted CO_2 emissions to keep increasing in the following decades. China's rise in CO_2 emissions can be attributed to the enormous challenge of energy consumption and substantial environmental burdens due to its rapid urbanization (Hong et al., 2018b).

In 2014, the urbanization rate in China reached 54.77% and was expected to increase to about 60% in 2020 (UN, 2017). In 2020, the Urbanization rate surpassed the projected figure by an additional 3.89% (CEADs, 2021). Recent data showed the China's urbanization in 2021 was about 64.72% (CEADs, 2021). However, the construction sector in China has risen to the increasingly demanding rise in rapid development with more than a 10% growth rate in energy consumption (Chang et al., 2010; Liu et al., 2011). The increasing urbanization growth, coupled with the expanding scope of the construction industry in providing amenities and facilities, presents considerable energy demands and energy-related CO_2 emissions challenges.

International Energy Agency (IEA) reported that the construction sector was responsible for approximately 25% of global CO_2 emissions (IEA, 2015). According to the report, 11% of global energy use originates from construction processes, and about 29% arises from the construction industry's products' operational use (Ogungbile, Shen, Xue, & Alabi, 2021). The sectoral contribution of the construction sector makes the industry arguably one of the most significant sectoral emitters of CO_2 (Li & Jiang, 2017). However, there is perceived neglect and generalization of the construction sector's immense CO_2 emission importance in many emissions literature, especially in China. In the existing literature, manufacturing, energy, and mining industries got significant focus, with the construction sector receiving less desirable attention. Mulder (2016) exclaimed that the sectoral categorization of emissions dominant industries in extant literature typically refers to CO_2 emitting installations in the oil, gas, cement, iron, steel, and paper industries. China's drive and commitment to the overall global emission charge would be better represented if the construction industry received more attention than it currently does. On the national, regional, and project levels, emission interactions must be adequately considered, especially the production and consumption influences in intermediate and final demands in China.

Although studies from other countries depict the construction sector as one with an efficient emission sector (Akan, Dhavale, & Sarkis, 2017; Leal, Marques, & Fuinhas, 2019), the Chinese construction industry remains one of the largest sources of CO_2 emitters of the economy (Chen, Shen, Shi, Hong, & Ochoa, 2019; Chen, Shi, Shen, Huang, & Wu, 2019). From the literature, CO_2 emissions in the construction sector tilted more toward investigations of the direct CO_2 contributions of the industry, creating a knowledge lag in the understanding of the industry's emission pattern. However, to ensure the success of the national drive for emission reduction in China, it is imperative to extend the investigation to non-direct injections of embodied energy emissions in the construction sector. According to Chen, Ni, et al. (2019b), embodied emissions of the sector should not be limited to direct emissions. Considering the nexus from upstream processes and interindustry trade of the industry and environment to quantify the CO_2 emissions in the sector would give a more accurate quantification and capture the hidden emission-flow linkages among the inter-industrial and inter-regional economic network.

Furthermore, there are major disparities between the present emissions estimated by academic institutes and experts (Shan et al., 2018a). There exist considerable differences between the various quantifications of CO_2 emissions in the Chinese construction sector (Liu et al., 2015). These discrepancies were attributed to the inconsistencies in the activity data and emission factors used in the quantifications. Many studies adopted IPCC world-average emission factors, while some used the United Nations or other statistical agencies' aggregated factors. The choice of datasets in computing the Chinese construction sector emission quantities has thwarted good policy decisions to ensure environmental sustainability. CO_2 emission flows induced by the construction industry are complicated. Analysis of CO_2 emission interaction's complexity using advanced analytical methods, such as SDA, Hypothetical Extraction Method (HEM) and Logarithmic Mean Divisia Method I (LMDI I), are useful in harmonizing the different emission analysis outputs.

1.3 Research Questions

Some key issues and problems to be addressed in this study were identified from the study background. The issues include entirely and accurately measuring both national and regional CO_2 emissions emitted by China's construction sector, considering indirect emission transfers from the economic structure's inter-regional trade. Also, the driving forces behind the observed increasing trend of energy-related CO_2 emissions in the construction sector in China remains another issue yet to be fully explored in the existing literature. Correspondingly, the complete decomposition and quantification of CO_2 emissions through the entire supply chain at the regional and sectoral levels in the construction sector. Conclusively, the need for a comprehensive assessment of embodied CO_2 emissions considering regional disparities. Therefore, the study's research questions are:

1. How can direct CO_2 emissions embodied in China's construction sectors (National and regional levels) be quantified?
2. What are the embodied CO_2 emissions linkages in China's sectoral and provincial construction sectors?
3. What are the driving forces of embodied CO_2 emissions interactions among provincial construction sectors?

1.4 Aim and Objectives

This study quantified the direct and indirect embodied CO_2 emissions in China's construction sector at the national, provincial, and project levels to determine the aggregated hidden linkages of CO_2 emissions embodied in trans-sectoral and inter-provincial upstream trades of the industry using a multi-regional and multi-scale assessment methodology. Therefore, the aim of the study was to track the Chinese construction sector's emission performance, formulate industry-specific policies to address the industry's contribution to climate change and realize a cleaner and sustainable built environment. The following objectives guided the research to achieve the aim of the study.

1. Quantify the direct CO_2 emissions embodied in China's construction sectors (National and regional levels).
2. Investigate embodied CO_2 emissions linkages from a sectoral and provincial perspective.

3. Investigate the driving forces of embodied CO_2 emissions interactions among provincial construction sectors from a multi-regional perspective.

1.5 Scope of the Study

The scope of a research endeavor represents the coverage of the study in the duration of its findings. In defining the scope of this study, two primary considerations were examined: the definition of China's construction sector in terms of the system boundary and the data availability for the study.

According to the definition of the construction industry in the World Input-Output Database (WIOD), the sector includes five main sub-sectors covering the entire process of on-site and off-site activities. These include building construction, civil engineering works, building services and installation, interior decorations and external works, and other addendum construction-related activities. Hong (2016) opined that the construction industry consists of all intricate construction-related activities made before and during the construction process but excluding those made after the completion of buildings and civil engineering projects. These activities could include extraction of construction raw materials, manufacturing of construction materials, transportation from the manufacturing plants to the construction sites, on-site construction and productions, and any other construction-related activities. These activities comprise the construction sector's embodied total economic value output represented in each I-O table. This study's scope is proposed to incorporate the production stages into the construction sector's use stage for clarity of purpose.

The use stage of the construction sector was added because of its importance in the amount of energy consumption requirement and the resulting CO_2 emissions. Figure 1.1 presents the system boundary adopted to define this research work's scope. Figure 1.1 describes the embodied CO_2 emissions assessment stages, which comprised three phases. The figure consists of four primary descriptors: embodied emission types, occurrence in life stages, stage composition, and system boundaries.

The first CO_2 embodied emissions emanate from raw material production and construction production stages on-site, known as the initial embodied emissions. This stage denotes the CO_2 emissions from direct construction activities from inception to completion of the construction project. The second type is the recurrent emission which are CO_2 emissions from the operational use of the project after its completion and handing over to the final users. The third stage is the last type of CO_2 emissions resulting from the project's demolition after the construction life cycle expiration. The system boundary is defined based on the start of the CO_2 emissions assessment up to the coverage extent. The start of the system boundary is known as the cradle, while the last stage is 'the grave'. To complete the whole system boundary, the complete dataset required for complete energy or CO_2 emissions assessment includes building data, material data, operational data, and demolition data. However, from the literature, demolition data in China is limited because of data requirements. Most data available are for the pre-construction stage, and operational stage data can be retrieved from operational data reading during the use of the construction project.

On the other hand, demolition data is very limited due to the inaccessibility and construction modifications that would have been done during the project's lifecycle. Also, the age of the buildings is another reason for the difficulty in retrieving these demolition data. Therefore, this study will be anchored on the embodied CO_2 emissions emanating from the production, construction, and use stages (operational stages) of the construction sector in China presented in various provincial and national statistics tables. The system boundary is defined as commencing from the 'cradle to use' of the construction industry in China.

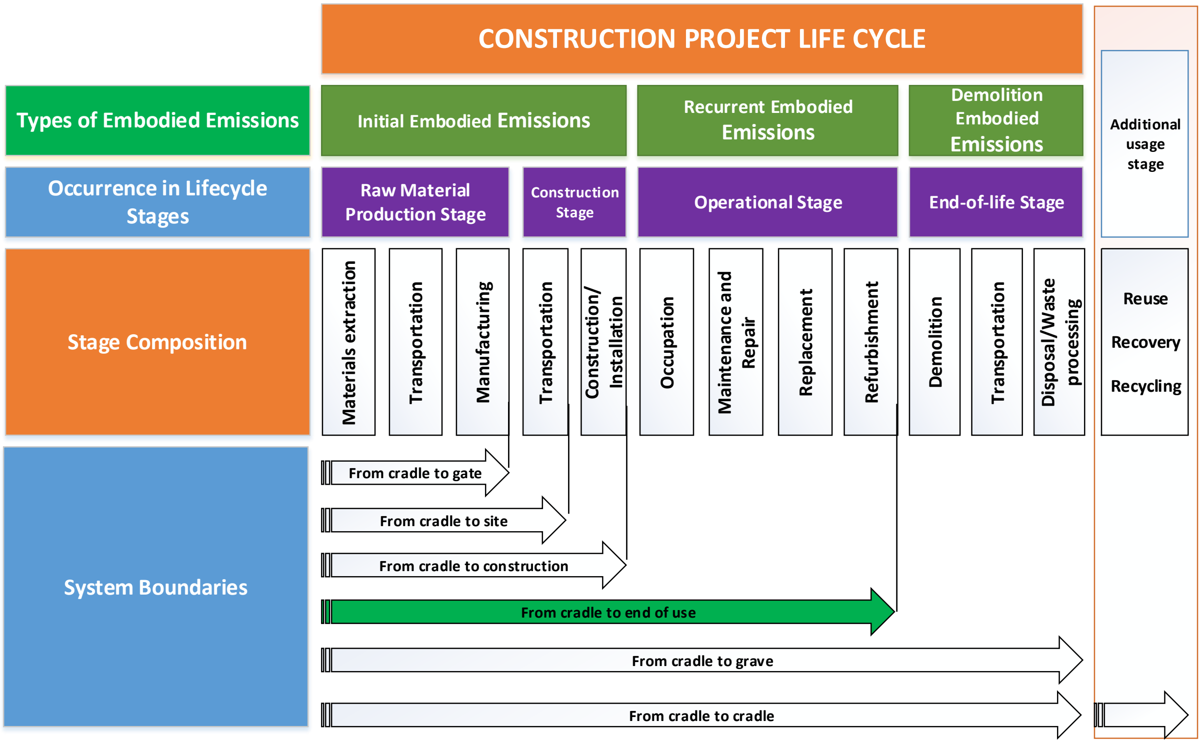

Figure 1.1 Energy consumption phases and system boundaries of the construction sector

The nature of the database and data availability was put into context while defining the scope of the study. The first set of data required for the study is the I-O tables. Two types of I-O tables are needed to achieve the research objectives for this study, including; the Single Regional Input-Output (SRIO) tables of China and the Multi-Regional Input-Output (MRIO) tables of China's provinces. The SRIO tables are required to quantify embodied CO_2 emissions at the national level of China's construction sector, while the MRIO tables are needed for regional/provincial measurement.

China's construction sectors energy data from 1997 to 2015 are currently available in the CEAD and the Chinese National Statistics. For the MRIO tables, the latest table available is the 2017 MRIO table. Further discussion of the I-O tables is presented in this report's methodology and data composition chapters.

1.6 Significance

The study proposes holistically quantifying CO_2 emissions embodied in China's construction sector at national and regional levels. The quantification at the national level aims to investigate the trend of CO_2 emissions concerning the various policies made to ensure environmental sustainability in China. Also, due to the disparities in existing CO_2 emissions quantification in the industry coupled with the limited system boundaries employed, this study is designed to extend the system boundary to the operational stage of the construction lifecycle stage, adopting a better-designed methodology. In the construction industry, embodied carbon refers to the greenhouse gas emissions arising from the manufacturing, transportation, installation, maintenance, and disposal of building materials. In contrast, operational carbon refers to the greenhouse gas emissions due to building energy consumption.

The definition of embodied carbon in the study is consistent with the ISO standard definition. However, the study redefined embodied carbon in this study based on the study’s objective to suit the end-goal of researching the direct and indirect carbon footprints of the Chinese construction sector. According to the ISO standard, embodied carbon means all the CO_2 emitted in producing materials. In construction research, embodied carbon accounts for the energy use in all life-cycle phases of the built asset, regardless of energy source. This could be explained in terms of contributing emissions from a material or object in the manufacturing or construction of another object/material. The ISO standard also defined embodied carbon in terms of embodied energy. However, embodied energy was not included in the study. Embodied carbon is different from embodied energy, which only accounts for the energy use in all life-cycle phases of the built asset, regardless of energy source. Some amount of embodied energy may be from renewable sources and would not be considered a source of greenhouse gas. The interconnectivity of different sectors in the national economy makes every sector a material or factor of production in another sector and vice vasal. The ISO definition of embodied carbon is very relevant and consistent with the study as the construction sector was not considered in solitude in the study. The interdependencies of the industry and other economic industries explained the system boundary adopted by the study. Net embodied carbon calculations may include carbon sequestration and end-of-life considerations. Therefore, the definition of embodied carbon in the study is in consonance with the ISO standard, however, with a slight study-specific moderation.

The study analyzed the inter-regional CO_2 emissions interactions and dependencies at the regional level. Decomposition and network transmission were conducted to explain the interregional exchanges, the driving forces, and the hidden paths embedded in regional and sectoral emission trading. The realization of the aim of the research will enable stakeholders and authorized state actors to strategically assess the current sustainability practices to formulate better approaches or improve on the existing ones.

The choice of CO_2 emission-efficient construction materials can positively impact environmental conservation. Computing the embodied CO_2 emissions of construction materials is thus one of the initial steps toward ecological safeguarding. The CO_2 emission efficiency is determined by analyzing critical emission paths and can suggest alternative material choices in reducing CO_2 emissions. Furthermore, in China's coal-fired electric power plants, significant process improvement has been achieved, with average coal usage lowered from 415g standard coal equivalent (SCE) per kWh to 319g SCE per kWh, a reduction of 18.75 percent (Chen, Ni, et al., 2019b). By ignoring these advances, policymakers may overestimate China's building and construction industry's carbon emissions, resulting in incorrect policy recommendations (Wu et al., 2019).

In addition, extant literature in the CO_2 emissions field in China's construction sector mainly omits the operational stages of the construction lifecycle. However, the operational phase of the construction industry, according to IEA (2015), emits at least 28% of global CO_2 emissions. China's construction sector produces almost half of the world's construction products, thereby becoming a significant stakeholder in construction-related CO_2 emissions. Considering this, a more thorough and precise study of production- and consumption-based CO_2 emissions utilizing the most up-to-date data was required for policymaking. This research endeavor formed lasting changes in CO_2 emissions simulations in entire China's energy and emission studies and caused a policy drive towards the construction industry's contributions to global CO_2 emissions.

1.7 Structure of the Thesis

The thesis consists of eight (8) chapters from introduction to conclusion. Chapter 1 is the introduction chapter to the study. The chapter discusses the background, the research rationale for the problem statement, and the questions necessitating the study. The chapter also discussed the aim, the objectives guiding the study, and the significance of the research. Finally, the thesis formats and steps are discussed along with the succeeding chapters in a research framework.

Chapter 2 is the literature review chapter. In this chapter, a synthesis of existing related studies on global and China's carbon emissions was made. The chapter introduced some of the methodologies used in carbon emissions research and justified the selected methods for the study. Topical issues on China's current approach and emission mitigation policies are discussed to understand the nature of climate engagement systems in place in the country. Most importantly, the research gaps in the literature upon which the study is anchored are discussed in the concluding parts of the chapter.

Chapter 3 is the methodology chapter. The chapter illustrates the methods of quantifying direct CO_2 emissions in the construction sector emanating from on-site construction materials, energy, and fuels for powering construction site equipment. The chapter discusses the modified HEM approach for CO_2 emissions decomposition in inter- and intra-sectoral trades and the sources and destinations of the emissions produced. Another highlight of the chapter is the discussion of the methodology used in determining the driving forces of CO_2 emissions in the sector, using SDA and LMDI-I methods.

The data needs for the research, the data gathering process, and data curation are discussed in Chapter 4. The databases from which the data were sourced are also discussed.

Chapter 5 presents the results and discussion of the direct CO_2 emissions at the project level of the construction sector in China. Chapter 6 focused on the outcomes of the study's second objective of decomposing the hidden paths of embodied CO_2 emissions in the Chinese construction sector. Results of the third objective of the study are discussed in Chapter 7, while Chapter 8, being the last chapter of the thesis, summarizes the findings of the research. Also, recommendations and policy implications of the study are discussed in Chapter 8. Conclusively, the underlying limitations of the study with future directions are topical points also discussed in chapter 8.

Figure 1.2 summarizes the research, the approaches employed, and the results achieved at each study stage. The research framework presented in Figure 1.2 includes the research objectives, the tasks to accomplish the objectives, and the research output at each stage (the deliverables). The tasks defined are the activities the researcher engaged in to achieve the aim of the research. These tasks are presented in terms of research input and techniques adopted. The processes are the stages of transforming the inputs into outputs, while the outcomes are the research results achievable from each research stage.

As illustrated in Figure 1.2, the first task of the research was to fully understand past work related to the study and determine a research direction from the gaps identified. The stage was followed by a comprehensive desktop study and document analysis to review the literature and identify the required datasets, databases, and methodologies. The next critical stage was the data retrieval and processing stage, followed by the research flow. The data stage included data from various economic, macro, and micro-regional sectors of China and energy data. The data were retrieved from multiple databases across many data depositories worldwide (see Chapter four). The data includes MRIO, SRIO, and fuel and energy data for China and its provinces.

The remaining stages of the flow chart illustrate the study's objectives, the data requirements, and the expected outcome from the different objectives. In the preceding sections of the thesis, various tasks and techniques described in Figure 1.2 are discussed.

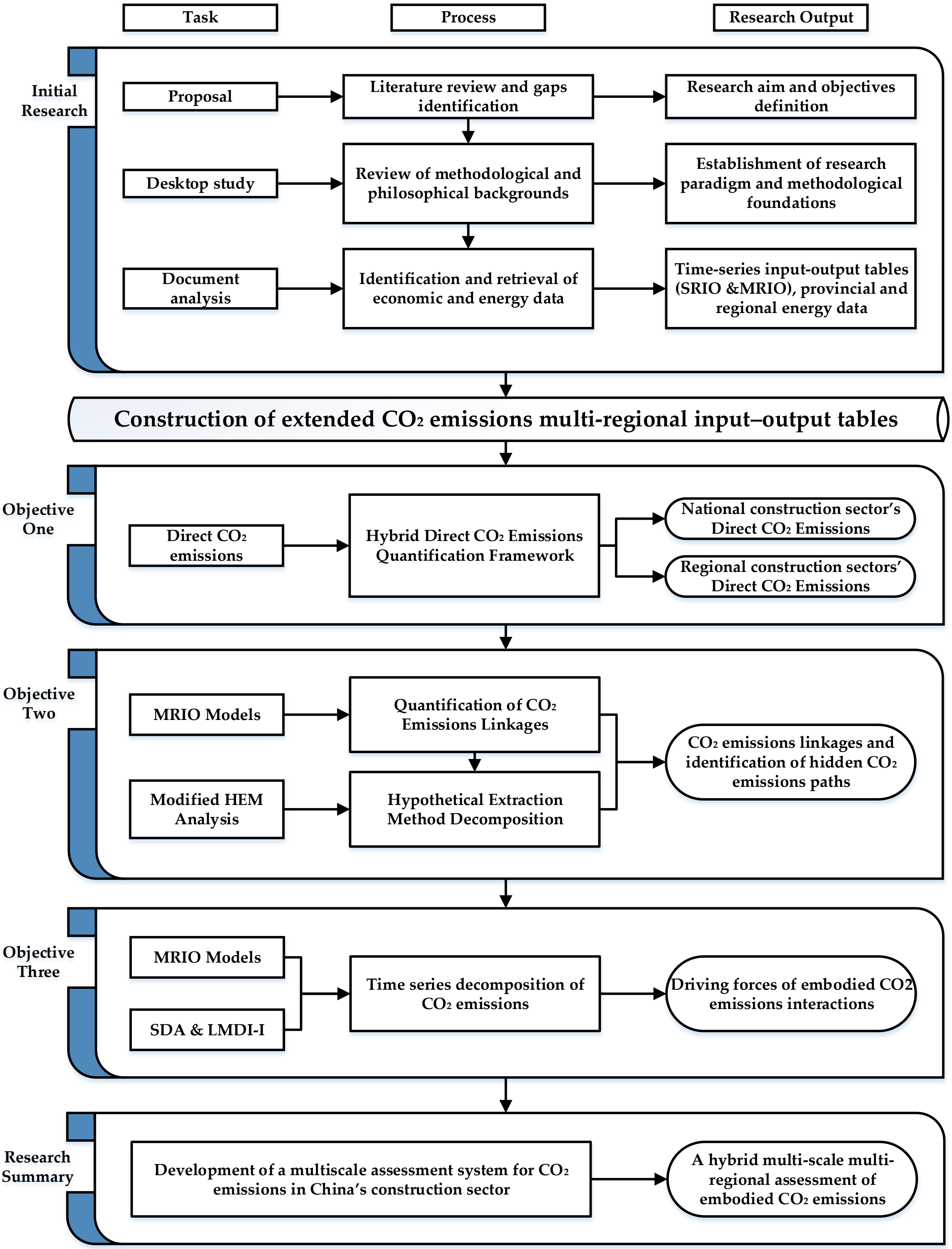

Figure 1.2 Research Flow Chart

1.8 Chapter Summary

The chapter gives an overall research intent, including background information, research problems, research questions, research aim and objectives, the scope of the study, and the significance of the research. In addition, the thesis structure and research framework are explained in relation to each component of the thesis.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

The chapter describes different existing literature types consulted and reviewed during the period of study that formulated the constructs of the research. The chapter is presented in logical sequence to indicate the broader topics of the construction sector in China to more specific components important to the aim and objectives of the study. The different climate interventions by the Chinese government in tackling the menace of climate change and the results of such interventions are discussed in this chapter. Also in this chapter, the construct of decomposition, the aggregation level, and the structure of carbon emission assessment techniques are discussed. Finally, the chapter indicates the gaps in previous studies and situates the research on its niche of knowledge contributions.

2.2 The Chinese Construction Sector

The construction industry in China is one of the most critical sectors of the country's economy due to the increase in the urbanization index recorded over recent years. Chen, Shen, et al. (2019) described the sector's importance in its value addition to the nation's economy. Chen, Shi, et al. (2019) averred the significance of the industry to the economic resurgence of China after the economic recession of 2008. Other researchers lined the success recorded in the Chinese construction industry as relating to the joining of the World Trade Organization in 2001. However, the reason to explain the boom experienced in the construction industry in China, the consensus is that the sector has, in recent years, grown to become one of the most significant contributors to the GDP of the nation. Also, the industry became the largest among other global competitors over the years on the international scene.

According to Chen, Shen, et al. (2019), the construction sector accounted for 6.68% of the total national GDP of China in 2015. In a study that compared the construction industry in

China and the United States of America (USA), Chen, Shi, et al. (2019) reported that the sector's role in the overall economic situation of the two countries is more significant in China than in the USA. Yu, Zhou, and Yang (2019) opined that the industry would continue its high trajectory growth over the coming years due to international demand for the sector and the urbanization rate in China. Hong, Li, et al. (2017) described the construction sector in China as a primary economic contributing sector for over thirty years.

Hong (2016) described the construction industry as a labor-intensive and product-extensive sector with very low efficiency. Based on the data retrieved from the China Statistical Yearbook (2019), the construction industry added over 22.5 billion Yuan (25%) to the GDP of China in 2018. Figure 2.1 describes the growth experienced in the construction industry over the years. In 1996, the construction industry's contribution to the national GDP stood at a little over 11% and had steadily increased over the years due to the increasing demand placed on the industry. The sector's contribution to the overall GDP growth of the country cannot be overemphasized.

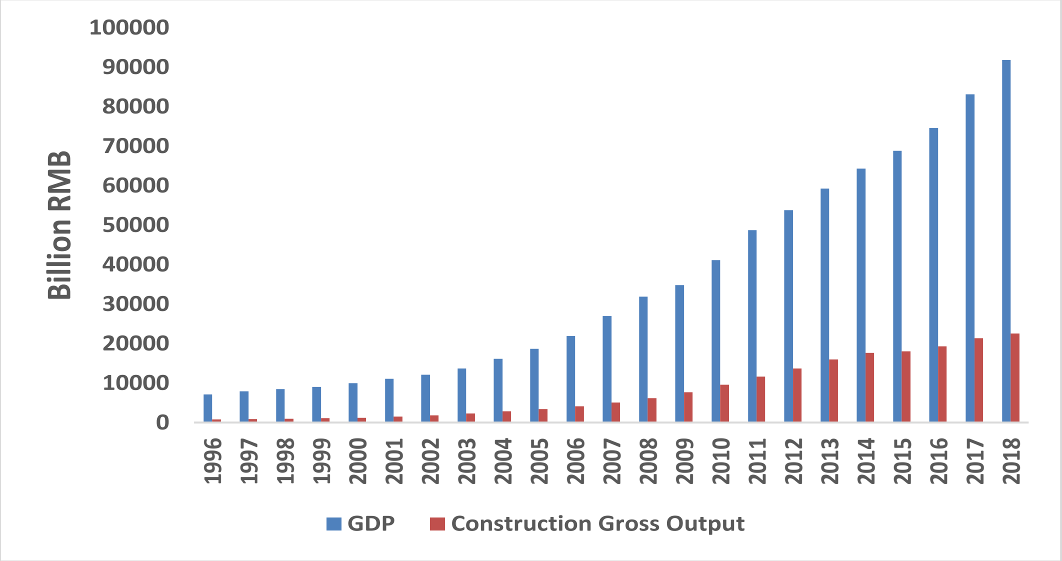

Figure 2.1 Gross Domestic Product and the Construction Industry Gross Output in China

Source: National Bureau of Statistics, China (2019)

The growth experienced in the construction industry is reflected in the number of initiated projects in China. The construction area of China grew from 1.5 million sq.m. in 2003 to 5.15 million sq.m. in 2019. Although, between 2013 and 2016, there was an observed drop in the project initiated, the completion rate was kept almost stable. However, as presented in Figure 2.2, the sector's efficiency, as represented by the percentage of project completion, remained almost the same since 2003. The highest project completion rate was recorded in 2016, with 88% of the initiated project. Therefore, many concerns regarding the industry's efficiency could be further validated.

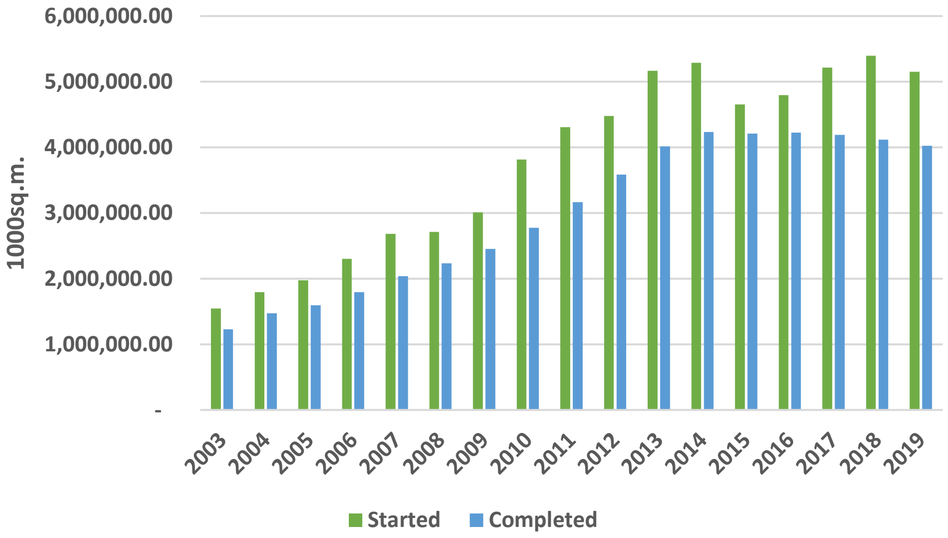

Figure 2.2: Initiated and Completed Project Areas in China

Source: National Bureau of Statistics, China (2019)

2.3 Emissions in China and China’s Construction Sector

China is regarded as the most significant contributor to global emissions stock in global emission ratings. China surpassed the USA in 2012 when it became the most extensive global trade emission exporter and producer (Dietzenbacher, Los, Stehrer, Timmer, & de Vries, 2013). The global growth of CO_2 emissions was credited to the influence of China’s exporting prowess. In 2013, global CO_2 emissions experienced an increase of 2.3% more than in 2012. The global CO_2 emissions in 2013 were 36.1 gigatons (Gt), a large proportion of which emanated from China. Friedlingstein et al. (2014) reported that China's CO_2 emissions growth rate was twice the global CO_2 emissions average of 10Gt (27.7% of global emissions) in 2013.

The reported increasing rates of China's emissions were traced to the deficiencies in the country's energy and carbon efficiencies (Friedlingstein et al., 2014). According to Chen, Shen, et al. (2019), observations showed that better carbon and energy efficiencies are attained in developed countries than in developing countries. Being the largest developing country globally, China possesses a lower carbon and energy efficiency than the USA, which is the world's largest developed country. In 2013, statistical data from the World Bank showed China's GDP was 1.74 times as low as the USA's (CEADs, 2021). However, the carbon emissions in China were nearly double that of the USA in 2013 (Friedlingstein et al., 2014). Also, there was an observed 439.8% increase between the USA and China's emissions difference between 1995 and 2009 (Chen, Shi, et al., 2019). The implication of the significant difference meant that, as the USA increased its carbon emission efficiency, China's carbon emission efficiency deteriorated.

On the other hand, many studies on China's emissions opined the increasing trend in the nation's carbon emissions to China's dependence on coal as the primary energy source (Wen & Li, 2020). Hong (2016) analyzed the embodied energy of China and described that over 77% of the energy source for electricity generation in 2012 was coal. 17.2% from hydro-powered stations, 1.8% from nuclear sources, 1.2% from gas, and 0.3% of electricity was generated from oil products. Hong (2016) suggested that the era of the surge in economic output of the construction industry from 2002 coincided with an upward trend in coal consumption in China. Hong, Shen, and Xue (2016) described the importance of the construction industry in the overall energy consumption in China. According to their findings, the construction industry alone consumed 793.74 million tons of coal, equivalent to almost 30% of China's national energy consumption in 2007. Li and Jiang (2017) noted that the industry is coal-dependent and described the importance of the construction sector to the national coal consumption. Figure 2.3 presents the percentage contribution of coal to China's yearly total national energy consumption stock. Figure 2.3 shows a decreasing trend in coal consumption in China, but a considerable amount of energy consumption is still dependent on coal. Figure 2.4 presents the total energy consumption in China from primary sources. Also shown in Figure 2.4 is the percentage of crude, natural gas and hydropower, nuclear power, and others. Coal, as explained earlier, generated the most energy in China over the years.

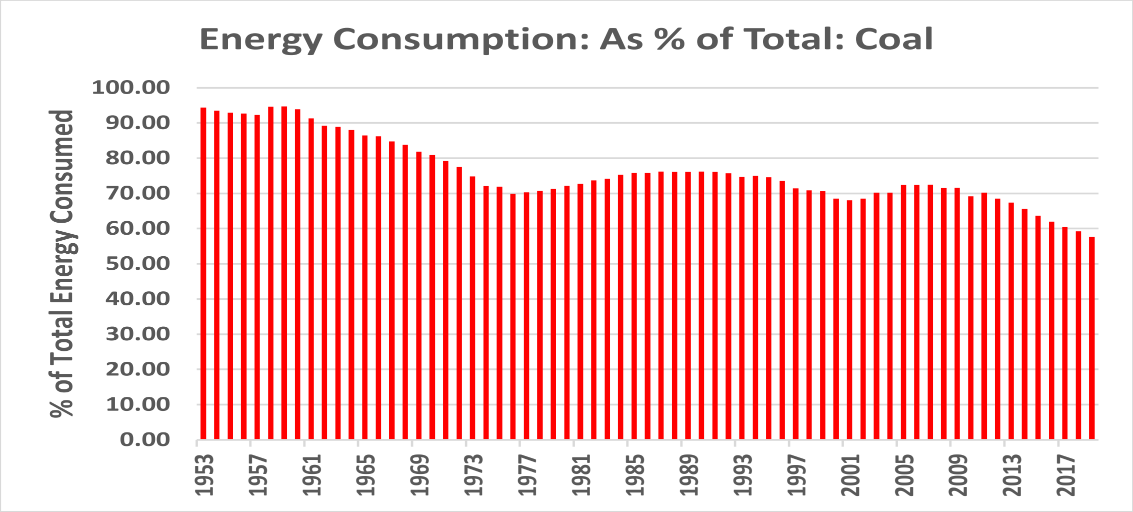

Figure 2.3: Percentage of Coal in Yearly Total Energy Consumption in China

Source: National Bureau of Statistics, China (2019).

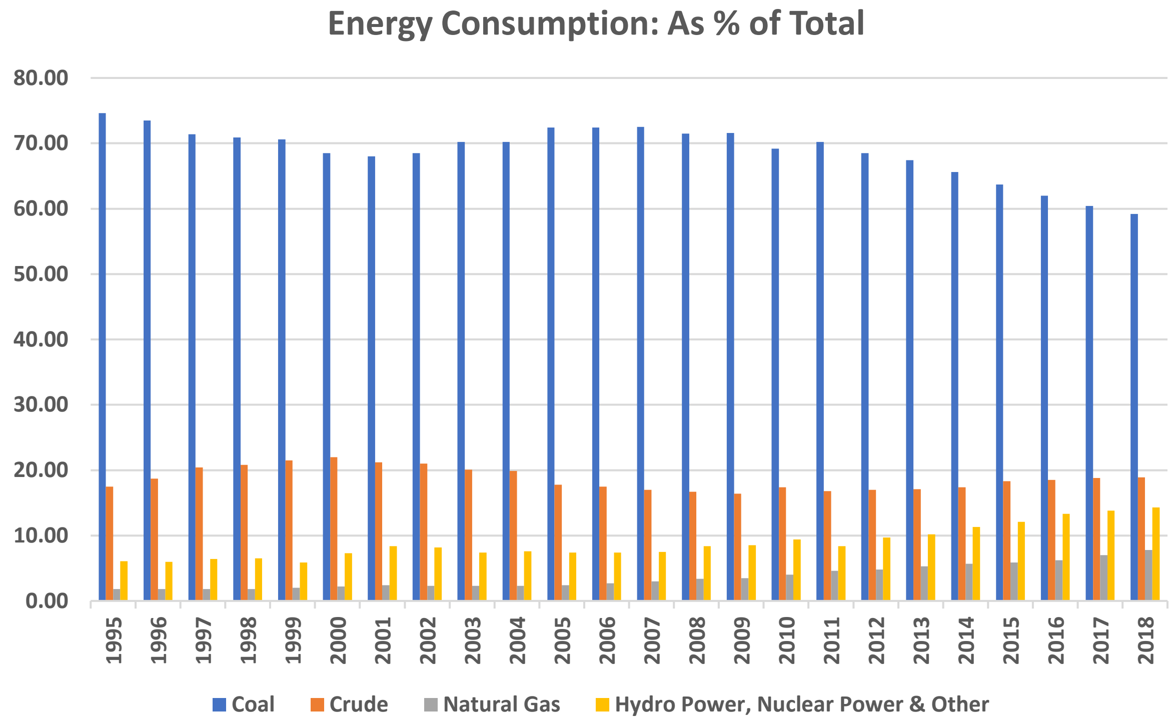

Figure 2.4: Yearly Energy Consumption in China

Source: National Bureau of Statistics, China (2019).

As China continues to experience a surge in urbanization and increasing civilization, the influence of the construction industry will be more significant to national development. The demand for Chinese expertise also grows worldwide, with Chinese construction companies increasing their presence globally, most notably in Africa and Southern Asia. Also, the Chinese government's Belt and Road Initiative (BRI) plan, birthed by President Xi in 2013, was structured around infrastructural developments. These demonstrate the importance of the construction sector to China's quest for global economic relevance and domestic sufficiency. The building sector alone consumes nearly two-fifths of the annual global energy supply in building operations, adding significant carbon emissions to the atmosphere. Chen, Ng, and Hossain (2018) noted the importance of not underestimating the significance of building materials to carbon emissions generation. Construction materials such as cement, steel, and iron contribute between 7% of global CO_2 to 10% of life-cycle carbon emissions (Chen et al., 2018), attesting to the importance of the construction industry as a primary emission source.

The construction industry in China is widely acknowledged as one significant sectoral CO_2 emissions contributor (Shi, Chen, & Shen, 2017). In a study by Chen et al. (2017), between 22.5% and 33.4% of China's total sectoral CO_2 emissions originated from the construction industry. Chen, Ni, et al. (2019b) found the construction industry, the tobacco processing industry, the food manufacturing industry, and the metal smelting and rolling processing industry concentrated the middle reaches of the Yangtze River's high emission carbon-locked inflows. Cheng et al. (2018) identified the construction industry as the third highest emitter of CO_2 in China. According to Chen et al. (2017), the construction industry contributed the most production emissions from the supply sectors of "Manufacture of Non-metallic Mineral Products, Smelting and Pressing of Ferrous Metals, and Production and Supply of Electric Power and Heat Power," with 72.1%, 46.9%, and 27.9% contribution respectively.

The rise in CO_2 emissions emanating from the construction industry in China increases environmental stress, thereby increasing the threat of climate change. Chang et al. (2010) described most of the emissions from the construction industry as resulting from the high intensity of energy use in completed buildings. The energy use in buildings accounted for 47% of China's total energy consumption in 2007 (Chang et al., 2010). The building lifecycle's CO_2 emissions mainly comprise those originating from embodied carbon of construction materials. Chen, Shen, et al. (2019) averred that the increasing rate of urbanization in many Chinese cities requires the construction industry's increasing intervention. The enormity of the influence of the construction sector's carbon contribution in China positioned the industry as a critical industry that deserves significant attention to reduce national and global carbon emissions.

2.4 China's Efforts in Tackling CO_2 Emissions

Many governments have adopted new policies to combat indiscriminate GHG emissions because of the Intergovernmental Panel on Climate Change's (IPCC) advocating for a need to re-strategize for a sustainable environment. Since the international declaration of a state of emergency on climate change and sustainable advocacy, various attempts have been made in many industrialized countries. Many policies have been devised by countries such as the United States, the United Kingdom, Japan, and China to reduce GHG emission stocks in their respective regions. According to Chen, Shi, et al. (2019), industrialized countries have higher emissions intensity than underdeveloped countries. Since the dawn of the industrial revolution, China has continued to increase its industrial output and construction activity, making it the world's largest developing nation and a significant carbon emitter.

China had the greatest percentage of world GHG emissions through domestic and international trade, according to a 2015 assessment by the International Energy Agency (IEA). China's GHG emissions would expand more than twice as fast as the global average, according to simulated forecasts from the IEA database (Hong et al., 2016). Rising to the occasion, the Chinese government has made numerous policies to cushion the effects of climate change and reduce China's generated emissions in the global stock. The policies cut across many industrial formations and energy use (Ogungbile, Shen, Wuni, Xue, & Hong, 2021).

The Kyoto protocol has, for long, been regarded as one of the foremost climate change advocacy conventions. Rising from the memorandum of understanding signed by the committee of nations in attendance, China inclusive, the birth of an era for climate change reduction efforts commenced. The convention was sub-divided into two parts. The first part was the agreement by attending nations on global warming and its peril to the continued existence of humans. The second part of the convention was the agreement that CO_2 emissions by humans have significantly caused global warming. The Kyoto protocol identified the six critical GHGs that needed to be closely monitored. They include; "Carbon dioxide (CO2), Methane (CH4), Nitrous oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), and Sulphur hexafluoride (SF6)." A target was set to reduce GHG emissions to "a level that would prevent dangerous anthropogenic interference with the climate system" (Akpan, Green, Bhattacharyya, & Isihak, 2015).

Since its ratification in Kyoto, Japan, in 1997, 192 countries have adopted the convention's recommendations regarding global warming. China is one such country to implement the Kyoto protocol recommendations (Acquaye & Duffy, 2010; Pu et al., 2018). Between 2008 and 2012, China was one of 36 countries that completely participated in the protocol's first set of obligations by decreasing GHG emissions (Ogungbile, Shen, Wuni, et al., 2021). The establishment of the National Development and Reforms Commission (NDRC) by the Chinese government in 2004 was a critical initiative (Chen, Ni, et al., 2019b). According to Chen, Ni, et al. (2019b), "the NDRC's functions are to study and formulate policies for economic and social development, maintain the balance of economic development, and guide the restructuring of the economic system of Mainland China." The NDRC of China is a proponent of industrial reform initiatives. In the 2011 edition of the Guideline Catalogue for Industrial Restructuring, the corporation collaborated with necessary authorities to raise energy-saving criteria for companies. The guideline emphasizes the need to improve the industrial sector, raising energy-saving requirements, and, in the end, reducing GHG emissions.

During the 12th five-year plan period, the NDRC released a national gas development plan with the goal of improving China's energy infrastructure by encouraging the use of clean fossil fuels. As a result of the policy, 18 percent of towns and municipal people used natural gas in 2012. The agency also revealed plans to expand China's non-fossil fuel consumption development in the 12th five-year plan. China expanded its investments in clean and renewable energy sources, spending about 62 billion RMB on wind power, 78 billion RMB on nuclear power, and 127.7 billion RMB on hydropower plants. Figure 2.4 indicates the results of these policies, with China's dependence on coal as an energy source gradually reducing.

At the Copenhagen conference in 2009, China and other UNFCCC member countries pledged to cut carbon emissions per unit of GDP by 40-45 percent by 2020, compared to 2005 levels. The Kyoto Protocol was endorsed by the Copenhagen Accord, which was written in sections. The United States drafted one section of the agreement, while the BASIC countries (China, Brazil, India, and South Africa) collaborated on the other. Climate change was identified as a key human challenge in the agreement. It emphasized: a "strong political will to urgently combat climate change in accordance with the principle of common but differentiated responsibilities and respective capabilities" (UNFCCC, 2009, pp. 2) Even though a few countries questioned the legitimacy of the agreement, China has remained committed to reduce carbon intensity by 40-45 percent below 2005 levels (Fan, Cao, Zhang, Liu, & Zhang, 2019).

In addition to the promise of carbon intensity reduction, another of China's pledged pact at the Copenhagen accord was to add 40 million hectares of forest coverage and a 1.3 billion cubic meter increase in forest stock increase level in 2005 by 2020. In addition, China stated that by 2020, non-fossil fuels will account for 15% of primary energy consumption. China's decision to achieve the projected reduction was stated in the Development Strategy Action Plan (2014-2020). A lot of irregularities marred the agreement. In 2010, the United Nations Environmental Program (UNEP) observed an emission gap between the emissions required to achieve a "likely" worldwide GHG emissions reduction (66% probability) and the emissions committed at the signing of the agreement. This disparity is particularly pronounced in China, which has the greatest emission discharge.

China further proved its resolve to reduce emissions during the recent Paris climate change pact of 2015. China joined the comity of nations to sign the historic Paris pact targeted at reducing global temperature increase below 2^0C and possibly attaining a mark of 1.5^0C. In response to the Paris agreement, China shut down many inefficient and antiquated production facilities, mostly cement production plants, to reduce China's overall emissions contributions.

In 2019, at the Climate Action Submit 2019 (COP25), China's foreign minister, Wang Yi, reaffirmed China's commitment to combating climate change and the Paris agreement in a meeting co-chaired by China and New Zealand. The minister stated, "China will earnestly fulfil its obligations under the United Nations Framework Convention on Climate Change and the Paris Agreement and achieve the target of voluntary contributions as scheduled." In 2018, China's primary energy consumption from non-fossil fuel almost reached 15% promised during the Copenhagen convention, as illustrated in Figure 2.4. In 2018, China's carbon emissions per GDP dropped below 40-45%, as pledged at the Copenhagen accord, to 46%. Since the opting out of the USA from the Paris accord agreement, China has taken the leading role in ensuring the promises made during the convention are kept and, ultimately, reducing global emissions.

Furthermore, China has launched a low-carbon city pilot project to reduce carbon emissions in pilot cities (Shen et al., 2018) and has said that carbon emissions will peak by 2030 (Chen, Shi, et al., 2019; Shen, Song, Wu, Liao, & Zhang, 2016). As a result, the Chinese government considers climate change to be a major concern and has established a set of enforceable emission reduction targets (Fan, Cao, Zhang, Wang, & Zhang, 2019).

2.5 Embodied Emissions Assessment

In literature, emissions are classified into direct and indirect emissions. There are three classifications of embodied emissions based on the construction life cycle. The three classifications include initial, recurrent, and demolition embodied emissions. The initial embodied emissions relate to the extraction, mining, and production of construction materials downstream of the construction chain. In addition, the emissions generated during the direct construction on the project site until the completion and handing over of the project are initial embodied emissions.

In comparison, the second type of emissions is recurrent emissions. These types of emissions result from the operational stages of a construction project. These include emissions from project users, repairs, and maintenance works throughout the usage stages of the construction project lifecycle. The last classification is the demolition stage of the construction project life cycle, including the emissions generated at the project's end of life. The emissions generated in transporting the demolition materials are classified under this stage.

The same applies to the construction sector's emissions classifications. Direct emissions are those produced by activities on the construction site, while indirect emissions are classified as emissions emanating from the upstream supply chain of the construction industry. Acquaye and Duffy (2010) described upstream emissions as emissions that result from activities done before the commencement of construction activities on sites. These activities include design team activities, excavation, and raw materials manufacturing. Embodied energy and, in extension, embodied emissions comprised of initial, recurrent, and demolition embodied energy (Hong et al., 2016). Dixit (2017) defined initial embodied energy as the sum of all indirect and direct energy consumed during building construction stages, while the recurrent is the energy consumption during the operational phases of the building. Figure 1.1 describes the various stages of embodied energy and embodied carbon emissions and the scope defined for this study.

Embodied carbon emissions accounted for 10-97% of the whole life-cycle carbon emissions in buildings (Abanda, Tah, & Cheung, 2013). Acquaye and Duffy (2010) noted that 11.7% of Ireland's national emissions in 2005 originated from the construction sector, and 71% were from embodied sources. In Norway, there was a significant reported increase in carbon emissions in 2007 from 4.2 $MtCO_2e$ to 5.3 $MtCO_2e$, with a substantial portion being embodied emissions. In 2012, embodied carbon emissions accounted for 96.6% of the carbon emissions from the Chinese construction industry (Abanda et al., 2013). Therefore, the embodied carbon emissions resulting from construction activities and operational use of construction sector's products are significant to the complete measurement of China's contribution to the global emission stock.

Unlike project time and cost, measuring embodied energy and CO2 generated in projects is difficult due to a lack of understanding of emissions from a long-chained construction process, a lack of accounting data, and a lack of agreement on the scope and boundary for CO2 measurement (Abanda et al., 2013). In the construction context, accounting methods for embodied energy and CO_2 have been minimal and lacking coherence. However, existing literature assessing embodied carbon emissions has adopted three primary assessment methods in its quantification- Process-based, input-output and hybrid assessment methods.

2.5.1 Input-Output Assessment

Based on environmental input-output analysis, Input-output (I.O.) life cycle assessment is a top-down strategy for examining environmental interventions from cradle to gate (Abanda et al., 2013). It was developed initially by Leontief for analyzing industrial interdependencies in national and regional economic systems (Leontief, 1970). The technique has extensive applications in many fields of study outside economics, such as supply chain, optimization, energy, and environmental research applications. The national accounts' underlying input-output table indicates how much an industry's inputs are used to produce its outputs (Abanda et al., 2013). It is one of the most widely used methodologies for calculating energy usage and greenhouse gas emissions today.

The I.O. assessment follows the traditional I-O framework for monitoring a region/country's input technologies and the resulting output in terms of local consumption and export. There are two main types of I.O. table: the Single Regional Input-Output (SRIO) tables and the Multi-Regional Input-Output (MRIO) tables. The SRIO contains the input-output values of different economic sectors within a named country. The MRIO, however, is a sub-division of the SRIO tables into economic values of industries in different regions of a designated country. The MRIO tables are more comprehensive and show more details than the SRIO. In the MRIO, comparisons can be made on different regions within the same country, unlike in SRIO, where comparisons can only be made between different sectors and with the SRIO of another country.

2.5.2 Process-Based Assessment

Process data are used to compile the life cycle inventory in process life cycle assessment. Process life cycle assessment data can be gathered directly from life cycle inventory databases or from other data sources that are presumed to reflect a process (Acquaye & Duffy, 2010). In most emissions calculations, the volume of fuel consumed serves as the activity data in the quantifications. The fuel mix reduces the activity data to suites the model developed. Emission factors are significant in this technique to extract each fuel type's carbon content and oxygenation efficiency (Abanda et al., 2013).

2.5.3 Hybrid Assessment

A combination of process, sectoral I.O., and environmental account data make the hybrid life cycle assessment. The hybrid technique optimizes the benefits of both process and input-output analyses and eliminates or minimizes the errors and limitations inherent in both approaches. Hybrid analytic approaches can be divided into two categories. Process-based hybrid and input-output-based hybrid analyses are the two types of hybrid analyses. (Hong, Zhang, et al., 2017).

Process-based hybrid analysis applies input-output-based analysis to complicated sections of upstream material-production processes, avoiding the incompleteness that comes with traditional process analysis (Abanda et al., 2013). Complex materials including many components, on the other hand, may cause a problem for this procedure. To eliminate indirect impacts, the input-output-based hybrid analysis detects and separates direct energy channels from the input-output-based study to incorporate trustworthy and accurate process-based data. According to Treloar (1997), the incompleteness or mistake in typical embodied energy computation and analysis is around 20%, and there is no entirely efficient approach available. In the life cycle analysis of structures, however, input-output-based hybrid analysis is regarded full and nearly perfect (Abanda et al., 2013).

2.5.4 Choice of Assessment Technique for Embodied Emissions

The optimization of the disadvantages and advantages of the three identified assessment methods informed the assessment technique used in this study. Table 2.1 presents the different assessment techniques for embodied emissions, data selection types, and characteristics. A hybrid analysis avoided double counting from the I.O. technique while keeping the intensity level. Also, the hybrid technique encourages improved accuracy, as seen in the process-based analysis technique. Overall, the hybrid technique uses the advantages and disadvantages of the process-based and input-output methods without compromising the datasets.

Table 2.1: Methods of assessing embodied emissions

Method	Data Type	Characteristics and Advantage
Statistical Analysis	Historical data	• Requires precise and sufficient data. • Data collection is difficult
Process-based Analysis	Material and process emission data	• Improved accuracy • Less cost and time-intensive
Input-Output Analysis	I-O tables and Emission factors	• Uses economic data and sectoral environmental impact • Reduced time and cost intensity
Hybrid Analysis	• Combines the advantages of both I-O and process-based analysis	

For this study, the hybrid analysis assessment model adopted to quantify CO_2 embodied emissions in the Chinese construction sector was further discussed in chapter three of this report. The system boundary selected to guide the study was described in detail in the Scope section of this report, while the hybrid methodology was fully explained in the methodology chapter of the report.

2.6 Hypothetical Extraction Method

The HEM improves on the traditional Classical Multiplier Method (CMM) by identifying and quantifying the significance of a sector's embodied emission flow within an economic system. Unlike the CMM, whose focus is the correlation of an industry only based on the averages of the technical coefficients (Lenzen, 2003), HEM's main idea is to measure the impact of an extracted sector on the economic system, allowing the effect of this extraction on the rest of the economy to be examined. The HEM expansively measures the two-directional influences of a sector's linkages compared to CMM, which only measures the first-round effects (Zhang, Liu, Du, Liu, & Wang, 2019). The HEM considers the relative size of each industry sector's final demand and its impact on total output; thus, it is more applicable to industrial correlation analysis (Andreosso-O'Callaghan & Yue, 2004). The difference in output before and after extraction demonstrates the impact and extraction department linkages with other sectors.

HEM use in GHGs studies is not limited to only construction-related research. HEM has a broad and interdisciplinary application in understanding the hidden linkages in sectoral emissions. One foremost use of the HEM was for water consumption usage patterns in the Spanish economy, and the impact of each block was divided into four parts (Duarte, Sánchez-Chóliz, & Bielsa, 2002). HEM was also used to investigate the economic influence of a sector in a region and identify the impacts of industrial key sectors (Zhang, Bian, & Tan, 2017). With concerns about climate change intensifying, the HEM was employed uniquely to explore the industrial CO_2 emission effects of inter-sectoral linkages in China (Wang et al., 2013), South Africa (Zhao, Zhang, Wang, Zhang, & Liu, 2015), and Beijing (Liao, Andrade, Lumbreras, & Tian, 2017). The relationships between sectoral CO_2 emissions and household consumption (Zhang, Yu, Cai, & Wei, 2017) and household income (Zhang, Bian, et al., 2017) were investigated. The HEM was used expansively to understand the linkages in global construction sectors and the trend of the sector's influence on international CO_2 emissions between 2000 and 2009 (Zhang, Liu, et al., 2019).

The HEM has been used in MRIO analysis to investigate industrial CO_2 emission linkages among eight Chinese regions (Zhao, Liu, Wang, Zhang, & Li, 2016), as well as the inter-regional and sectoral linkage analysis of air pollution in China's Beijing–Tianjin–Hebei urban agglomeration (Wang, Liu, Mao, Zuo, & Ma, 2017). Furthermore, the HEM has been used to detect synergies between two indicators such as water–energy consumption and water–carbon interactions among economic sectors and identify each sector's position in the supply chain (Fang & Chen, 2018). The HEM application in emission studies in China is mainly unpopular, with most research using common approaches like CMM and life-cycle analysis. The few studies to have used the HEM approach are limited to determining the interactions on national and sub-regional level decomposition. With the lack of adequate studies using HEM in sectoral and provincial level decomposition, the study adopted the method to determine the sector's double-directional impacts in intra- and intersectoral linkages in the Chinese construction sector.

2.7 Decomposition Analysis in Construction Sectors' Energy and Emissions Studies

2.7.1 Introduction

Decomposition analysis has been a valuable tool in studying factor contribution and driving forces analysis of aggregator indicators over time. These analyses have been employed to understand a change in energy factors' effect on energy consumption and energy use patterns (Wang, Zhang, Wang, Lei, & Zhang, 2015). There are two commonly used decomposition analysis techniques, which are Structural Decomposition Analysis (SDA) and Index Decomposition Analysis (IDA) (Malla, 2009). Many studies have used the two interchangeably to understand and explain the driving forces in energy and emissions related studies (Zhou & Ang, 2008). IDA has been used more by energy researchers because of the specificity it presents to investigate drivers of energy change for a particular energy consumption sector/industry, which has been extended to energy emissions-related studies. However, researchers have used SDA together with input-output analysis and energy-related emissions or energy consumption studies for an entire economic system.

When analyzing variations in energy consumption and CO_2 emissions caused by various influencing factors, two decomposition approaches, structural decomposition method (SDA) and index decomposition analysis (IDA), are often utilized (Peng, Li, Zou, Shen, & Sun, 2015; Peng & Pheng, 2011). Researchers that prefer to use the input-output model, which has been enhanced to help identify changes in energy consumption or CO_2 emissions in the economy, use SDA. IDA, on the other hand, is mostly used to better understand the contributing drivers of energy consumption and CO_2 emissions in a certain industry, such as manufacturing or construction (Wu et al., 2019). In comparison to SDA, IDA has a lower data requirement and is more flexible in terms of the analysis timeframe (Lin, Zhu, Song, & He, 2016; Peng et al., 2015).

Unambiguously, the SDA model has been widely used to investigate how changes in individual factors influence the rise of embodied carbon emissions through trade outflows. Based on the type of data aggregation, the IDA model investigates the direct effects of changes in economic, structural, and population factors on carbon emissions (Chen, Ni, Xia, & Zhong, 2019a; Chen, Ni, et al., 2019b). Although the SDA model is based on classical input-output theory, the data are more extensive and analytically detailed, compensating for the IDA model's incapacity to analyze the indirect influence of changes in the final demand sector on carbon emissions (Peters, Weber, Guan, & Hubacek, 2007). The SDA model uses a variety of estimating approaches, with the weighted average process being the most theoretically developed (Peng et al., 2015). This method is rarely utilized due to the high level of computing required and the difficulty of operation. The bipolar decomposition approach, on the other hand, can avoid the foregoing drawbacks while providing a solution that is comparable to the weighted average method (Peng et al., 2015).

IDA and SDA present differences and similarities in method formulation, study scope, data requirements, and results (Su & Ang, 2012). In recent times, there has been a rising interest in decomposition analysis in construction energy-related studies. The growing interest could be attributed to increased interest in climate change studies and the corresponding energy consumption reduction strategies being put in place as a viable response to curbing energy wastage. In varying capacities, SDA and IDA have been employed in these studies, with different methodological approaches constituting confusion in method selection for intending energy researchers. However, no research has addressed this conflict issue by comparing IDA and SDA in construction energy consumption and energy emissions-related studies.

2.7.2 SDA Literature in Construction Sector's Energy and Emissions studies

Following the introduction of the extended input-output framework by Leontief (1970), the SDA application has since been used in energy and emissions studies. Since the extension of SDA to energy and emissions studies, many studies have been made to decompose various economic systems' driving forces of energy consumption. Some of the pioneering studies in this field include the works of (Chang & Lin, 1998; Gowdy & Miller, 1987), (Pløger, 1983, 1984), and (Leontief & Ford, 1972). In one of the early studies, KLEM effects were formed based on the KLEM production functions by decomposing changes in input technology coefficients by Rose (1995), generally referred to as the KLEM two-tiered decomposition model. However, according to (Hoekstra & van den Bergh, 2002), the foremost inclusion of SDA in emissions-related change studies could be seen (Casler & Rose, 1998; Rose, 1995). In recent years, SDA was incorporated into studying energy intensity change in the construction industry, and by extension, SDA was introduced into emission drivers in the industry. Gerilla, Teknomo, and Hokao (2005) were among the earliest adopters of SDA in emission studies in the construction industry. The study was based on the Japanese housing sector's carbon emission change pattern. There are many usages and methodologies of SDA that have evolved over the years in the construction sector.

The construction industry has been criticized as one particular industry that adopts innovations late. A similar pattern occurred in introducing SDA into the industry's research inputs. SDA was introduced when the methodology had been well established and improved.

Therefore, it was noticed that the traditional ad-hoc decomposition methods were less prevalent in the studies considered in this review. The ad-hoc decomposition methods were anchored on a change of parameters, while other parameters were kept fixed (Su & Ang, 2012). In these methods, the arbitrarily chosen base year greatly determines the results obtained using the Paasche and Laspeyres indices. The results of these methods have complicated interpretations due to the residual terms contained in the poor decomposition results generated. These complications were eliminated when two general exact decompositions were introduced (Betts, 1989). However, the two exact and ad-hoc decomposition methods were not sufficient to be classified as ideal decomposition. Su and Ang (2012) defined an ideal decomposition as ensuring the exact decomposition of aggregate while satisfying other conditions of the factor-reversal test.

To achieve an ideal decomposition (D&L), Dietzenbacher and Los (1998) introduced the average of all n!. The exact equivalent form was improved upon by proposing approximate D&L techniques like two polar decompositions averaging in overcoming the cumbersome problem encountered with a large number of primary factors. After these methodological formulations, many other models have been proposed over the last two decades, including the Logarithmic Mean Divisia Index Methods I and II (LMDI-I&II) related to the Montgomery-Vartia index decomposition and Sato-Vartia decomposition, respectively, and the MRIO method, the S/S methods. The details of these decomposition models can be seen in Hoekstra and van den Bergh (2002) and Lenzen and Murray (2010).

In the construction industry's energy and emissions decomposition analysis, various additive decomposition methods and models have been explored in determining energy and emissions drivers and patterns. Hoekstra and van den Bergh (2002) reviewed three of the most popular methods: the D&L methods, the S/S methods in IDA, and the refined Divisia (LMDI-II). Su and Ang (2012) concentrated on SDA studies with additive decomposition methods. The two reviews were based on the general composition of the methods with less focus on the results generated. Also, previous reviews were done on decomposition studies in varying fields and sectors of the economy. However, we have construed ours to focus only on decomposition analysis applications in energy and emissions studies in the construction industry, focusing on evaluating the results generated from the studies. Table 2.2 summarizes the publication employed for the review. The countries where the studies were covered, and the type of research (energy or emissions) are shown in Table 2.2. The review was based on three main groups: The indicator used (as explained earlier), the Decomposition Model Adopted and the Decomposition Methods Adopted in the studies.

The demography details in Table 2.2 show the geographical distribution of decomposition analysis in the construction industry. Notably, most of the studies were conducted in China; however, with varying study focus and within different regions of China. The studies adopted year ranges from 1974 to 2050, with available data not exceeding (in most cases) 2012. Predict predictions, data modelling, machine learning, and scenario analysis generated results for future years. Decomposition studies in the construction industry focused on energy and emissions modelling, with a few combining the two research contexts. The differences in the studies are in the indicator used, the decomposition models, and the methods adopted. Table 2.2 shows that most of the emission-related construction research has focused on carbon emissions at the construction stages of the sector, with observable neglect of the embodied emissions from the upstream supply chain. Also, the operation emissions discharge phase of the construction industry was neglected in some of the research publications.

One of the vital components of the decomposition methods used in Table 2.2 is the factors selected for decomposition. The factors represent the numbers of factors decomposed in the studies, while the DM-S1 and DM-S2 denote One-stage and Two-stage decomposition models, respectively. The factors under investigation determine whether the DM-S1 or DMS2 model would be adopted. Table 2.3 summarizes some of the factors decomposed in the decomposition analysis. The factors range from carbonization effect and energy intensity effect to many others listed in the table. The difference between the DM-S1 and DM-S2 is the treatment given to a Leontief matrix change (the Leontief Structure) (Su & Ang, 2012). One-way decomposition analysis considers the Leontief structure as a single effect, while the two-way decomposition treats it as a combination of two or more sub-effects (Jacobsen, 2000). Some notable sub-effects distinguish between input-technology effect, domestic input effects, total input technology effect, and exact decomposition (KLEM) effects (Rose & Chen, 1991).

The decomposition method group is sub-divided into Four (ad-hoc, D&L, LMDI, and others). The ad-hoc represents decomposition approaches that have not been generally accepted in other studies. The D&L represents the Divisia and Laspeyres decomposition methods, while the LMDI represents the Logarithmic Mean Divisia Index. Others represent new methods developed by the publication's author, still awaiting general acceptance.

Table 2.2: Energy and Emissions Literature in the Construction Industry

Publication Details		**Focus Area**		**Indicator Used**			**Decomposition Model Adopted**			**Decomposition Method Adopted**			
Author	**Year**	**Range**	**Area**	**Energy**	**Emissions**	**Aggregate Indicator**	**#Factors**	**DM-S1**	**DM-S2**	**Ad hoc**	**D&L**	**LMDI**	**Others**
Murtishaw et al.	2001	1974-1994	IEA Countries	x	x	Energy and CO_2	2	x					x
Gerilla et al.	2005	1980-1995	Japan		x	CO_2	3	x			x		
Liu et al.	2009	1994-2007	China	x		Energy Intensity	2					x	
Minx et al.	2011	1992-2007	China		x	CO_2	6	x					x
Liu et al.	2011	1999-2007	China		x	CO_2						x	
Das and Paul	2013	1994-2007	India	x		Energy	3	x			x		
Fernández González et al.	2013	1995-2010	EU	x		Energy Intensity	5					x	
Geng et al.	2013	1997-2007	China		x	CO_2	6	x			x		
Kahrl et al.	2013	2002-2007	China	x		Energy Intensity	4	x		x			
Li et al.	2014	2007-2010	China	x		Energy	5	x		x			
Kanitkar et al.	2015	1971-2010	Developing Countries	x		Energy	3					x	
Lin and Liu	2015	1995-2012	China		x	CO_2	5					x	
Lu et al.	2016	1994-2012	China		x	CO_2	7					x	
Meng et al.	2016	2005-2012	China		x	Black Carbon	5					x	
Guan et al.	2016	2005-2010	China	x		Energy Intensity	3	x					x
Liu et al.	2016	2009-2050	China		x	Carbon	4					x	
Shi et al.	2017	1995-2009	China	x	x	Energy and CO_2	5	x			x		
Wei et al.	2017	2000-2010	China		x	CO_2	4	x			x		
Zhao et al.	2017	2005-2012	China		x	CO_2	5					x	
Zhu et al.	2017	1997-2012	China		x	CO_2	8	x			x		
Hong et al.	2017	1990-2012	China	x		Embodied Energy	5	x					x
Jiao et al.	2017	1997-2012	China		x	SO_2	4	x			x		
Li and Jiang	2017	2005-2013	China		x	CO_2	7					x	
Lin et al.	2017	1995-2009	China	x		Embodied Energy	5	x			x		
Liu and Wang	2017	2007-2010	China		x	SO_2 and Chemical Oxygen		x			x		
Lu et al.	2018	2007-2015	China	x		Energy	5					x	
Wang and Feng	2018	2000-2014	China		x	CO_2	7					x	
Yang et al.	2018	1996-2015	China		x	CO_2	6					x	
Jiang et al.	2018	2000-2014	China		x	CO_2	4					x	
Li et al.	2018	2005-2012	China		x	CO_2	5	x			x		
Tian et al.	2019	2002-2012	China		x	CO_2	6	x			x		
Zhang et al.	2019	2002-2012	China		x	CO_2	4	x			x		
Zhang et al.	2019	2007-2012	China	x	x	Energy and CO_2	5		x	x			
Leal et al.	2019	1990-2015	Australia		x	GHG	4					x	
Chen et al.	2019a	2007-2012	China		x	CO_2	3	x		x			
Fan et al.	2019a	2008-2015	China		x	CO_2	5					x	
Chen et al.	2019b	1995-2009	China and the USA		x	CO_2	5	x			x		
Fan et al.	2019b	1997-2012	China		x	CO_2	4	x			x		

Table 2.3: Factor Composition of SDA Literature

Factors	Description	Articles
Carbonization effect		(Chen, Shen, et al., 2019; Chen, Shi, et al., 2019; Fan, Cao, Zhang, Wang, et al., 2019; Jiang, Zhou, & Li, 2018; Liu, Hao, et al., 2016; Shi et al., 2017; Zhang, Li, Zhang, Tian, & Shi, 2019)
Energy intensity effect		(Chen, Shen, et al., 2019; Chen, Shi, et al., 2019; Das & Paul, 2014; Fan, Cao, Zhang, Liu, et al., 2019; Fernández González, Landajo, & Presno, 2013; Jiang et al., 2018; Kahrl, Roland-Holst, & Zilberman, 2013; Li & Jiang, 2017; Lin & Liu, 2015a; Liu, Hao, et al., 2016; Liu & Lei, 2018; Liu, Tu, & Chen, 2009; Lu, Cui, & Li, 2016, 2018; Meng et al., 2016; Murtishaw, Schipper, Unander, Karbuz, & Khrushch, 2001; Shi et al., 2017; Wang & Feng, 2018; Yang, Yang, Zhang, & Tang, 2018)
Production structure effect		(Chen, Shen, et al., 2019; Chen, Shi, et al., 2019; Fernández González et al., 2013; Hong, Li, et al., 2017; Li, Zhou, et al., 2018; Lin & Liu, 2015a; Liu, Hao, et al., 2016; Lu et al., 2018; Shi et al., 2017; Tian, Bai, Jia, Liu, & Shi, 2019; Zhang, Li, Zhang, et al., 2019)
Final demand and final demand structure		(Chen, Shi, et al., 2019; Fan, Cao, Zhang, Wang, et al., 2019; Hong, Li, et al., 2017; Li, Zhou, et al., 2018; Liu & Wang, 2017; Lu et al., 2018; Shi et al., 2017; Tian et al., 2019; Zhang, Li, Ma, Chong, & Ni, 2019; Zhu, Liu, Tian, Wang, & Zhang, 2017)
Final demand ratio effect		(Chen, Shi, et al., 2019; Shi et al., 2017)
Leontief effect (input and output effect)		(Guan, Jiang, & Zhang, 2016; Liu & Lei, 2018; Liu & Wang, 2017)
Final consumption expenditure		(Das & Paul, 2014; Fan, Cao, Zhang, Liu, et al., 2019; Fernández González et al., 2013; Lu et al., 2016)
Per capital on GDP (economic structure)		(Das & Paul, 2014; Fan, Cao, Zhang, Liu, et al., 2019; Fan, Cao, Zhang, Wang, et al., 2019; Kahrl et al., 2013; Kanitkar, Banerjee, & Jayaraman, 2015; Leal et al., 2019; Li, Song, & Liu, 2014; Li & Jiang, 2017; Lin & Liu, 2015a; Liu & Lei, 2018; Liu et al., 2011; Meng et al., 2016; Minx et al., 2011; Wei et al., 2017; Zhao, Zhao, & Wang, 2017)
Industrial or sectoral structure effect		(Fan, Cao, Zhang, Liu, et al., 2019; Kanitkar et al., 2015; Li, Zhou, et al., 2018; Li & Jiang, 2017; Liu, Hao, et al., 2016; Liu et al., 2011; Meng et al., 2016; Wang & Feng, 2018)
Population effect		(Fan, Cao, Zhang, Liu, et al., 2019; Fan, Cao, Zhang, Wang, et al., 2019; Geng et al., 2013; Guan et al., 2016; Leal et al., 2019; Li, Zhou, et al., 2018; Liu et al., 2011; Meng et al., 2016; Zhao et al., 2017)
Urban household consumption and urbanization		(Geng et al., 2013; Lin, Fan, Xu, & Sun, 2017a; Liu & Lei, 2018; Lu et al., 2018; Minx et al., 2011; Peters et al., 2007; Zhu et al., 2017)
Fixed capital investment and per capital on consumption		(Geng et al., 2013; Mai, Chan, & Zhan, 2019; Zhang, Li, Zhang, et al., 2019; Zhang, Li, Ma, et al., 2019; Zhu et al., 2017)
Energy structure effect		(Geng et al., 2013; Hong, Li, et al., 2017; Jiang et al., 2018; Leal et al., 2019; Li & Jiang, 2017; Lin & Liu, 2015a; Lin et al., 2017a; Liu et al., 2011; Liu et al., 2009; Lu et al., 2016; Meng et al., 2016; Murtishaw et al., 2001; Peters et al., 2007; Wang & Feng, 2018; Zhao et al., 2017)
Technology and efficiency effect		(Akpan et al., 2015; Gerilla et al., 2005; Jiang et al., 2018; Jiao, Han, Li, Bai, & Yu, 2017; Kahrl et al., 2013; Lin et al., 2017a; Liu & Wang, 2017; Lu et al., 2016; Peters et al., 2007; Wang & Feng, 2018; Wei et al., 2017; Yang, Yang, et al., 2018; Zhang, Li, Ma, et al., 2019; Zhao et al., 2017)
Emission structure and intensity (direct and indirect)		(Gerilla et al., 2005; Jiao et al., 2017; Leal et al., 2019; Li & Jiang, 2017; Lin & Liu, 2015a; Liu & Wang, 2017; Zhao et al., 2017)
Others	Apart from the above-listed drivers/factors that were researched in the articles, the listed factors/drivers below are some others that were included in the decomposition analysis of the energy and GHG emissions within the scope of the review: Trade, resources, material, labour,	(Geng et al., 2013; Gerilla et al., 2005; Hong, Li, et al., 2017; Jiao et al., 2017; Kahrl et al., 2013; Kanitkar et al., 2015; Li et al., 2014; Li & Jiang, 2017; Lin & Liu, 2015a; Lin et al., 2017a; Liu & Wang, 2017; Minx et al., 2011; Murtishaw et al., 2001; Peters et al., 2007; Tian et al., 2019; Wang & Feng, 2018; Wei et al., 2017; Yang, Yang, et al., 2018; Zhang, Li, Zhang, et al., 2019; Zhang, Li, Ma, et al., 2019; Zhu et al., 2017)

	International trade, exports, imports, activity effect, investment (foreign and domestic), government expenditure, utility mix, fuel mix	

2.7.3 Driving Forces of CO_2 Emissions in the Construction Industry

After a careful review of literature and previous studies in the carbon emissions driving forces in China's construction sector, one of the main gaps identified is the choice of factors investigated. In addition, a few studies were concerned with only the first-degree decomposition of the factors. The decomposition model and methods adopted are likewise very important to the study and informed the choice of factors examined in the research. Therefore, the study decomposed four (4) factors namely: Final Demand Effects, Final Demand Structure Effects, Leontief Inverse Effects, and Direct Carbon Emission Intensity Effects. These factors were carefully selected to fill a gap in literature to showcase a different dimension to factor classifications in the Chinese construction sector's carbon emission studies.

Final demand is a combinatory effect of five different constructs (Miller & Blair, 2009). It comprises of effects based on exports, government consumption, urban household consumption, rural consumption, and total capital formation of the entire economic structure of China (Fan, Cao, Zhang, Wang, et al., 2019). The effect represents the changes caused by these five economic constructs on carbon emissions in China's construction industry within the time investigated. Basically, the effect measures the change in national demand and supply outlook of the construction sector and the various sectors comprised in the economy. The mathematical structure of the final demand effect is presented in the methodology chapter of the thesis.

On the other hand, the final demand structure effect considers the multiplicative effects of the final use of the industry's demand on other sectors of the economy. This structural effect is specific to products of the sector being investigated (construction sector in this case). The effect considers the products of the construction sector in comparison with the resultant potential to change carbon emissions in the destination or eventual sector. Unlike the final demand effect whose focus is on five-dimensional change monitoring, the final demand structure is focused on treating the individual change caused by the sector's product on each sectoral carbon emission.

Direct carbon emission intensity effect measures behavioral pattern changes on carbon emissions generation in the national economic structure (Miller & Doh, 2015). The change effect shows how responsive the human factor of the economy is based on the measure of direct energy consumption in relation to the eventual carbon exchange within the investigated period (Miller & Blair, 2009). Of the four factors measured in the study, the direct carbon emission intensity is more people and behavioral oriented than others. It's a measure of social changes, social impulses, and adaptation to climate change policies by government and the industry regulators.

The Leontief structure change is purely an economical monitoring change effect. It measures the interactions because of trade between various sectors, provinces, and regions within an economic spectrum (Miller & Blair, 2009). It stems from the Leontief inverse which results from the measure of the economy's A matrix or intersection matrix. The change effect reflects the substitutions made because of relative price changes and fluctuations, material substitutions based on functionality, availability, or legislation (Miller & Doh, 2015). The effect also measures the change caused by technological advancements and economies of scale.

2.8 Structural Path Analysis

Over the years, the Input-output analysis raised concerns about the need to probe intersectoral relationships. These intrinsic and hidden relationships exist between different sectors in and out of many regions of an economy (Defourny & Thorbecke, 1984). These further network analysis probes led to the structural path analysis (SPA). Sonis and Hewings (1998) defined the SPA as a primary technique used in extracting essential nodes and routes along a production chain of an economic structure. Wood and Lenzen (2003) described the SPA as the use of series to extend Leontief's inverse in the I.O. analysis. This study considered SPA as an alternative analysis tool to SDA.

Lantner (1974) first proposed the SPA with its basics and formulation on the I.O. analysis. Crama, Defourny, and Gazon (1984) rearranged the proposed SPA models by generalizing and defining them to the modern applications of the technique. Since adoption, the SPA has been used in analyzing the critical and hidden paths of economic networks and, in recent years, has been extended to environmental and energy studies (Li, Su, & Dasgupta, 2018).

SPA techniques have become an essential method in production and supply chain studies. According to Xie, Zhao, and Chen (2020), SPA methods are used in supply chain and production studies to investigate the path relationship and transfer influence of different factors in the process. Xie et al. (2020) described the SPA as a technology based on consumer accounts. SPA is used to analyze and measure the individual path's contribution rate by breaking analysis indicators into the sum of many production chains called paths (Li, Su, et al., 2018). The use of SPA in network studies varies from one field to the other. SPA technique is basically used for analyzing paths of different influencing factors in the energy environment, while it is used in describing complex economic structures in economics.

However, many researchers allured that the SPA aggregates sector by extracting inter-industry relationships to explain industries on different paths and the defining roles of each sector (Aroche-

Reyes, 2003; Sonis & Hewings, 1998). The identification of varying production chains, significant upstream effects of organizations, and product hierarchy can be decomposed using the SPA method (Xie et al., 2020). Yang, Dong, Xiu, Dai, and Chou (2015) averred SPA as a technique based on environmentally extended input-output analysis (EEIOA), helpful in measuring environmental-economic system significant flows and hidden paths. The SPA possesses an advantage in displaying significantly intricate sectoral inter-relationships along the production chain. SPA in national environmental impacts analysis has proven to be of grave importance. It has aided substantially in policies formulated to mitigate climatic and ecological implications from an economic approach.

2.8.1 Application of Structural Path Analysis

The technique was further developed from the introduction of SPA by Lantner 1974 (Lantner, 1974). The recent development saw the adoption of the SPA in different fields and contexts other than the use in economic network analysis. Defourny and Thorbecke (1984) integrated the SPA with the SAM for financial network analysis. Li, Su, et al. (2018) noted that the early introduction of the SPA in studying environmental and energy problems focused on applying the technique transmission stages/layers. The transmission layers application explicitly investigated the backward and forward transmission linkages (Li, Su, et al., 2018). Also, Wang, Du, Wang, Liang, and Xu (2019) studied the flow of natural resources in China’s economy, from raw material mining to final production.

On the other hand, introducing the SPA methods to I-O has received more extensive attention with the integration of the SRIO. The wide acceptance and adoption of the SPA with the SRIO models are often related to the data requirement, data availability, and reduced computational resource requirements. Moreover, Yang et al. (2015) opined that the SRIO models are more used because although incurred transactions might transcend the boundaries, inter-industrial transactions could be assumed as happening within a region or country (as the case may be). However, recent studies have started using SPA with MRIO models because of the possibility of simultaneously considering the global production chain and calculating detailed importation emissions originating from final domestic use.

Hong et al. (2016) adopted the SPA technique integrating with the MRIO model to investigate the hidden critical paths in the Chinese construction industry’s energy consumption supply chain. Hong et al. (2016) discovered that on-site construction activities (the 0^{th} layer) coupled with direct energy input (the 1st layer) contributed to 50% energy consumption in the construction industry. The first two layers were found significant in analyzing the industry's energy intensity as they comprised more than 50% of information on the entire SPA path. Hong et al. (2016) opined that other sectors such as metal smelting, rolling processing, and non-metallic industries greatly impacted the construction industry’s energy intensity. Qu, Meng, Sun, and Zhang (2017) and Zhang, Guan, Wu, and Zhao (2018) corroborated the results of Hong et al. (2016), where the construction, service, and manufacturing industries were found to have great significance on the embodied energy consumption in China.

The SPA methodology used by Hong et al. (2018a) was adopted in proposing a computer module and data source framework to explain embodied energy indicators at different computing technologies and geographical features. Hong et al. (2018a) depicted the construction industry's embodied energy in China. The total energy consumption was primarily occupied on the higher layer by energy production and services in the upstream sector. Zhang, Guan, et al. (2018)

discovered that construction, manufacturing, power, thermal, and service industries have higher impacts on energy consumption in China using the SPA method. According to their findings, these sectors alone contribute almost a quarter of China's embodied energy supply. The study suggested that a better analysis of the downstream industries using the SPA will help make more informed energy policies (Zhang, Guan, et al., 2018). The SPA method was adopted to study significant paths in the fishery transmission business in Alaska (Seung, 2016). Presented in Table 2.4 are some of the SPA’s notable publications.

2.8.2 Structural Path Analysis Studies in the Construction Industry

SPA was first adopted in economics for analyzing intricate intersectoral economic interactions. Since its wide adoption in economic studies, the SPA has been taken by other researchers across various fields to study complex network relationships. One such area is construction-related studies. One of the famous studies in the construction industry using the SPA was (Treloar, 1997). In the research, process analysis was combined with the SPA to determine significant paths in the embodied energy of the residential construction industry. The study showed that the 1st and 2nd layers substantially impact the embodied energy consumption in the sector (Xie et al., 2020).

Hong et al. (2016) is another study made in the construction industry using the SPA technique. The study investigated the construction industry’s embodied energy in the supply chain of the upstream sector. In the study, the influential contribution of the construction sector to the overall energy consumption profile of the Chinese economy was established. Hong et al. (2018a) furthered the discussion on the construction sector’s contributions to China’s energy consumption with a computational framework for determining the impact level of energy consumption in the industry. The study assumed the use of an MRIO approach against the SRIO model used in Treloar (1997) and Treloar, Love, and Holt (2001). Table 2.4 summarizes some of the notable SPA studies, describing the technique combined with the SPA and the country of research interest.

Table 2.4: Summary of SPA Related Literature

Source	**Technique Used**	**Focus**	**Country**
Sonis and Hewings (1998)	SPA and MRIO	Social accounting metrics	Indonesia
Llop and Ponce-Alifonso (2015)	SPA with extended SRIO framework	Water Use	Spain (Catalonia)
(Treloar, 1997; Treloar et al., 2001)	Combined SPA, process analysis, and SRIO	Building	Australia
(Lenzen, 2002, 2003; Lenzen & Murray, 2010)	LCA, SPA, process analysis, and SRIO	Energy consumption, emissions, Land disturbance, and water use	Australia
Mo, Zhang, Mihelcic, and Hokanson (2011)	Hybrid LCA, SRIO, and SPA	Water supply	USA (Florida and Michigan)
Mattila (2012)	Sensitivity analysis, SRIO, and LCA	Ecological footprints	Finland
Butnar, Gallego, Llop, and Castells (2011)	SPA and SRIO	Pollution study	Spain
Huang, Lenzen, Weber, Murray, and Matthews (2009)	SRIO and SPA for complete upstream	Carbon footprint	Australia and the USA
(Peters & Hertwich, 2006a, 2006b)	MRIO based SPA	Embodied carbon emissions	Norway
Skelton, Guan, Peters, and Crawford-Brown (2011)	MRIO based SPA	CO_2 emissions	Global study
Hong et al. (2016) Hong et al. (2018a)	MRIO based SPA	The construction industry embodied energy	China
Liang, Qu, and Xu (2016)	MRIO based SPA	Extraction of supply chain transmission centers	China
Wilting and van Oorschot (2017)	MRIO based SPA	Biodiversity path	Netherlands
Yang et al. (2015)	MRIO based SPA	Fossil fuel-based CO_2 emissions	China
Peng, Xie, and Lai (2018)	MRIO based SPA	Carbon emissions in the steel industry	China
Owen, Wood, Barrett, and Evans (2016)	MRIO based SPA	Embodied carbon emission paths	Global study
Wang, Cui, and Peng (2018)	I.O. and SPA	Carbon emissions in the supply chain	China
Li, Su, et al. (2018)	SRIO and SPA	Carbon emission path	India
Shao et al. (2018)	MRIO based SPA	Carbon emissions	China
Yang, Zhang, Fan, Li, and Meng (2018)	SRIO based SPA	SO_2 emissions embodied path	China

2.9 Summary of Findings and Gap

From the literature review, the efforts and commitments made by China’s government to arrest the issues of climate change, most significantly, CO_2 emissions are commendable. They reflect significant differences in the last few decades. However, research has focused more on energy generating industries like petrochemicals and electricity sectors, with visual neglect of the construction industry described by the IPCC as one of the most CO_2 emitting sectors globally. Also, the omission of the downstream stages of the system boundary in CO_2 emissions studies was observed. The focus of many CO_2 emissions studies has been on the construction stages, with the downstream stage with over 28% global contribution to CO_2 stock overlooked.

In addition, the use of MRIO tables is uncommon in CO_2 emissions studies in China. The SRIO tables are primarily used in emission studies in China. The SRIO tables lack genuine intensity and regional aggregation and comparison data. However, MRIO tables enable regional comparison and inter-regional and inter-sectoral reliability analysis. Therefore, the study was formulated to cognizance the identified gaps and incorporate them into the research objectives.

2.10 Chapter Summary

The chapter described the literature review and document integration that formed the core of the research work. The nature of emissions in China and the Chinese construction industry’s contributions to the global GHG stock were also discussed. The chapter also discussed China’s efforts to combat emissions and achieve a global quest to fight climate change in the environment. The chapter also discussed the various methodologies used in GHGs emission studies and justified the choice of the methodology used in the study.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Introduction

The chapter describes the methodological approach employed in this study and situates the study within a philosophical research paradigm. The chapter shows the sequential and logical flow of the various methodologies and models to achieve the study's objectives. The methodology is divided into three parts following the research objectives, as described in Figure 3.1. The first part computes the direct CO_2 emissions in China’s construction sector using primary economic and environmental data. The second part describes China’s construction sector CO_2 emissions linkages within a domestic economy context and at the interprovincial economy level. The domestic linkages are CO_2 emissions interactions of a local construction sector with other economic sectors within the same province.

On the other hand, the interprovincial linkages are CO_2 emissions interactions of a provincial construction sector with economic sectors in other provinces in China, using an advanced and modified Hypothetical Extraction Method (HEM). The last part of the chapter gives a detailed account of the methods used to combine SDA, and LMDI II approaches to decompose the driving forces of CO_2 emissions linkages in China’s construction sectors at both provincial and regional levels. In summary, the three methodologies used in this study investigated the embodied CO_2 emissions of China’s construction sector in projects, provincial and national level aggregations.

3.2 Research Paradigm

The three dimensions to the philosophical views are the ontology, epistemology, and axiology. Ontology relates to the nature of reality and includes interpretation of what constitutes reality from the researcher's perspective. Saunders (2016) noted that there is no one fit all philosophical view for research questions, and none is better than the other. Ontology relates to the nature of reality and includes interpretation of what constitutes reality from the researcher's perspective. The second dimension, epistemology, refers to what constitutes acceptable knowledge in a field, and the final dimension, axiology, is concerned with the role of the researcher's values in the research process. Johannesson and Perjons (2014) averred research paradigm methodological, epistemological, and ontological concerns on research community’s commonly held assumptions and beliefs. The opinions and assumptions of the research community dictate the metal model and structure of a researcher’s field of study. There exist many research paradigms in the academic and research community, but interpretivism and positivism are the two most established.

3.2.1 Positivism

Positivism could be traced back as far back as the days of Plato. However, its formulation in natural science was accounted to the work of thinkers such as Laplace, Saint-Simon and Comte (Johannesson & Perjons, 2014). Positive experimentation, common sense, and experience are the basics for accepting knowledge in positivism. An attribute of a positivist researcher is the ability to distance himself or herself from the object being researched to achieve objectivity and value-free investigation.

3.2.2 Interpretivism

Max Weber was one of the foremost contributors to this research paradigm as a reaction to positivism. Human actions and intentions, according to interpretivism, are inherent in the social world and cannot be separated from the research community (Creswell, 2018). Interpretivists believe “researchers can only achieve a deep understanding of a social phenomenon by actively participating in that phenomenon together with the people who actually create it” (Johannesson &

Perjons, 2014). However, how engaging the researcher gets with the subject, one major fault of the interpretive research paradigm is its ability to produce subjective research outputs.

Other research paradigms include **pragmatism** - arises from consequences and actions rather than antecedents' conditions (Creswell, 2018) and focuses more on the research problems and questions than methods, and **realism** - This stems from the Platonic philosophy and holds that reality exists independently of the human minds and perceptions.

3.2.3 Research Paradigm Adopted for the Study

The study is basically empirical in nature, with no social interaction required of the researcher and the subject. The most suitable of the research paradigm for the study is **positivism**. However, "positivism is generally described to seem natural and commonsensical, but it fails to capture essential aspects of the social world, in particular, the subjective construction of social phenomena" (Johannesson & Perjons, 2014). However, to counter the criticism of the shortcomings of the chosen paradigm, improved positivism is adopted for the study called post-positivism. Postpositivist belief perceptions and observations are fallible, and research constructions are mostly imperfect. This paradigm was adopted as it allowed for triangulation and introduction of non-empirical approaches into the research process.

3.3 Direct CO_2 Emissions in China's Construction Sector

The study's first objective aims to quantify the CO_2 produced in China's construction sector from 1997 to 2015. The study adopted a hybrid quantification technique to achieve the aim of the objective. The hybrid method proposed was used by many researchers that have worked on energy and emissions accounting. Acquaye and Duffy (2010) adopted its use to quantify GHG emissions in Ireland. It was preferred above other techniques to eliminate the double-counting problem in quantification. Besides, the approach leverages the advantages and the disadvantages of both the conventional Input-Output quantification techniques and the product-based approaches, as discussed in the literature review chapter.

The flow chart in Figure 3.1 shows the steps to calculate the amount of direct CO_2 emissions in China's construction sector using the hybrid process. This approach thoroughly considered the embodied emissions generated by the construction sector, focusing more on CO_2 emissions originating directly from the operations on the construction sites during construction and pre-construction phases.

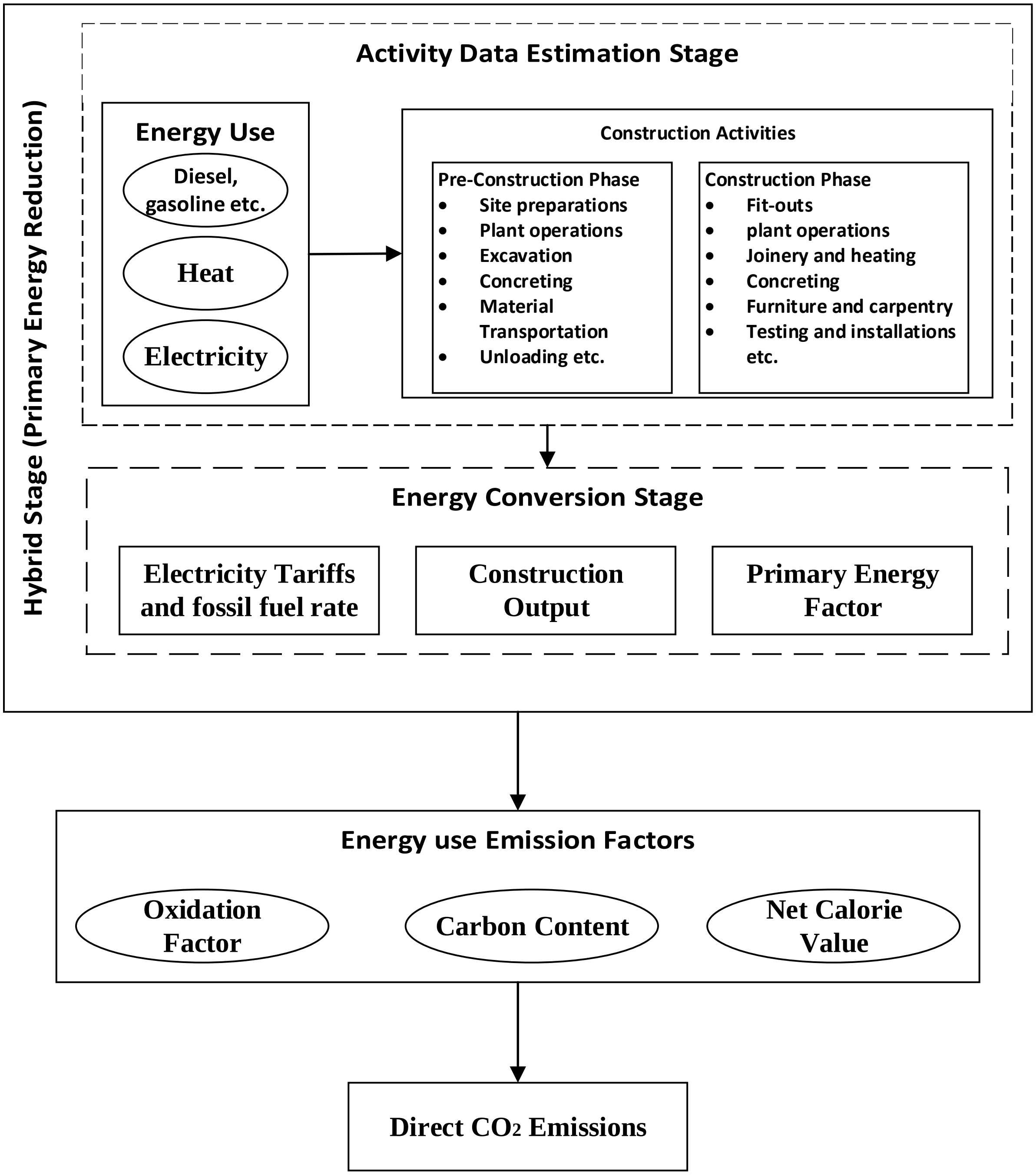

Figure 3.1: Flow Chart for Direct CO_2 Emissions Quantification

3.3.1 Scope of Quantification and Datasets

In the construction sector, emissions are classified as direct and indirect emissions. (Acquaye & Duffy, 2010; Hong 2016). Plant operations, fit-out, excavation, mixing, and concrete pacing are all sources of direct emissions on the construction site. In this study, emissions arising from fossil fuels utilized on the construction site were classified as direct emissions in addition to site operation-related emissions. Emissions from indirect sources are those that come from the economy's upstream sectors, which supply materials and other economic inputs for the construction industry. The study employed primary data from the Chinese Energy Yearbook of the National Bureau of Statistics (NBS) to aggregate energy (fossil fuel, electricity, and heat) consumption data for construction-related activities. The data includes the amount of various fuels consumed on building sites in China, both nationally and regionally, as well as the tariff charged per unit of each fossil fuel utilized and the emission factors for each fossil fuel. The study used the IPCC's well-established technique to emissions quantification, in which each fossil fuel's oxidation factors, carbon content, and net calorie values were used to generate the appropriate emission factor. The methodology quantified the sector's direct CO_2 emissions as well as other economic and tariff variables. When employing primary and secondary energy sources, combining the two ways helps minimize double counting.

3.3.2 Emission Factors

The quantification activity data in the GHG emissions calculation is the volume of fuel consumed. The fuel mix modifies the activity data to fit the model, whereas emission factors are important for determining the carbon content and oxygenation efficiency of each fuel type used. The net carbon content (expressed in tonnes of carbon per joule), net heating value (joules per tonne fuel), total carbon content (tonnes of carbon per tonne fuel), and oxidation rate are used to calculate emission factors (carbon oxidized per carbon content). Fuel consumption data (electricity and heat consumption included) by China's construction sector in direct site operations, emission factors for each fuel type, primary energy factors, and the sector's total yearly output were used in the quantification.

Between 1997 and 2015, 26 different types of fuel were used in the Chinese construction industry (Appendix Table A7). Due to the small quantity consumption of some fuels and the methodology used by Shan et al. (2018a), we merged some fuels to have 19 fossil fuels. Notably, 19 of the fuels are primary energy sources, such as coal, crude oil, and natural gas, whereas the remaining fuels are secondary fuels. Shan et al. (2018a) identified various energy agencies around the world publish fossil fuel emission factors for GHGs. As a result, the emission factors for 17 of the fuels used in this study were obtained from various sources. The IEA and IPCC inventory databases are two of the most well-known emission factor sources for GHGs. However, many countries have revised the original factors contained in the IEA and IPCC databases over the years to create country-specific emission factors. The study identified six sources of emission factors, some of which had multiple versions. We retrieved data from the Climate Transparency (2018) report for heat and electricity CO_2 emission factors specific to China. Table 3.1 presents the emission factors, the sources, and retrieved versions. The CO_2 emissions in the Chinese construction industry were calculated on a national level using this set of emission factors. However, in order to uniquely aggregate the study's direct CO_2 emissions in each sub-regional classification, the UN-average emission factor was chosen as described by Liu et al. (2015) to better represent Chinese improved emission technology.

Electricity emission factors are supplied by two bodies: UN-IPCC and IEA. According to the data obtained from the two agencies and the EFs published by Climate transparency (2018), the electricity EFs value was consistent in both, and no local-technology change was mentioned as a possible effect that could cause it to differ in different regions or countries around the world. In addition, unlike other energy sources, electricity and heat are non-primary energy sources. Thus, varying contents and compositions resulting from means of extraction, component analysis difference, and geographical influences are not applicable. For example, crude content in Nigeria is slightly different from crude extracted in USA based on different geographical reasons and constituents' compositional analysis. However, a kilowatt of electricity is the same everywhere notwithstanding the source or eventual consumption location. With that in mind, the study assumed that electricity EFs are the same regardless of country. Therefore, a consistent value of 0.623600 tCO_2/GJ was used for electricity and heat EFs in the study.

Table 3.1 Emission factors for fuels specific to China's construction industry

	Sector-Fuel	**Unit**	**IPCC**	**NBS**	**NDRC-tier 1**	**NDRC-Tier 2**	**NDRC-Tier 3**	**NC 1994**	**NC 2005 tier 1**	**NC 2005 Tier 2**	**NC 2005 Tier3**	**MEIC**	**UN-China**	**UN average**
1	Raw Coal	tCO_2/GJ	0.713009	0.518263	0.518263	0.512957	0.512957	0.456565	0.519570	0.532320	0.532320	0.491710	0.539426	0.755940
2	Cleaned Coal	tCO_2/GJ	0.701249	0.656013	0.577971	0.591437	0.577971	0.580206	0.581132	0.589772	0.592755	0.679613	0.560334	0.785240
3	Other Washed Coal	tCO_2/GJ	0.701249	0.383313	0.577971	0.597797	0.577971	0.452007	0.581132	0.589772	0.592755	0.397103	0.560334	0.785240
4	Briquettes	tCO_2/GJ	0.652327	0.537510	0.527362	0.551457	0.527362	0.435562	0.527362	0.527990	0.527362	0.459095	0.539426	0.755940
5	Coke	tCO_2/GJ	0.806971	0.777999	0.777999	0.754949	0.777999	0.814669	0.738059	0.776062	0.761021	0.725802	0.770203	0.770203
6	Coke Oven Gas	tCO_2/m^6	2.252052	2.192480	2.333106	2.191706	2.333106	3.228984	2.405264	2.405264	2.405264	2.536039	2.274800	2.274800
7	Other Gas	tCO_2/m^6	2.252052	1.018055	1.903300	1.884074	1.903300	1.009710	1.903300	1.903300	1.903300	0.792531	2.274800	2.274800
8	Other Coking Products	tCO_2/GJ	1.098306	0.780114	0.780114	0.822056	0.780114	0.711614	0.528891	0.776062	0.761021	0.832443	1.109400	1.109400
9	Crude Oil	tCO_2/GJ	0.837540	0.822872	0.838693	0.796696	0.838693	0.820613	0.838693	0.837838	0.837838	0.832443	0.846000	0.846000
10	Gasoline	tCO_2/GJ	0.831330	0.798743	0.829786	0.829786	0.829786	0.829786	0.829786	0.829786	0.829786	0.857407	0.848591	0.848591
11	Kerosene	tCO_2/GJ	0.845559	0.828326	0.859558	0.859558	0.859558	0.859558	0.859558	0.859558	0.859558	0.857407	0.842388	0.842388
12	Diesel Oil	tCO_2/GJ	0.859914	0.844339	0.857761	0.857761	0.857761	0.886861	0.857761	0.858235	0.859511	0.849085	0.858419	0.858419
13	Fuel Oil	tCO_2/GJ	0.843916	0.864671	0.831049	0.831049	0.831049	0.831049	0.831049	0.834893	0.835289	0.832443	0.852440	0.852440
14	LPG	tCO_2/GJ	0.805424	0.854448	0.805595	0.797457	0.805595	0.805595	0.805595	0.804781	0.804781	0.998927	0.783288	0.783288
15	Refinery Gas	tCO_2/m^6	0.769379	0.829819	0.829729	0.821348	0.829729	0.624673	0.829729	0.828891	0.828891	0.916830	0.657453	0.657453
16	Other Petroleum Products	tCO_2/GJ	0.792000	0.819594	0.883960	0.883960	0.883960	0.787724	0.883960	0.883960	0.883960	0.832443	0.849920	0.849920
17	Natural Gas	tCO_2/GJ	0.521057	0.590459	0.590459	0.583731	0.590459	0.590733	0.590459	0.590459	0.590459	0.590282	0.526320	0.526320
21	Electricity and Heat	tCO_2/GJ	0.623600	0.623600	0.623600	0.623600	0.623600	0.623600	0.623600	0.623600	0.623600	0.623600	0.623600	0.623600

3.3.3 Direct CO_2 Emissions Calculation

The total direct CO_2 emissions include the sum of CO_2 emissions from each fossil fuel used in China's onsite construction activities. These direct emissions are calculated using primary energy data from the National Statistics Office's Chinese Energy Yearbook. The data includes the industrial output of each Chinese province, aggregated into regional divisions. The output data includes both building and civil engineering work completed in the construction industry in a single year. Energy tariffs were obtained from the Census and Economic Information Center (CEIC) global database, which showed the average energy rates over 170-198 observations between 2003 and 2019 (CEIC, 2021). The mathematical model used to calculate direct CO_2 emissions is shown in Equation (3.1).

The model adopted the method used in Acquaye and Duffy (2010) to quantify the GHGs emissions in the Irish construction industry. Some other studies (Kang, Zhao, Ren, & Lin, 2012; Shi & Zhao, 2016) used the IPCC guidelines for quantifying direct CO_2 emissions without considering specific technological peculiarities in China. The approach by Acquaye and Duffy (2010) is preferred because of its comprehensibility, as it is an improvement on the standard direct CO_2 emissions by the IPCC guidelines. The methodology considers many economic factors such as energy tariffs, delivered energy on construction sites, and energy consumption aggregated directly on construction sites. An advantage of this approach is that it eliminates total reliance on activity data of energy consumption with no consideration and adjustments for double counting. However, the methodology's reliance on quantifying CO_2 emissions using economic factors could be problematic when such data are not published regularly. Also, the integrity of published economic data could skew results with reduced chances of validation requirement. Notwithstanding, the methodology presents a robust and comprehensive approach to quantifying direct CO_2 emissions, considering other economic and environmental construction industry factors. With the improved method, direct integration could be made in overall direct and indirect CO_2 emissions quantification with better data reliability.

Primary energy factors were used to convert the direct energy consumed with the energy tariffs and fuel-specific emission factors. The primary energy factors are the primary energy ratio supplied to the delivered energy. The primary energy factors employed in the study are presented in Table 3.2.

$$\boldsymbol{E_d} = \left[\frac{\boldsymbol{Q}_{(\boldsymbol{e},\boldsymbol{i})} \times \boldsymbol{T}_{(\boldsymbol{e},\boldsymbol{i})} \times \boldsymbol{P}_{(\boldsymbol{e},\boldsymbol{i})}}{\boldsymbol{C}}\right] \times \sum_{\boldsymbol{k}}^{\boldsymbol{CO_2}} \boldsymbol{F}_{(\boldsymbol{e},\boldsymbol{i})} \tag{3.1}$$

Where: E_d – direct CO_2 emissions ($MtCO_2$); Q – Quantity of energy (fossil fuel and electricity) consumed; T – Average energy tariff measured in RMB per unit of energy consumed; P – Primary Energy Factor; F – CO_2 Emission Factors estimated in tCO_2/GJ for electricity and fossil fuels and tCO_2/m^6 for gases; e – electricity and heat; i – other energy consumed (fossil fuels) and C – Sum of construction sector output measured in monetary values (RMB).

Table 3.2 Primary energy factors (Acquaye & Duffy, 2010; Climate Transparency, 2018)

Countries	Mains gas	LPG	Oil - general	Diesel or heating oil	Fuel oil	Coal - general	Biomass - general	Wood - general	Wood pellets	Grid Electricity	Heating - general
EU countries in average	1.00- 1.26	1.00- 1.20	1.00-1.23	1.00- 1.14	1.00-1.20	1.00-1.46	0.01-1.10	0.01-1.20	0.01-1.26	1.5- 3.45	0.15- 1.50
IEA (nonrenewable) defaults	1.1	1.1	1.1	1.1	1.1	1.1	0.2	0.2	0.2	2.3	1.3
China	1.1	1.1	1.1	1.1	1.1	1.1	0.2	0.2	0.2	2.93	1.3

3.4 Development of Hybrid Economic-Environmental CO_2 Emissions MRIO Tables

Table 3.3 illustrates the hybrid MRIO table combining China’s national economic data and the CO_2 emissions of each economic sector.

Table 3.3 Extended CO_2 Emissions Multi-Regional Input-Output Table

Output/Input			**Intermediate Outputs**													**Final Demands**							**CO_2 Emissions**	
			…	p					q					…	Total	…	p	…	q	…	Total	Total Output	Amount	Intensity
			…	1	…	j	…	n	1	…	l	…	m	…		…		…		…				
Intermediate Inputs	⋮	⋮																						
	r	1																						
		⋮																						
		i				$\boldsymbol{U_{ij}^{rp}}$					$\boldsymbol{U_{il}^{rq}}$				$\boldsymbol{U_i^r}$		$\boldsymbol{f_i^{rp}}$		$\boldsymbol{f_i^{rq}}$		$\boldsymbol{F_i^r}$	$\boldsymbol{T_i^r}$	$\boldsymbol{C_i^r}$	$\boldsymbol{e_i^r}$
		⋮																						
		n																						
	⋮	⋮																						
	s	1																						
		⋮																						
		k				$\boldsymbol{U_{kj}^{sp}}$					$\boldsymbol{U_{kl}^{sq}}$				$\boldsymbol{U_k^s}$		$\boldsymbol{f_k^{sp}}$		$\boldsymbol{f_k^{sq}}$		$\boldsymbol{F_k^s}$	$\boldsymbol{T_k^s}$	$\boldsymbol{C_k^s}$	$\boldsymbol{e_k^s}$
		⋮																						
		m																						
	⋮	⋮																						
	Total					$\boldsymbol{U_j^p}$					$\boldsymbol{U_l^q}$													
Total Value Added						$\boldsymbol{V_j^p}$					$\boldsymbol{V_l^q}$													
Total Input							$\boldsymbol{T_j^p}$				$\boldsymbol{T_l^q}$													

T_i^r is the sector *i* output in region r

u_{ij}^{rk} is the inter-industrial coefficient of sector *i* in region r for sector j in region k

The model illustrated in Table 3.3 follows the conventional MRIO model, which can be expressed in matrix form as:

$$T = TO + F = (I - U)^{-1}F \tag{3.2}$$

The whole economy matrix establishment can be written as follow:

$$T = \begin{bmatrix} \begin{pmatrix} T_1^1 \\ \cdots \\ T_n^1 \end{pmatrix} \\ \cdots \\ \begin{pmatrix} T_1^m \\ \cdots \\ T_n^m \end{pmatrix} \end{bmatrix}, \quad U = \begin{bmatrix} \begin{pmatrix} u_{11}^{11} & \cdots & u_{1n}^{11} \\ \cdots & \cdots & \cdots \\ u_{n1}^{11} & \cdots & u_{nn}^{11} \end{pmatrix} & \cdots & \begin{pmatrix} u_{11}^{1m} & \cdots & u_{1n}^{1m} \\ \cdots & \cdots & \cdots \\ u_{n1}^{1m} & \cdots & u_{nn}^{1m} \end{pmatrix} \\ \cdots & \cdots & \cdots \\ \begin{pmatrix} u_{11}^{m1} & \cdots & u_{1n}^{m1} \\ \cdots & \cdots & \cdots \\ u_{n1}^{m1} & \cdots & u_{nm}^{m1} \end{pmatrix} & \cdots & \begin{pmatrix} u_{11}^{mm} & \cdots & u_{1n}^{mm} \\ \cdots & \cdots & \cdots \\ u_{n1}^{mm} & \cdots & u_{nn}^{mm} \end{pmatrix} \end{bmatrix}, \quad F = \begin{bmatrix} \begin{pmatrix} F_1^1 \\ \cdots \\ F_n^1 \end{pmatrix} \\ \cdots \\ \begin{pmatrix} F_1^m \\ \cdots \\ F_n^m \end{pmatrix} \end{bmatrix}$$

Where: *i* is the sector (construction sector); T is the Total Output of the Sector; r, q, p, s is the region/province; *u* is the sectoral technical coefficient, and F is the Final Demand of the sector. The final demand usually includes the final demand categories of the I-O tables (the final use), which include government expenditure, exports, capital formations, and stock increase – all defined on the input-output tables of China. The sum of all the final demand categories results in the final demand used in the study.

3.4.1 Total and Direct CO_2 Emission Intensities

The blocks' total and direct CO_2 emissions were calculated using the Multi-Regional Extended Input-Output (MRE-IO) table in Table 3.3. The direct CO_2 emission intensities of each block are calculated as a ratio of total sectoral CO_2 emissions and total sectoral output:

$$e_i^r = \frac{C_i^r}{T_i^r}, i = 1,2,\ldots,n \tag{3.3}$$

Where e_i^r is the direct emission intensity for region i in country r. C_i^r is the total CO$_2$ emission of sector i in country r. T_i^r is the total output of block i in country r. r represents a region in the national economic data, and i is the region of r. The total CO$_2$ emission intensities of the blocks, q_i^r indicating the CO$_2$ emission intensities of the whole economic structure for each block are calculated by the multiplication of the Leontief inverse matrix by the direct CO$_2$ emission intensities, e_i^r, of the blocks.

$$q = e(I - A)^{-1} \tag{3.4}$$

Therefore, equation (3.5) expresses the total CO$_2$ emissions for each sector in terms of the Leontief inverse matrix:

$$C = eT = e(I - A)^{-1}F = HF \tag{3.5}$$

Where $H = e(I - A)^{-1}F$ is the matrix of both direct and indirect CO$_2$ sectoral emissions intensities of the MRE-IO economic model.

3.5 Determining the Critical Paths of CO$_2$ Emissions in China's Provincial Construction Sectors

Objective two aims to identify the hidden CO$_2$ emission paths in the supply chain of China's construction sector, both in sectoral and provincial linkages. A modified Hypothetical Extraction Method (HEM) was identified from the literature as a suitable method to use to achieve the set goal effectively. The HEM method expands the conventional I-O analysis, which can also be linked with the SDA method. For this study, a HEM analysis based on the MRIO analysis was used to identify China's construction sector's CO$_2$ emissions effects on domestic (intersectoral) and provincial paths. HEM uses basic assumptions in its formulation. The premise follows a principle of dividing the entire economic structure into two blocks based on sector similarities or, in rare cases, sectoral energy-use intensities. For this study, it was assumed that the economic form of the MRIO tables could be divided into two industrial blocks, namely, ‘c’ and ‘-c’ blocks. The ‘c’ block represents the construction industry, and the ‘-c’ block represents other industrial structures other than the construction industry. The following equations were used in expressing the critical path determination of the embodied CO_2 emissions from the construction sector in China.

3.5.1 HEM Analysis of Critical CO_2 Emission Paths of the Construction Industry

The section adopted the HEM methodology from Zhao et al. (2015). HEM foundation assumes the MRE-IO tables to be categorized into two blocks of similar energy use, consumption, or industrial types (Schultz, 1977). This section organised the entire Chinese economic structure into two blocks: Hc and H_{-c}. The categorization was made based on industrial types. Construction industries in the provinces were categorized into block $H_{c,}$ while other industrial types were classified into block H_{-c}. Therefore, equation (3.6) represents the matrix expression of the economic structure as:

$$\boldsymbol{H} = \begin{bmatrix} \boldsymbol{H}_{c,c} & \boldsymbol{H}_{c,-c} \\ \boldsymbol{H}_{-c,c} & \boldsymbol{H}_{-c,-c} \end{bmatrix} \tag{3.6}$$

With the modified economic structure in equation (3.6), we calculated the total CO_2 emissions linkages for the economic system as thus:

$$\begin{bmatrix} \boldsymbol{C}_{c} \\ \boldsymbol{C}_{-c} \end{bmatrix} = \begin{bmatrix} \boldsymbol{e}_{c} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{e}_{-c} \end{bmatrix} \begin{bmatrix} \boldsymbol{T}_{c} \\ \boldsymbol{T}_{-c} \end{bmatrix} = \begin{bmatrix} \boldsymbol{H}_{c,c} & \boldsymbol{H}_{c,-c} \\ \boldsymbol{H}_{-c,c} & \boldsymbol{H}_{-c,-c} \end{bmatrix} \begin{bmatrix} \boldsymbol{F}_{c} \\ \boldsymbol{F}_{-c} \end{bmatrix} \tag{3.7}$$

Expansively, following equation (3.5), the total CO_2 emissions can be expressed as:

$$\begin{bmatrix} \boldsymbol{C_c} \\ \boldsymbol{C_{-c}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{e_c} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{e_{-c}} \end{bmatrix} \left(\begin{bmatrix} \boldsymbol{A_{c,c}} & \boldsymbol{A_{c,-c}} \\ \boldsymbol{A_{-c,c}} & \boldsymbol{A_{-c,-c}} \end{bmatrix} \begin{bmatrix} \boldsymbol{T_c} \\ \boldsymbol{T_{-c}} \end{bmatrix} \right) + \begin{bmatrix} \boldsymbol{F_c} \\ \boldsymbol{F_{-c}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{e_c} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{e_{-c}} \end{bmatrix} \begin{bmatrix} \Delta_{\boldsymbol{c,c}} & \Delta_{\boldsymbol{c,-c}} \\ \Delta_{\boldsymbol{-c,c}} & \Delta_{\boldsymbol{-c,-c}} \end{bmatrix} \begin{bmatrix} \boldsymbol{F_c} \\ \boldsymbol{F_{-c}} \end{bmatrix} \quad (3.8)$$

Where $\begin{bmatrix} \Delta_{\boldsymbol{c,c}} & \Delta_{\boldsymbol{c,-c}} \\ \Delta_{\boldsymbol{-c,c}} & \Delta_{\boldsymbol{-c,-c}} \end{bmatrix}$ is the Leontief inverse matrix $(I - A)^{-1}$; $\begin{bmatrix} \boldsymbol{e_c} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{e_{-c}} \end{bmatrix}$ is the diagonal matrix of the direct CO_2 emission intensities; and $\begin{bmatrix} \boldsymbol{A_{c,c}} & \boldsymbol{A_{c,-c}} \\ \boldsymbol{A_{-c,c}} & \boldsymbol{A_{-c,-c}} \end{bmatrix}$ represent the technical coefficients matrix of direct consumption in the economic sectors.

3.5.2 Sectoral Extraction of CO2 Emissions Critical Paths

Following the model description of the HEM methodology in Cella (1984), an extracted sector i from the categorized block H_c is considered to be self-existing within the block i.e. it does not trade with other sectors in the same categorized block. The assumption implies that the direct technical coefficients of the intermediate consumption relationship are nonexistent (Zhang, Bian, & Tan, 2018); therefore, we set them to zero (0). Consequently, we expressed the total CO_2 emissions from the extracted economic system as:

$$\begin{bmatrix} \boldsymbol{C_c^*} \\ \boldsymbol{C_{-c}^*} \end{bmatrix} = \begin{bmatrix} \boldsymbol{e_c} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{e_{-c}} \end{bmatrix} \begin{bmatrix} \boldsymbol{T_c^*} \\ \boldsymbol{T_{-c}^*} \end{bmatrix} = \begin{bmatrix} \boldsymbol{e_c} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{e_{-c}} \end{bmatrix} \left(\begin{bmatrix} \boldsymbol{A_{c,c}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{A_{-c,-c}} \end{bmatrix} \begin{bmatrix} \boldsymbol{T_c^*} \\ \boldsymbol{T_{-c}^*} \end{bmatrix} + \begin{bmatrix} \boldsymbol{F_c} \\ \boldsymbol{F_{-c}} \end{bmatrix} \right) =$$

$$\begin{bmatrix} \boldsymbol{e_c} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{e_{-c}} \end{bmatrix} \begin{bmatrix} (\boldsymbol{I} - \boldsymbol{A_{c,c}})^{-1} & \boldsymbol{0} \\ \boldsymbol{0} & (\boldsymbol{I} - \boldsymbol{A_{-c,-c}})^{-1} \end{bmatrix} \begin{bmatrix} \boldsymbol{F_c} \\ \boldsymbol{F_{-c}} \end{bmatrix} \quad (3.9)$$

The total CO_2 emissions linkages, C* from equation (3.9), describe the hypothetical relationship between the extracted industrial sector (construction sector in this case) and other sectors within the categorized block, H_c, in which the final demand of the economy remains the same. The difference in the total CO_2 emissions of the unextracted and the extracted hypothetical block can be expressed as a difference between C and C^*:

$$\boldsymbol{C} - \boldsymbol{C}^* = \begin{bmatrix} \boldsymbol{C_c} - \boldsymbol{C_c^*} \\ \boldsymbol{C_{-c}} - \boldsymbol{C_{-c}^*} \end{bmatrix} \quad (3.10)$$

Combining both equations (3.8) and (3.9) in (3.10), we expressed the difference in total CO_2 emissions as:

$$\boldsymbol{C}-\boldsymbol{C}^{*}=\begin{bmatrix}\boldsymbol{e}_{\boldsymbol{c}} & \boldsymbol{0}\\ \boldsymbol{0} & \boldsymbol{e}_{-\boldsymbol{c}}\end{bmatrix}\begin{bmatrix}\Delta_{\boldsymbol{c},\boldsymbol{c}}-(\boldsymbol{I}-\boldsymbol{A}_{\boldsymbol{c},\boldsymbol{c}})^{-1} & \Delta_{\boldsymbol{c},-\boldsymbol{c}}\\ \Delta_{-\boldsymbol{c},\boldsymbol{c}} & \Delta_{-\boldsymbol{c},-\boldsymbol{c}}-(\boldsymbol{I}-\boldsymbol{A}_{-\boldsymbol{c},-\boldsymbol{c}})^{-1}\end{bmatrix}\begin{bmatrix}\boldsymbol{F}_{\boldsymbol{c}}\\ \boldsymbol{F}_{-\boldsymbol{c}}\end{bmatrix}$$

$$=\begin{bmatrix}\boldsymbol{e}_{\boldsymbol{c}}\left(\Delta_{\boldsymbol{c},\boldsymbol{c}}-(\boldsymbol{I}-\boldsymbol{A}_{\boldsymbol{c},\boldsymbol{c}})^{-1}\right) & \boldsymbol{e}_{\boldsymbol{c}}\,\Delta_{\boldsymbol{c},-\boldsymbol{c}}\\ \boldsymbol{e}_{-\boldsymbol{c}}\Delta_{-\boldsymbol{c},\boldsymbol{c}} & \boldsymbol{e}_{-\boldsymbol{c}}\left(\Delta_{-\boldsymbol{c},-\boldsymbol{c}}-(\boldsymbol{I}-\boldsymbol{A}_{-\boldsymbol{c},-\boldsymbol{c}})^{-1}\right)\end{bmatrix}\begin{bmatrix}\boldsymbol{F}_{\boldsymbol{c}}\\ \boldsymbol{F}_{-\boldsymbol{c}}\end{bmatrix}$$

$$=\begin{bmatrix}\boldsymbol{\delta}_{\boldsymbol{c},\boldsymbol{c}} & \boldsymbol{\delta}_{\boldsymbol{c},-\boldsymbol{c}}\\ \boldsymbol{\delta}_{-\boldsymbol{c},\boldsymbol{c}} & \boldsymbol{\delta}_{-\boldsymbol{c},-\boldsymbol{c}}\end{bmatrix}\begin{bmatrix}\boldsymbol{F}_{\boldsymbol{c}}\\ \boldsymbol{F}_{-\boldsymbol{c}}\end{bmatrix} \tag{3.11}$$

3.5.3 CO_2 Emissions Critical Paths of the Chinese Construction Sector

Equations (1) to (11) present the foundational methodological expressions for HEM analysis as presented in (Cella, 1984; Zhao et al., 2015). Duarte et al. (2002) further decomposed emission linkages into two components in a study of water usage in Spain using an input-output approach. The two decomposed components are the forward and the backward linkages. Duarte et al. (2002) proved that the addition of the two components must equal the total emission linkages. The approach followed the foundational concept of a vertically integrated sector of the hypothetical economy extraction method of Pasinetti (1977). This study focused on the critical paths of CO_2 emissions in the construction sector in China. Therefore, we analysed the emission linkages explicitly in both the forward and the backward directions in regional construction sectors in China. From this point forward, the construction sector of China represents the extracted sector 'c' in block H. The total CO_2 emission linkages, $\boldsymbol{TE}_{\boldsymbol{c}}^{\boldsymbol{c}}$, in the Chinese construction sector is expressed in equation (12), indicating the linkage influence of the industry in other regions within the national economy.

$$\boldsymbol{TE}_{\boldsymbol{c}}^{\boldsymbol{c}}=\boldsymbol{u}'(\boldsymbol{C}-\boldsymbol{C}^{*})=\boldsymbol{u}'\begin{bmatrix}\boldsymbol{\delta}_{\boldsymbol{c},\boldsymbol{c}} & \boldsymbol{\delta}_{\boldsymbol{c},-\boldsymbol{c}}\\ \boldsymbol{\delta}_{-\boldsymbol{c},\boldsymbol{c}} & \boldsymbol{\delta}_{-\boldsymbol{c},-\boldsymbol{c}}\end{bmatrix}\begin{bmatrix}\boldsymbol{F}_{\boldsymbol{c}}\\ \boldsymbol{F}_{-\boldsymbol{c}}\end{bmatrix}=\boldsymbol{u}'\begin{bmatrix}\boldsymbol{\delta}_{\boldsymbol{c},\boldsymbol{c}}\\ \boldsymbol{\delta}_{-\boldsymbol{c},\boldsymbol{c}}\end{bmatrix}\boldsymbol{F}_{\boldsymbol{c}}^{\boldsymbol{c}}+\boldsymbol{u}'\begin{bmatrix}\boldsymbol{\delta}_{\boldsymbol{c},-\boldsymbol{c}}\\ \boldsymbol{\delta}_{-\boldsymbol{c},-\boldsymbol{c}}\end{bmatrix}\boldsymbol{F}_{-\boldsymbol{c}} \tag{3.12}$$

Where $\boldsymbol{TE}_{\boldsymbol{c}}^{\boldsymbol{c}}$ represent the total CO_2 emissions linkages of the Chinese construction sector. $\boldsymbol{u'}$ is a unit vector $\boldsymbol{u'}$= **(1, …, 1)** with a dimension of the entire economic structure.

However, according to Duarte et al. (2002), the total linkage was decomposed into forward and backward effects, $\boldsymbol{FE_c^c}$**,** $\boldsymbol{BE_c^c}$**.** The forward effects are the transferred CO_2 emissions from block 'c' (construction sector) into other sectors in block '-c' (other sectors), to satisfy their intermediate products and final demand, and the backward effects are the transferred CO_2 emissions generated in producing intermediate production in the construction sector from other sectors in block '-c' of the entire economic structure (Zhang, Liu, et al., 2019). As expressed in equation (3.15), the sum of the two effects gives the total linkages from the sector.

$$\boldsymbol{BE_c^c = u'\begin{bmatrix}\delta_{c,c}\\ \delta_{-c,c}\end{bmatrix}F_c^c = u'\left(\delta_{c,c}\right)F_c^c + u'\left(\delta_{-c,c}\right)F_c^c} \tag{3.13}$$

$$\boldsymbol{FE_c^c = u'\begin{bmatrix}\delta_{c,c}\\ \delta_{-c,c}\end{bmatrix}F_{-c} = u'\left(\delta_{c,c}\right)F_{-c}^c + u'\left(\delta_{-c,c}\right)F_{-c}^c} \tag{3.14}$$

$$\boldsymbol{TE_c^c = BE_c^c + FE_c^c} \tag{3.15}$$

3.5.4 Modified HEM Decomposition of CO_2 Emissions Linkages

The forward and backwards effects are further decomposed to follow the (Duarte et al., 2002) approach, which modified HEM to divide the two-directional effects into four inter-directional components. The modified components are the net forward effects, the mixed forward effects, the net backward effects, and the mixed backward effects (Zhang, Bian, et al., 2018). Zhao et al. (2015) used the approach to decompose the directional impact of sectoral CO_2 emissions linkages in South Africa. This section uses the same method to decompose further the total CO_2 emissions linkages in the Chinese construction sector.

The mixed forward CO_2 emissions effects, $\boldsymbol{mFE_c^c}$ of the construction sector are the CO_2 emissions generated in the sector's products exported to other sectors of the national economic framework, which were used as intermediate inputs of the construction sector but sourced initially from other federal sectors. The net forward CO_2 emissions effects, $\boldsymbol{nFE_c^c}$, are CO_2 emissions embodied in the construction sector's products sold to satisfy the final demands of other sectors. The mixed backward effects, $\boldsymbol{mBE_c^c}$**,** are linkages of final demands of the construction sector produced by other national sectors from materials initially sourced from the construction sector. The net backward effects, $\boldsymbol{nBE_c^c}$**,** on the other hand, are CO_2 emissions embodied in products of other global sectors purchased by the construction sector, which do not return to the national economic structure again. Figure 3.2 illustrates the relationship and pictorial representation of this study's four CO_2 emissions linkages. In this section, we expressed the four decomposed effects in terms of CO_2 emission intensity in Equations (16) to (19) as:

$$\boldsymbol{mFE_c^c = u'\delta_{-c,-c}F_{-c}^c = u'e_{-c}^c\left[\Delta_{-c,-c} - \left(I - A_{-c,-c}\right)^{-1}\right]F_{-c}^c} \tag{16}$$

$$\boldsymbol{nFE_c^c = u'\delta_{c,-c}F_{-c}^c = u'\,e_{-c}^c\,\Delta_{c,-c}\,F_{-c}^c} \tag{17}$$

$$\boldsymbol{mBE_c^c = u'\delta_{c,c}F_c^c = u'e_c^c\left[\Delta_{c,c} - \left(I - A_{c,c}\right)^{-1}\right]F_c^c} \tag{18}$$

$$\boldsymbol{nBE_c^c = u'\delta_{-c,c}F_c^c = u'\,e_{-c}^c\,\Delta_{-c,c}\,F_c^c} \tag{19}$$

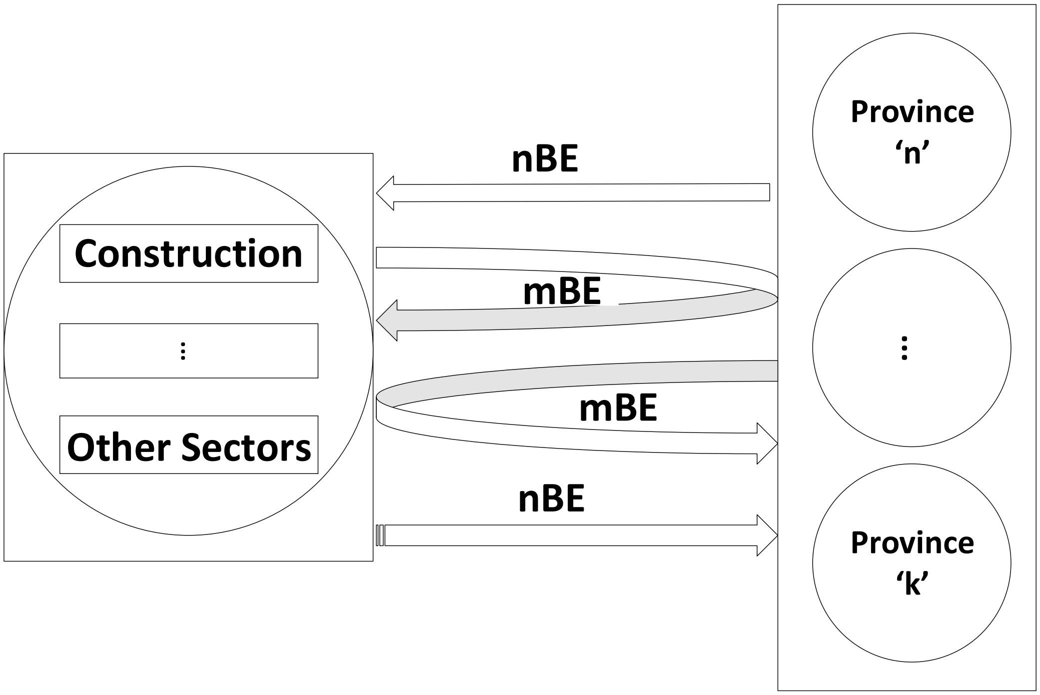

Figure 3.2 Conceptual Diagram of Provincial Construction CO_2 Emission Linkages

One of the numerous advantages presented by HEM is the ability to modify the methodology and decompose the foundational components of the total CO_2 emissions linkages of any sector under consideration. In this study, we decomposed BE and FE into another four sub-components, namely, mixed forward linkages (MFE), mixed backward linkages (MBE), net forward linkages (NFE), and net backward linkages (NBE). Figure 3.3 illustrates the relationship between the TE, FE, BE, MFE, NFE, MBE, and NBE of a sector's economic structure. The summation of the four sub-components is the sum of the FE and BE, representing the TE. i.e., **MFE + NFE + MBE + NBE = FE + BE = TE.**

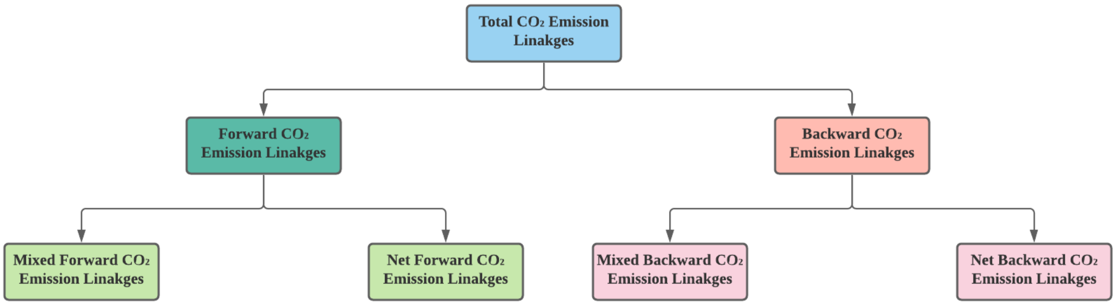

Figure 3.3. Hierarchical Decomposition of HEM MRIO CO_2 emissions Linkages

Furthermore, the relationship between the different decomposed components can be checked using the relationship definition in Duarte et al. (2002), expressed in equation (3.20). While the net transfer (NT) of CO_2 emissions from the construction sector was calculated by the difference between the net forward effects and the net backward effects of the industry, as expressed in equation (21). In addition, to determine the effects of each linkage component among the blocks, the relative indicators were calculated as defined in equation (3.22). Where M_c^c represent one of the decomposed components, $\boldsymbol{mFE_c^c}$, $\boldsymbol{nFE_c^c}$, $\boldsymbol{mBE_c^c}$., $\boldsymbol{nBE_c^c}$.

$$\boldsymbol{FE_c^c = mFE_c^c + nFE_c^c}$$

$$\boldsymbol{BE_c^c = mBE_c^c + nBE_c^c}$$

$$\boldsymbol{TE_c^c = BE_c^c + FE_c^c = mBE_c^c + mFE_c^c + nBE_c^c + nFE_c^c} \qquad (3.20)$$

$$\boldsymbol{NT_c^c = nFE_c^c - nBE_c^c} \qquad (3.21)$$

$$\boldsymbol{RI_c^c = \frac{M_c^c}{TE_c^c}} \qquad (3.22)$$

3.5.5 Inter-Sectoral and Inter-Provincial CO_2 emissions Linkages

To further understand the nature of the interactions between the construction industry and other sectoral blocks in a provincial economy and interactions with other provinces, we decomposed the net forward and the net backward effects. The method followed the approach of Zhang et al. (2020) by decomposing in terms of domestic and international connections. The domestic linkages are CO_2 emissions embodied in trade between the construction sectors and other local industrial blocks within the same province. In contrast, we define the international interactions as CO_2 emissions embodied in trade between the construction sectors and industrial blocks in other provinces in China. To achieve this, we divided the whole economy into hypothetical two blocks, c and -c. Block *c* represents a particular province, while block -c represents other China provinces. Assuming c_p represents the construction sector for a specific province p, $-c_p$ as other sectors in province p, and $-c_i$ represents all sectors in the remaining 29 provinces in China. Equations (3.23) to (3.26) express the domestic and inter-regional linkages of provincial construction sectors in China.

$$\boldsymbol{DNBE_c^p = u'\, e}_{\,-c_p}\Delta_{-c_p,c}\, \boldsymbol{F_c} \tag{3.23}$$

$$\boldsymbol{INBE_c^p = u'\, e}_{\,-c_i}\Delta_{-c_i,c}\, \boldsymbol{F_c} \tag{3.24}$$

$$\boldsymbol{DNFE_c^p = u'\, e}_{\,c}\Delta_{c,-c_p,}\, \boldsymbol{F}_{-c_p} \tag{3.25}$$

$$\boldsymbol{INFE_c^p = u'\, e}_{\,c}\Delta_{c,-c_i}\, \boldsymbol{F}_{-c_i} \tag{3.26}$$

Where F_c represents the Final demand of the specific province, $\boldsymbol{F}_{-c_p}$ represents the final demand of other sectors in the specific province but the construction industry. $\boldsymbol{F}_{-c_i}$ represents the final demand of all sectors, including the construction sector in the other 29 provinces.

3.6 Structural Decomposition Analysis of China's Construction Embodied CO_2 Emission Linkages

Objective three investigates the driving forces behind the increasing trend of embodied CO_2 emissions in the Chinese construction industry. The investigation of the driving forces is captured at both the provincial, regional, and national levels. The Structural Decomposition Analysis (SDA) is a suitable data analysis tool that adequately identifies the forces and quantity of their effects on the industry's embodied CO_2 emissions is the Structural Decomposition Analysis (SDA). As discussed in chapter two, SDA is useful in determining the driving forces and structural linkages between two or more sectors of an economy using input-output tables. Chapter two of the thesis discussed the SDA technique and its choice for analysis. One of the years is set as the base year in SDA, while others are the reference year(s). In this study, 2012 is the base year ('0'), while 2015 and 2017 are the reference years ('1').

$$\boldsymbol{x^t} = (\boldsymbol{0}, \boldsymbol{t-1}, \dots, \boldsymbol{t}) \tag{3.27}$$

Where **0** is the base year

t is the observing year and t>0 (***t*** is selected to be a latter year(s) to 0)

1 is the reference year(s)

SDA methodology follows the basic assumption of HEM in which the entire economy is divided into two blocks: c, -c. Where 'c' represents the construction sector and '-c' denotes other economic sectors in the IO tables. Also, SDA assumes that the extraction of the construction sector from the entire economy caused an interruption in other sectors. The interruption is referred to as the Total CO_2 emissions linkages, ***TL***. The ***TL*** is expressed as:

$$TL_{rk}^{ji} = e_r^j l_{rk}^{ji} f_k^i y_k \tag{3.28}$$

From equation (3.28), e_c^j represents direct CO2 emissions intensity of sector *j* in province *r*; l_{rk}^{ji} = $\Delta_{rk}^{ji} - \Delta_{s,rk}^{c,ji}$ denotes the difference in the Leontief inverse matrix before and after the assumed extraction of construction sector *c* in province s. f_k^i $(= y_k^i/y_k)$ is the ratio of the final products of sector *i* in province *r* to the final demand in province *k*. y_k^i represent the total output of sector *i* in province *k*, and y_k is the total output of province *k*.

The total CO2 emissions linkages of construction sector *c* in province *r* would be the addition of each interrupted CO2 emissions linkages in the entire economy. Equation (3.29) expresses the relationship:

$$TL_c^r = \Sigma_j \Sigma_i \Sigma_r \Sigma_k TL_{rk}^{ji} = \Sigma_j \Sigma_i \Sigma_r \Sigma_k e_r^j l_{rk}^{ji} f_k^i y_k \tag{3.29}$$

From (30), SDA considers the change in total CO2 emissions linkages over two years (base and the reference years) by decomposing (3.29) into the addition of the driving factors. The relationship is defined in equation (3.30).

$$\Delta TL_{rk}^{ji} = TL_{rk.1}^{ji} - TL_{rk,0}^{ji} = \Delta TL_{rk}^{ji}(e) + \Delta TL_{rk}^{ji}(l) + \Delta TL_{rk}^{ji}(f) + \Delta TL_{rk}^{ji}(y) \tag{3.30}$$

Equation (33) depicts the difference in total CO2 emissions linkages of the construction sector in region *r* over the two years being considered. As expressed in Table 3.4, using the LMDI-I approach, the expansion of the equation could be expressed in natural logarithm forms (Ang, 2004; Ang & Zhang, 2000; Inglesi-Lotz & Blignaut, 2011).

Table 3.4: SDA Equations for Regional CO2 Emissions Driving Forces

Factors	Equation	Factor Definition
$\Delta TL_{rk}^{ji}(e)$	$\theta_{rk}^{ji}.\ln(\frac{e_{r,1}^j}{e_{r,0}^j})$	Direct carbon emissions intensity effect (DCEIE)
$\Delta TL_{rk}^{ji}(l)$	$\theta_{rk}^{ji}.\ln(\frac{l_{rk,1}^{ji}}{l_{rk,0}^{ji}})$	Leontief structure effect (LSE)

$\Delta TL_{rk}^{ji}(f)$	$\theta_{rk}^{ji}.\ln(\frac{f_{k,1}^{i}}{f_{k,0}^{i}})$	Final demand structure effect (FDSE)
$\Delta TL_{rk}^{ji}(y)$	$\theta_{rk}^{ji}.\ln(\frac{y_{k,1}}{y_{k,0}})$	Final demand effect (FDE)

Note: $\theta_{rk}^{ji} = \frac{\left(e_{r,1}^{j} l_{rk,1}^{ji} f_{k,1}^{i} y_{k,1}\right) - \left(e_{r,0}^{j} l_{rk,0}^{ji} f_{k,0}^{i} y_{k,0}\right)}{\left(e_{r,1}^{j} l_{rk,1}^{ji} f_{k,1}^{i} y_{k,1}\right) / \left(e_{r,0}^{j} l_{rk,0}^{ji} f_{k,0}^{i} y_{k,0}\right)}$

Expanding (3.30), the total regional CO_2 emissions linkages can be expressed as:

$$\Delta TL_c^r = \Delta TL_c^r(e) + \Delta TL_c^r(l) + \Delta TL_c^r(f) + \Delta TL_c^r(y) \quad (3.31)$$

The total CO2 emissions linkages are the sum of backward and forward CO_2 emissions linkages. Therefore, the driving forces of both backward and forward CO_2 emissions can be disaggregated from the total CO_2 emissions linkages in equation (3.32) as:

$$BL_c^r = \Sigma_j \Sigma_{i=c} \Sigma_s \Sigma_{k=r} TL_{sk}^{ji} = \Sigma_j \Sigma_{i=c} \Sigma_s \Sigma_{k=r} e_r^j l_{rk}^{ji} f_k^i y_k \quad (3.32)$$

Recall, *TL* = *BL* + *FL*.

Therefore, *FL* = *TL* - *BL*

$$FL_c^r = TL_c^r - BL_c^r = \Sigma_j \Sigma_i \Sigma_r \Sigma_k TL_{rk}^{ji} - \Sigma_j \Sigma_{i=c} \Sigma_s \Sigma_{k=r} TL_{sk}^{ji} \quad (3.33)$$

$$FL_c^r = \Sigma_j \Sigma_i \Sigma_r \Sigma_k e_r^j l_{rk}^{ji} f_k^i y_k - \Sigma_j \Sigma_{i=c} \Sigma_s \Sigma_{k=r} e_r^j l_{rk}^{ji} f_k^i y_k \quad (3.34)$$

The change in CO_2 emissions linkages of backward and forward directions can be expressed in equation (3.35) to depict each driving force.

$$\Delta BL_c^r = \Delta BL_c^r(e) + \Delta BL_c^r(l) + \Delta BL_c^r(f) + \Delta BL_c^r(y) \quad (3.35)$$

$$\Delta BL_c^r = \Sigma_j \Sigma_{i=c} \Sigma_s \Sigma_{k=r} TL_{sk}^{ji}(e) + \Sigma_j \Sigma_{i=c} \Sigma_s \Sigma_{k=r} TL_{sk}^{ji}(l) + \Sigma_j \Sigma_{i=c} \Sigma_s \Sigma_{k=r} TL_{sk}^{ji}(f) + \Sigma_j \Sigma_{i=c} \Sigma_s \Sigma_{k=r} TL_{sk}^{ji}(y) \quad (3.36)$$

Similarly, the change in forward linkages is expressed in equations (3.37) and (3.38):

$$\Delta FL_c^r = \Delta FL_c^r(e) + \Delta FL_c^r(l) + \Delta FL_c^r(f) + \Delta FL_c^r(y) \quad (3.37)$$

$$\Delta FL_c^r = \left(\left[\Sigma_j\Sigma_i\Sigma_r\Sigma_k TL_{sk}^{ji}(e) - \Sigma_j\Sigma_{i=c}\Sigma_s\Sigma_{k=r} TL_{sk}^{ji}(e)\right] + \left[\Sigma_j\Sigma_i\Sigma_r\Sigma_k TL_{sk}^{ji}(l) - \Sigma_j\Sigma_{i=c}\Sigma_s\Sigma_{k=r} TL_{sk}^{ji}(l)\right] + \left[\Sigma_j\Sigma_i\Sigma_r\Sigma_k TL_{sk}^{ji}(f) - \Sigma_j\Sigma_{i=c}\Sigma_s\Sigma_{k=r} TL_{sk}^{ji}(f)\right] + \left[\Sigma_j\Sigma_i\Sigma_r\Sigma_k TL_{sk}^{ji}(y) - \Sigma_j\Sigma_{i=c}\Sigma_s\Sigma_{k=r} TL_{sk}^{ji}(y)\right]\right) \quad (3.38)$$

3.7 Chapter Summary

The chapter described the research rationale in detail regarding the various methodologies adopted for the study. The selected data analysis, the models, and the equations developed to investigate the different objectives of the study were highlighted. The analytical tools explained in the chapter include a direct CO_2 emissions hybrid quantification model, MRIO, HEM, LMDI-I, and SDA, used to form the basis for investigating the direct and indirect embodied CO_2 emissions and driving forces in China’s construction sector.

CHAPTER FOUR: DATA COMPOSITION AND MANAGEMENT

4.1 Introduction

Data used in the study were sourced and retrieved from different documents, databases, and online repositories. However, one of the main limitations of this study is data availability and access to recent data. The study carefully worked around the available data sourced from different sources. In this chapter of the thesis, the data collected, analysed, and presented in the study were discussed.

4.2 Data Collection and Data Analysis

The research questions and strategies inform the data collection methods. It invariably follows that different research questions/objectives might warrant different data collection methods. Table 4.1 provides the data collection and analysis techniques for each of the objectives in this study.

Table 4.1 Data Collection and Data Analysis Techniques

Research Objective	**Data Collection Method**	**Data Analysis Technique**
1. Quantification of CO_2 emissions emanating from China's construction sectors (National emissions and of different regions in China)	• Desktop study • Document analysis • Secondary data collection	• Literature review • Content analysis • CO_2 emission models
2. Investigation of CO_2 emissions linkages and identify critical CO_2 emissions paths from a sectoral, provincial, and regional perspective	• Document analysis • Secondary data collection	• Content analysis • MRIO analysis • HEM analysis
3. Investigation of the driving forces of CO_2 emissions among provincial construction sectors from a multi-regional perspective	• Document analysis • Secondary data collection	• Content analysis • SDA and LMDI 1 • Descriptive statistics

4.2.1 Document Analysis

Document analysis is an organized research method designed to explore research problems by searching through published documents and investigating recorded information. Information needed for document analysis is found in public reports, government gazettes, releases and databases. In this study, document analysis formed the dominant part of the qualitative approach. There are mainly two types of document analysis: analysis from existing datasets and content analysis. The choice of the type suitable for a study depends on the need and characteristics of the research activity.

In this study, both content and secondary data analysis were used to retrieve data used for further analysis. The literature review method formed the essential systematic tools for content analysis to extract information and data from existing literature and public documents. Documents consulted included academic publications, international joint publications, United Nations reports on climate change, government policy documents, government reports, and official media statements. However, time-series data published in public statistical yearbooks (national and regional) formed the analysis basics for existing data analysis.

4.2.2 Secondary Data Collection

The main data for this study are secondary data retrieved from various sources such as GHGs emissions accounting online databases and websites, government ministries' yearly statistical releases, and research institutes databases. This section discusses data sources for the approaches employed in the study in the following sub-sections:

4.2.2.1 Direct CO_2 Emissions Database Selection

The data used in this study, including the construction output data, regional demography, and energy consumption statistics covering 1997 to 2015, were retrieved from the National Statistics Office of China (National Bureau of Statistics of China, 2021) and the CEIC database. The most recent published energy data during the period of this study was in 2015. Furthermore, data prior to 1997 were presented in different formats and contained fewer fossil fuels. Therefore, the study was limited to data from 1997 to 2015. The construction industry's output data are measured over the sector's GDP contribution to the national economy. The unit of measurement of the economic data is a million RMB, with 1997 taken as the constant price to accommodate inflation's impact over the investigated period. This study's energy data includes primary and secondary energy sources compiled in China's NBS and the various regional energy statistics yearbooks. The study's energy sources include aggregated energy consumption on the construction industry's sites by fuel types, with renewable energy sources not included. The energy consumption data were made available in a million tonnes unit of standard coal equivalent (Mtce) and the gases in a million cubic meters unit in calorific value. The secondary data in this section are consumption data of cement and steel products consumed in the construction industry. The choice of the two datasets is due to the embodied emission potentials of the two construction materials. The two materials could have a combined 80% contribution to CO_2 emissions in the industry (Jayapalan, Lee, & Kurtis, 2013; Kariyawasam & Jayasinghe, 2016).

4.2.2.2 Input-Output Database

We considered many international and local databases when selecting data for the study. The World Input-Output Database (WIOD), Carbon Emissions Accounts and Datasets (CEADs), OECD, Eurostat, Eora, EXIOPOL, ADB-MRIO, and IO accounts by the National Bureau of

Statistics in China are among the databases considered. In this study, each IO account presents a unique set of challenges. As a result, the study used CEAD data from 2012, 2015, and 2017 (the most recent MRIO tables from China) and corresponding CO_2 emissions data for the three years. Compared to previous years, the IO tables for 2012, 2015, and 2017 were built on 42 sectoral categories instead of 30 in tables of earlier years. Reclassifying data from earlier years would have required assumptions, which could have invalidated the data integrity. Because of the sectoral classifications of the IO tables in these years, we chose data from three years. According to the CEAD website, all data published in the database are the results of recent and ongoing research funded by the Chinese Academy of Science, China's Ministry of Science and Technology, the National Natural Science Foundation of China, the Newton Funds, the Science and Technology Research Council of the United Kingdom, and other sponsoring institutions and agencies.

4.3 Data Verification and Validation

The best form of data validation is to ensure the genuineness of the source. All data used in the study were retrieved from international and government acclaimed institutions' data depositories. Vast of the data were extracted from published regional and provincial energy yearbooks, official websites of government ministries and data depositories approved by the Chinese government. In addition, various studies have used the same sources of data and the study isn't different in terms of data retrieval means and verification. Data verifications were done by cross-checking the data used was consistent with data from similar studies. This was achieved through different rigorous screening and evaluations. Format and random consistency checks were done to ensure the data used was complete and consistent all through.

4.4 Data Preparation

A study of this nature requires large data availability. As discussed earlier, data were retrieved from many international and Chinese databases. Some data sources include the National Bureau of Statistics (NBS), where most economic data were collected. Chinese I-O tables were retrieved from the NBS and CEAD to prepare the MRIO extended models. The energy data used in the study were extracted from the Annual Chinese Energy Yearbooks (both national and regional releases) and the NBS data. Also, some missing data were retrieved from the CEIC database accessed via the university library online database.

Due to the difference in the data sources, these data require adequate understanding, sorting, and adjustments. For example, the MRIO tables for the years were prepared using different sectoral classifications from the environmental data. Therefore, a need to aggregate the data for uniformity's sake and fit the study's purpose. The data preparation process follows the analogy presented in Figure 4.1.

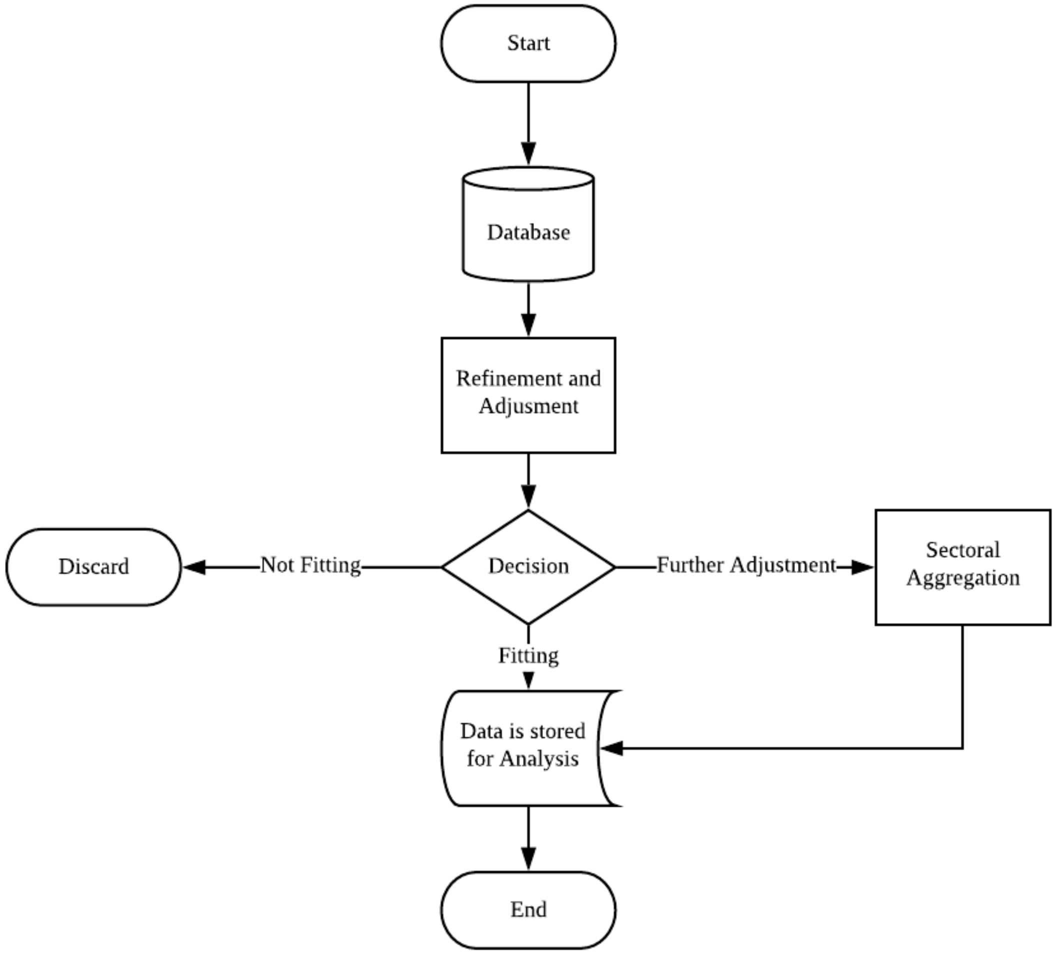

Figure 4.1: Data Preparation Flow Chart

The flow chart presents the holistic approach undertaken in data preparation for the study. Many computational tools were used to analyse the data, including MATLAB, Microsoft Excel, and Origin Pro for data visualization.

4.5 Chapter Summary

The chapter discussed the different data sources, data collection, and data processing techniques employed in the study. Data were retrieved through four primary and secondary sources, adjusted, and refined to suit the study's objectives. The modified data formed the backbone for further analysis using the methodologies discussed in chapter three of this thesis to generate the results in the subsequent chapters.

CHAPTER FIVE: DIRECT CO_2 EMISSIONS QUANTIFICATION IN CHINA'S CONSTRUCTION SECTOR[1]

5.1 Introduction

As explained in previous chapters, direct CO_2 emissions in this study result from construction activities during pre-construction and construction phases, plant operations, concreting, material transportation, testing and installations, etc. This chapter discusses the direct CO_2 emissions calculations for the construction sector in China.

5.2 National Direct Energy Consumption

Table 5.1 shows the distribution of annual energy consumption from direct onsite construction activities in the Chinese construction sector between 1997 and 2015. The data shows an increase in the industry's dependence on coal energy sources between 1997 and 2003, with a significant decrease in 2004. Although there has been a steady increase in coal use in the industry from 2004 and 2015, a downward dependence on coal energy sources is observable when the data is juxtaposed with the sector's output in those years. In Table 5.1, coke products were shown to contribute less as the years went by, from 126,000 tonnes in 1997 to 67,000 tonnes in 2015.

During the investigation period, gasoline consumption as a source of energy on construction sites jumped from 1.1 million tonnes in 1997 to 4.7 million tonnes in 2015. Also, there was a significant increase in diesel oil usage from 1.461 million tonnes in 1997 to 10.35 million tonnes

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[1] This chapter of the thesis was published in the International Journal of Environmental Research and Public Health as Ogungbile, A. J., Shen, G. Q., Wuni, I. Y., Xue, J., & Hong, J. (2021). A Hybrid Framework for Direct CO_2 Emissions Quantification in China's Construction Sector. International Journal of Environmental Research and Public Health, 18(22), 11965. Retrieved from https://www.mdpi.com/1660-4601/18/22/11965.

in 2015. There was an increase in other petroleum products between 1997 and 2009, while a downward trend was observed in subsequent years. The energy generated on construction sites using natural gas sources has significantly increased between 1997 and 2015 from less than 10 million cubic meters to 620 million cubic meters. The energy input from heat and electricity sources increased by over 360% and 820%, respectively, between 1997 and 2015.

5.3 National Direct CO_2 Emissions in China's Construction Industry

Emission factors from six official data sources formed the basics of the quantifications in Figure 5.1. We computed the standard deviation between the CO_2 emission values, with results ranging between 0.455 and 1.751. Although this range could be taken to be negligible, the size of the data involved makes it significantly high. The IPCC data resulted in the highest emission values than the other five sources. The NBS data has the second-highest results, while the National Communication on Climate Change (NC) data factors disaggregated by fuel types and sectors with the most negligible CO_2 emissions results.

According to Liu et al. (2015), the UN-China data source reflects China's improved technology obtainable. The UN-China emission factors were computed as China-specific and aggregated by Chinese researchers and research agencies. Globally, emission studies are geo-localized to show the progress or regress made in a specific country over time. One method of identifying process improvements in the country is to use emissions factors based on the country's technology, industrial processes, fuel mix, activity data segregation, and source-to-delivered energy ratio (Liu et al., 2015). Thus, for further analysis in this study, we chose the UN-China CO2 emission factors developed specifically for China's peculiarity to appropriately distinguish and be guided by China's technological differences to global averaged emission factors.

Table 5.2 shows the direct CO_2 emissions in the Chinese construction industry using UN-China specific factors. The construction industry in 1997 generated 8.7 $MtCO_2$ direct emissions, with almost 30% from Coal sources. The industry's dependence on coal energy sources continued from 1997 to 2003, where CO_2 emissions peaked at approximately 58% of national emissions in the sector. A steady reduction in the industry's reliance on coal energy sources was experienced between 2004 and 2015, reducing coal-generated CO_2 emissions from 25% to 13%. However, with the decrease in coal reliance, the industry shifted along with more diesel, gasoline, heat, and electricity sources for energy generation. The CO_2 emissions from these sources increased from 2005 to 2015.

Table 5.2 shows a steady increasing trend of direct CO_2 emissions from 1997 to 2004, with a massive leap from 2005 to 2015.

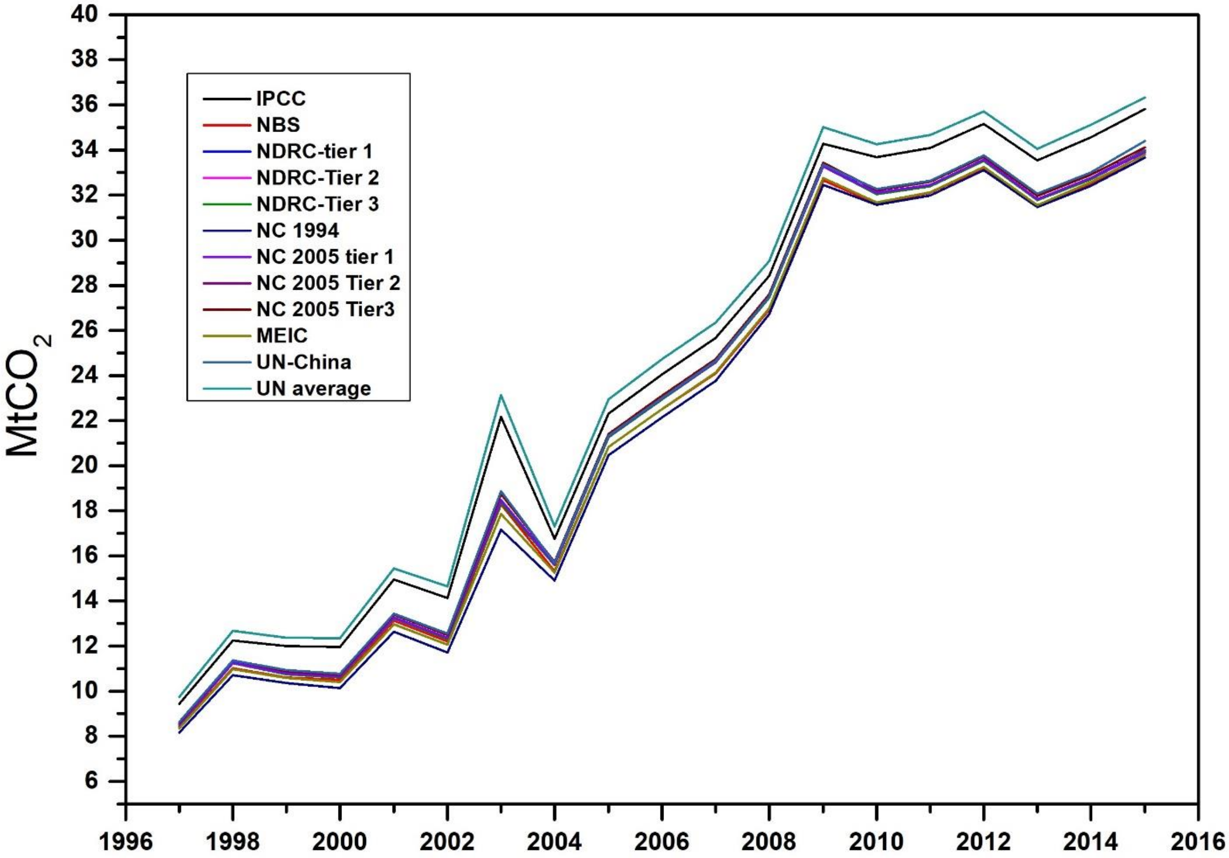


Figure 5.1 National direct CO_2 emissions in China's construction industry

Table 5.1 National construction industry's energy and fossil fuel consumption (Shan et al., 2018b)

Year	**Raw Coal**	**Cleaned Coal**	**Other Washed Coal**	**Briquettes**	**Coke**	**Coke Oven Gas**	**Other Gas**	**Other Coking Products**	**Crude Oil**	**Gasoline**	**Kerosene**	**Diesel Oil**	**Fuel Oil**	**LPG**	**Refinery Gas**	**Other Petroleum Products**	**Natural Gas**	**Heat**	**Electricity**
	10^4 tn	**10^4 tn**	**10^4 tn**	**10^4 tn**	**10^4 tn**	**10^8 cu.m**	**10^8 cu.m**	**10^4 tn**	**10^4 tn**	**10^4 tn**	**10^4 tn**	**10^4 tn**	**10^4 tn**	**10^4 tn**	**10^4 tn**	**10^4 tn**	**10^8 cu.m**	**10^{10} kj**	**10^4 kwh**
1997	497.0	0.7	8.5	0.0	12.6	0.0	0.0	5.5	3.1	111.6	4.2	146.1	19.2	5.1	0.0	89.4	0.0	207.3	197.60
1998	601.3	0.1	10.6	0.0	14.6	0.0	0.0	6.3	2.2	134.0	3.4	240.9	16.1	5.7	0.0	256.6	0.1	166.1	195.6
1999	651.2	4.3	11.7	0.0	16.4	0.0	0.0	0.0	3.2	199.3	3.3	293.4	16.4	7.8	0.0	98.1	0.7	132.7	171.60
2000	716.0	4.0	3.5	0.0	22.7	0.0	0.0	0.0	7.6	137.7	2.1	197.7	24.1	9.0	0.0	121.8	0.8	232.7	158.0
2001	916.0	4.0	4.7	0.0	23.6	0.0	0.0	0.0	11.3	129.7	3.5	213.8	24.2	7.5	0.0	128.4	0.5	455.0	162.2
2002	957.7	3.3	3.6	0.1	23.1	0.0	0.0	0.0	14.8	144.2	2.8	251.8	28.3	13.1	0.0	129.3	0.5	162.2	188.4
2003	1963.1	3.0	4.1	5.2	20.8	0.0	0.0	0.8	2.0	146.1	0.9	276.6	26.3	7.9	0.0	166.0	1.4	216.0	215.0
2004	737.8	3.1	4.5	0.3	16.4	0.0	0.0	0.0	0.0	155.0	0.4	325.3	26.7	8.8	0.0	360.5	1.4	418.6	232.5
2005	737.7	3.4	5.7	3.8	28.5	0.0	0.0	0.6	0.0	207.7	0.6	444.5	14.2	6.5	0.0	522.0	1.4	860.9	238.4
2006	776.4	3.9	5.4	0.9	27.3	0.0	0.0	0.6	0.0	232.7	0.8	497.5	16.7	7.6	0.0	526.2	1.6	951.1	271.9
2007	746.3	0.1	30.4	2.6	27.7	0.0	0.0	1.1	0.0	276.6	0.3	502.7	15.8	7.2	0.0	520.4	3.6	1118.9	312.2
2008	692.6	1.2	29.4	3.6	18.1	0.0	0.0	1.2	0.0	247.5	7.1	703.3	26.2	4.7	0.0	525.1	4.3	1329.8	350.8
2009	729.4	1.1	32.0	5.6	5.7	0.0	0.1	13.5	0.0	301.2	7.8	791.3	23.6	6.0	0.0	607.8	4.1	1874.2	396.7
2010	845.1	1.4	67.0	5.5	5.8	0.1	0.0	0.7	0.0	350.6	6.6	939.0	21.1	5.8	0.0	189.2	6.6	1788.2	501.9
2011	904.9	5.5	0.5	14.9	4.9	0.2	0.1	0.7	0.0	360.3	8.7	984.0	20.8	5.8	0.0	189.3	6.4	1674.0	597.2
2012	868.8	6.0	0.5	22.1	6.3	0.0	0.1	0.7	0.0	363.8	5.7	977.9	18.6	5.3	0.0	193.9	7.3	1842.3	635.0
2013	875.7	6.8	20.5	15.1	7.6	0.0	0.0	0.8	0.0	425.5	8.5	1039.6	30.7	10.9	0.0	72.9	3.1	1468.4	690.0
2014	875.6	63.4	20.0	16.8	9.7	0.0	0.0	0.9	0.0	432.1	7.6	1030.4	24.6	14.7	0.0	62.3	3.0	1534.0	741.1
2015	841.0	8.1	18.8	18.0	6.7	0.0	0.0	46.3	0.0	468.1	10.8	1035.6	44.2	12.4	0.0	43.5	6.2	1712.7	727.8

Table 5.2 National Chinese construction industry CO_2 emissions based on UN-China emission factors ($MtCO_2$)

Year	Raw Coal	Cleaned Coal	Other Washed Coal	Briquettes	Coke	Coke Oven Gas	Other Gas	Other Coking Products	Crude Oil	Gasoline	Kerosene	Diesel Oil	Fuel Oil	LPG	Refinery Gas	Other Petroleum Products	Natural Gas	Heat	Electricity	Total
1997	2.6	0.0	0.0	0.0	0.3	0.0	0.0	0.1	0.0	1.0	0.0	1.2	0.2	0.0	0.0	0.8	0.0	1.3	1.2	8.7
1998	3.2	0.0	0.2	0.0	0.1	0.0	0.0	0.1	0.0	1.2	0.0	2.0	0.1	0.0	0.0	2.2	0.0	1.0	1.2	11.3
1999	3.5	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	1.7	0.0	2.5	0.1	0.1	0.0	0.9	0.0	0.8	1.1	10.9
2000	3.8	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	1.2	0.0	1.7	0.2	0.1	0.0	1.1	0.0	1.5	1.0	10.8
2001	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.1	0.0	1.8	0.2	0.1	0.0	1.1	0.0	2.8	1.0	13.1
2002	5.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	1.2	0.0	2.2	0.2	0.1	0.0	1.1	0.0	1.0	1.2	12.3
2003	10.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	2.4	0.2	0.1	0.0	1.4	0.0	1.3	1.3	18.5
2004	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	2.8	0.2	0.1	0.0	3.1	0.0	2.6	1.5	15.5
2005	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	3.8	0.1	0.1	0.0	4.4	0.0	5.4	1.5	21.0
2006	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.0	4.2	0.1	0.1	0.0	4.4	0.0	5.9	1.7	22.5
2007	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	0.0	4.3	0.1	0.1	0.0	4.4	0.0	7.0	1.9	24.1
2008	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.1	6.1	0.2	0.0	0.0	4.4	0.0	8.3	2.2	27.1
2009	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	2.5	0.1	6.8	0.2	0.0	0.0	5.2	0.0	11.7	2.5	33.1
2010	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.9	0.1	8.0	0.2	0.0	0.0	1.6	0.0	11.2	3.1	31.6
2011	4.8	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	3.0	0.1	8.4	0.2	0.0	0.0	1.7	0.0	10.4	3.7	32.4
2012	4.6	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	3.0	0.0	8.3	0.2	0.0	0.0	1.7	0.0	11.5	4.0	33.4
2013	4.6	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	3.5	0.1	8.9	0.3	0.1	0.0	0.7	0.0	9.2	4.3	31.8
2014	4.6	0.4	0.0	0.1	0.0	0.0	0.0	0.0	0.0	3.6	0.1	8.9	0.2	0.1	0.0	0.5	0.0	9.6	4.6	32.7
2015	4.6	0.0	0.0	0.1	0.0	0.0	0.0	0.5	0.0	3.9	0.1	8.9	0.4	0.1	0.0	0.4	0.0	10.7	4.5	34.2

5.4 Regional Direct CO_2 Emissions in China's Construction Industry

Table 5.3 shows the aggregation of the direct CO_2 emissions in the regional construction industries of China. As of 1997, China's north region construction industry had the most CO_2 emissions of the other regional construction industries, with 3.0 million tonnes of carbon ($MtCO_2$). The total direct CO_2 emissions from the North increased from 3.0 $MtCO_2$ to 11 $MtCO_2$ in 2010, when the industry experienced its peak emissions. Apart from the surge in CO_2 emissions in the Northeast construction industry in 2003, the region's CO_2 emissions have remained steady. The most significant increase in CO_2 emissions was experienced in East China's construction industry between 2005 and 2009 before decreasing from 2010 to 2015. The same scenario can be seen to have played out in the southwest and northwest of China's construction industry from 1997 to 2015. However, the Southcentral construction industry results show an increasing trend in CO_2 emissions unlike other regional construction industries.

Figure 5.2 illustrates the regional construction industry's percentage contributions to China's construction sector's CO_2 emissions from 1997 to 2015. Although a plunge in CO_2 emissions from the east region resulted in a corresponding surge in the North in 2003, the east's construction industry has contributed more than other regions from 1997 to 2015. As of 1997, the construction industry in the east, southcentral, southwest, and northwest had approximately equal contributions to the industry's direct CO_2 emissions stock. However, the direct CO2 emission generated in the east construction industry is more than in the southwest and south-central regions in recent years.

Table 5.3 Regional construction industries direct CO_2 emission inventories ($MtCO_2$)

Year	North China	Northeast China	East China	South Central China	Southwest China	Northwest China	National Average
1997	2.7	1.6	1.4	1.4	0.6	1.0	8.7
1998	3.1	1.4	2.6	2.0	0.7	1.2	11.0
1999	2.3	0.9	4.0	1.3	0.8	1.2	10.5
2000	2.8	1.0	3.3	1.6	0.8	1.2	10.7
2001	3.0	1.0	5.5	1.6	0.8	1.1	13.0
2002	3.0	1.1	4.4	1.5	1.0	1.3	12.3
2003	3.2	8.0	2.8	1.4	1.0	1.5	17.9
2004	4.8	1.2	5.0	1.9	1.0	1.3	15.2
2005	4.5	1.7	9.6	2.7	1.2	1.1	20.8
2006	5.0	1.7	10.2	2.9	1.4	1.2	22.4
2007	5.5	1.9	10.5	3.2	1.4	1.4	23.9
2008	6.3	1.6	11.3	3.1	1.6	2.6	26.5
2009	10.8	1.9	12.5	3.6	1.9	2.1	32.8
2010	10.6	2.5	9.3	4.2	2.1	2.6	31.3
2011	9.3	2.7	9.8	5.0	2.4	2.7	31.9
2012	10.0	2.6	10.4	5.0	2.3	2.5	32.8
2013	7.4	3.2	9.1	5.5	2.6	3.2	31.0
2014	7.7	2.8	9.4	6.2	2.7	2.8	31.6
2015	8.6	3.0	8.9	6.5	3.3	2.9	33.2

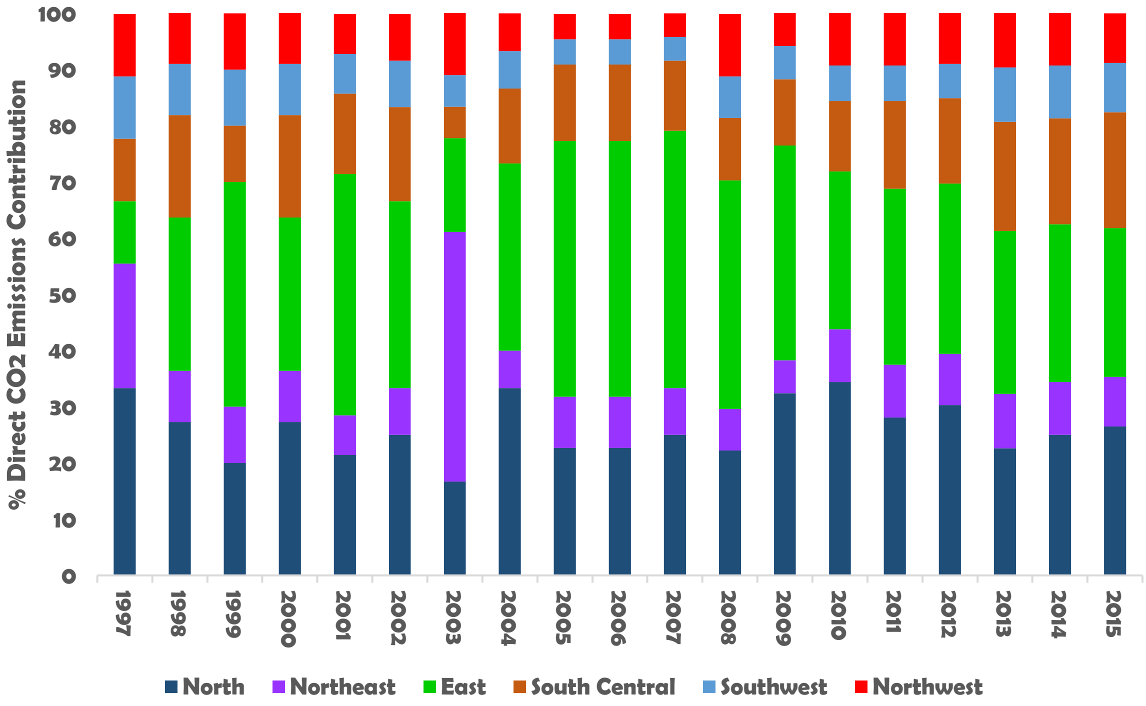
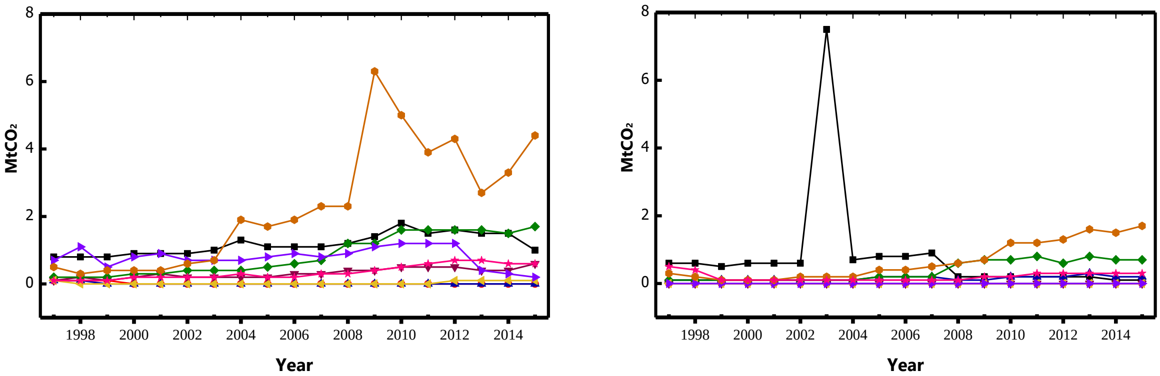
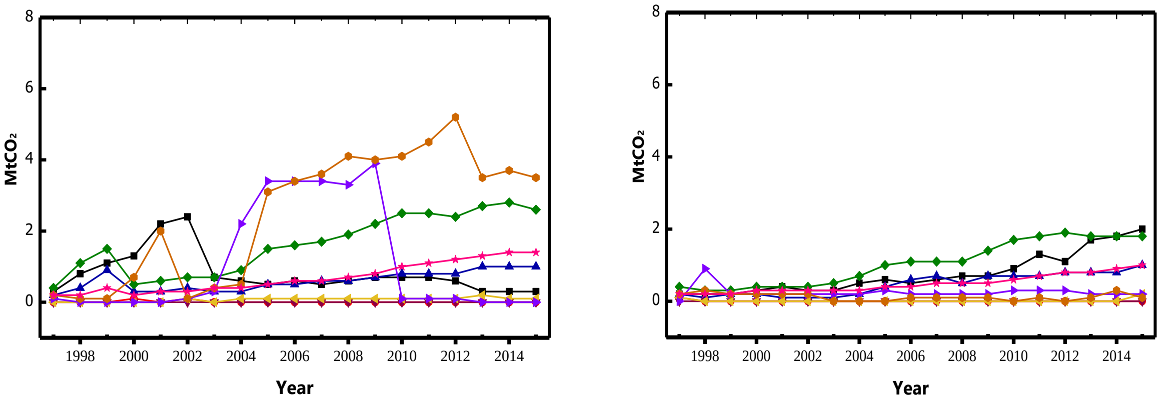


Figure 5.2 Changes in regional construction industry's contributions to national direct CO_2 emission from 1997 to 2015.

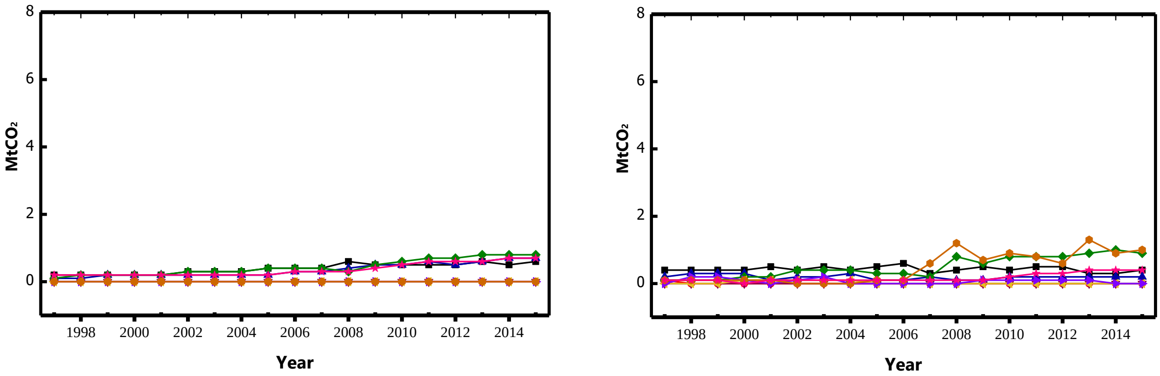
Parallel to Figure 5.2, Figure 5.3 illustrates the energy sources for the direct CO_2 emission from the regional construction industries in China. The share of each fuel considered in this study is presented in total direct CO_2 emissions in the regional construction industry. In the North construction industry's direct CO_2 emissions inventory, there is a spike in the emissions originating from heat sources used on construction sites. Similarly, heat-related CO_2 emissions increase in east and northeast China's construction industries while its proportion in other regions is relatively stable. In all the regions, the relatively low emissions are generated from natural gases because of their relatively low carbon content. However, the CO_2 emissions resulting from diesel oil and other petroleum products increased in the emission inventories. The direct CO_2 emissions from raw coal are on a massive decline in all the regions except for a recent increase in the south-central construction industry observable from 2010. In the North-East region, Figure 5.3 (b) indicates a spike in coal-based CO_2 emissions in 2003. However, in 2004, there was an observable drop in coal-related CO_2 emissions and a continuous drop in subsequent years as seen in other regions. The decrease in raw coal contribution to direct CO_2 emissions in the construction industry connotes the shift from absolutes dependence on coal as the primary energy generation source in the Chinese economy.



(a) North China (b) North-East China



(d) South Central China (d) South Central China



(e) Southwest China (f) North-West China

■ Raw Coal ● Coke ▲ Other Coking Products
▼ Gasoline ◆ Diesel Oil ◀ Fuel Oil
▶ Other Petroleum Products ● Heat ★ Electricity

Figure 5.3 Energy sources of direct CO_2 emission in regional construction industries of China

5.5 Econometric Analysis of Regional Direct CO_2 Emissions in China's Construction Sector

A Pearson correlation analysis was conducted to establish the relationship between the dependent and independent variables. The study identified the direction and strength of the relationship between the variables, with the significance reported at a 0.01 level (99% confidence interval). Table 5.4 presents the correlation analysis reports in China's six regional construction sectors. Significant relationships were found between the variables in all the regions except in the Northeast regional construction sector, which has none of the factors correlated with the others. The results show that the relationship between the factors is strong, with the medium effect size of 0.3 recommended in Leung, Liang, and Pynoos (2019). Therefore, we furthered the analysis to regress the variables using multiple linear regression analysis to determine the effects of the factors on CO_2 emissions in the regions.

Table 5.4 Eco-RDCO$_2$ Direct CO_2 Emission in China's Construction Sector Correlation Analysis Report

		Regional Direct CO2 Emissions						
Variables	**Factors**	**North**	**Northeast**	**East**	**South Central**	**Southwest**	**Northwest**	**National**
RDCO$_2$	Direct CO_2	1	1	1	1	1	1	1
A	Annual Construction Output	0.832**	0.265044	0.630**	0.983**	0.973**	0.922**	0.879**
B1	Cement Consumption	0.608**	0.070884	0.854**	0.922**	0.918**	0.906**	0.947**
B2	Steel Consumption	0.892**	0.053849	0.838**	0.961**	0.858**	0.912**	0.979**

**. Correlation is significant at the 0.01 level (2-tailed).

Regression, a statistical tool used, explains the unique contribution of each independent variable and the amount of variance their combination can predict (Kothari & Garg, 2016; Leung et al., 2019). We input ‘EcoF’ factors for each region as independent variables, and RDCO$_2$ were the dependent variable. Table 5.5 presents the resulting models. The variances explained by the models range from 86% to 98%, indicating the strength of the models. We discontinued modelling for northeast China because of its lack of regression significance, confirming the correlation analysis. Expressed in equations (5.5) to (5.9) are direct CO_2 emissions models for each of the five regional construction sectors extracted from the regression model in Table 5.5. The models depict positive predictive powers of the EcoF-factors in the five regions, indicating an increase in direct CO_2 emissions if any of the three factors increases and vice versa. Figure 5.4 shows a pictorial illustration of the relationship and the predictive correlational values between the dependent and the independent variables in each region of China's construction sector. The relationship of the independent variables in the Northeast region is drawn in broken lines to depict the insignificance and lack of predictive appropriateness with the direct CO_2 emissions in the region.

Table 5.5 EcoF-RDCO2 Direct CO_2 Emission Regression Model in China's Construction Sector

									ANOVA	
Model	**Factors**	**Code**	**Constant (c)**	**ß**	**S.E.**	**R**	**R^2**	**ΔR^2**	**F**	**Sig.**
North	Output	A	1.959882	0.3968	1.2073	0.927	0.860018	0.832021	30.71877	0.000
	Cement	B1		0.2654						
	Steel	B2		0.4130						
Northeast	*Output*	*A*	*1.808724*	*0.3219*	*1.6544*	*0.295*	*0.086883*	*0.09574*	*0.475752*	*0.7038*
	Cement	*B1*		*0.3705*						
	Steel	*B2*		*-0.4585*						
East	Output	A	2.714384	0.6328	1.7063	0.894	0.799625	0.75955	19.9532	0.000
	Cement	B1		0.4411						
	Steel	B2		0.9806						
South Central	Output	A	1.225556	0.7396	0.3047	0.987	0.974397	0.969276	190.2864	0.000
	Cement	B1		0.0846						
	Steel	B2		0.1765						
Southwest	Output	A	0.609027	0.6811	0.1126	0.992	0.983579	0.980295	299.496	0.000
	Cement	B1		0.2494						
	Steel	B2		0.1071						
Northwest	Output	A	0.814057	0.5862	0.2406	0.958	0.91824	0.901888	56.15448	0.000
	Cement	B1		0.5914						
	Steel	B2		0.1734						

ß = independent variables coefficients, S.E. = Standard Error, ΔR^2 = Adjusted R^2

$$North = 1.959882 + 0.396789\ (A) + 0.265402\ (B1) + 0.413016\ (B2) \qquad \text{Equation (5.5)}$$

$$East = 2.714384 + 0.63278\ (A) + 0.441105\ (B1) + 0.980634\ (B2) \qquad \text{Equation (5.6)}$$

$$South\ Central = 1.225556 + 0.739552\ (A) + 0.08464\ (B1) + 0.176465\ (B2) \qquad \text{Equation (5.7)}$$

$$Southwest = 0.609027 + 0.681099\ (A) + 0.249427\ (B1) + 0.10714\ (B2) \qquad \text{Equation (5.8)}$$

$$Northwest = 0.814057 + 0.586157\ (A) + 0.591359\ (B1) + 0.1734\ (B2) \qquad \text{Equation (5.9)}$$

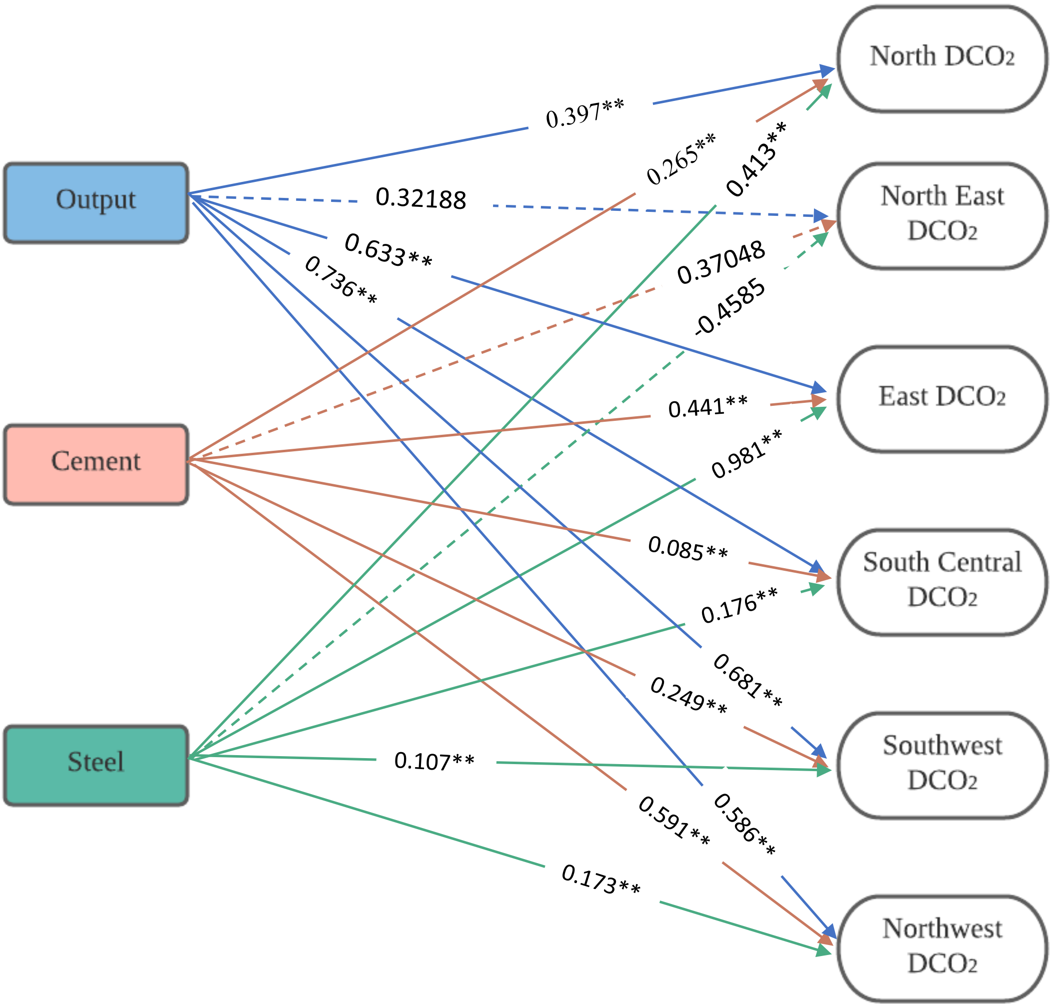


Figure 5.4 EcoF-RDCO2 Direct CO_2 Emission Model in China's Construction Sector

5.6 Discussion of Findings in Objective One

The Chinese construction industry's growth was observed in many other studies (Wang, Su, Xie, & Long, 2020; Wen & Li, 2020). The Chinese government's resolve to re-strategize the sector towards a sustainable environment was a focal point of this study. The results show an increase in the construction industry’s size in the six regions. The direct CO_2 emissions from the construction sector in the six regions reflect such growth in output. The result shows an increase in the direct CO_2 emissions produced in the years considered, the largest observed in the northeast China construction industry in 2003. The construction industry's CO_2 emissions increased significantly around 2001, with all the six regional construction sectors contributing more to the national emissions inventories. This supports the view from previous studies suggesting China's joining the WTO is instrumental in China's CO_2 emissions growth (Chen et al., 2017; Lin, Fan, Xu, & Sun, 2017b; Liu, Geng, et al., 2016). The admittance of China into the WTO significantly increased export in the construction industry, thereby increasing energy consumption. The resultant increase in energy consumption and exports in the sector was observed in a corresponding rise in coal consumption between 2000 and 2003. The construction sector in Northern China contributes an average of 30% of CO_2 emissions in the industry. Minor emissions are observed in the Southwest construction sector. In 2003, CO_2 emissions in China experienced a spike in the North-East region in response to a peak in coal production in China, with most being locally consumed (Tu & Johnson-Reiser, 2012). Although the sharp increase in coal-related CO_2 emissions in the North-East construction industry was adequately regulated in 2004, the study observed a stable rise in other regional construction industries, especially in the South-central provinces.

Nonetheless, the results show a gradual move away from the construction industry in the six regions from primary dependence on coal as the primary energy source on the construction sites. On the national scale, coal's influence as the primary fuel source for plants and energy sources has been reduced. Although the south-central and southwestern construction industries are yet to significantly cut their dependence on coal and fossil fuels as much as other regions, the construction industry's energy profile's overall improvements are targeted at reducing CO_2 emissions from the sector. The study also shows that the most significant source of direct CO_2 emissions is heat and electricity use on construction sites. Electricity and heat are the two most potent energy sources of the construction industry, amounting to over 30% of the total CO_2 emissions generated in the industry during the investigation period. The result resonates with Fe et al. (2017) claims that China is shifting away from the usual energy generation means such as coal, crude, and other fossil fuels to electricity and more secondary energy sources.

Electricity-related CO_2 emissions profile in the North indicates a move away from coal between 2007 and 2009. Heat sources are the most significant sources of CO_2 emissions in four of the six regional construction industries.

The result shows an improved and more efficient construction industry in China instead of indications from past studies where the sector was regarded as having very low carbon efficiency (Wang et al., 2013; Zhao et al., 2015). Wang et al. (2013) categorized the Chinese construction sector as a low-carbon industry with a high potential to increase national CO_2 emissions stock due to massive construction activities and a low technological adoption to improve carbon efficiency. Meanwhile, the rise in direct CO_2 emissions may not be directly linked to the industry's technology. Still, the overall increase in construction output has resulted in more fuel sources in the sector's production processes at different stages and in various regions of China.

The analysis results show significant relationships between construction material (cement and steel products) consumption, annual construction output, and direct CO_2 emissions in the regional construction sectors in China. The results align with past studies on the effects of construction materials on CO_2 emissions in China and other countries. De Wolf et al. (2016) averred the importance of materials such as cement and steel in driving increased embodied CO_2 emissions. In the same vein, Galvez-Martos et al. (2016) argued the chemical composition of cement is a critical driver of CO_2 emissions in the construction sector. Also, many studies campaigned for process change in the industry to reduce cement and steel usage to manage CO_2 emissions effectively (Chiaia, Fantilli, Guerini, Volpatti, & Zampini, 2014; Gonzalez-Kunz, Pineda, Bras, & Morillas, 2017; Lin & Liu, 2015b). Inductively, based on the regression results from the study, an increase in cement and steel usage can increase direct CO_2 emissions in the industry.

However, as China continues to expand in construction and infrastructural developments, more cement and steel products will be needed to satisfy the increased demand for construction product delivery (Climate Transparency, 2018). Cement and steel are two of the most critical construction materials required in the construction process, thereby indicating an excepted rise in their consumption. Therefore, it is expedient to find ways of improving the carbon content and CO_2 emissions generating potentials of both materials by finding alternative construction materials that can serve similar functional requirements and enhance manufacturing. Achieving acceptable global sustainability practices in the construction sector of China depends on the efficiency of the industry in managing its CO_2 emissions profile with more focus on construction material improvements.

5.7 Chapter Summary

The chapter identified the North construction sector as the most critical emitter of direct CO_2 emissions. The chapter shows a gradual shift in China's construction industry from coal and crude oil as the primary sources of energy generation on construction sites and the corresponding reduction in CO_2 emissions from both sources on a national level. However, two construction sector regions depended more on coal and crude oil as direct energy sources. The chapter reflects that China's commitment to the global climate change campaign lacks sufficient policies specific to the construction sector. To achieve sustainability, all industrial sectors (construction industry inclusive) require specific policies to manage CO_2 emission profiles and energy resource redistribution amongst the regions.

In addition, the chapter established the relationships between direct CO_2 emissions, annual construction output, and construction materials. Cement and steel consumption directly affect the direct CO_2 emissions generated on construction sites in China's five regional construction industries. Considering the population of China, the increase in emissions in China can be attributed to an increased urbanization rate and a corresponding rise in building stock demand in the regions. Although results showed a positive relationship between construction output due to increased urbanization and direct CO_2 emissions, it will be prejudicial to measure the emission profile of China solely on the amount of generated CO_2 emissions from the country without considering other economic indices. In conclusion, the chapter assessed direct CO_2 emissions based on three selected factors; however, China's government and industrial sectors need to consider other economic indices and environmental sustainability campaigns to generate a perfect predictive model.

CHAPTER SIX: CO_2 EMISSIONS LINKAGES IN THE PROVINCIAL CONSTRUCTION SECTOR IN CHINA[2]

6.1 Introduction

The chapter highlights the importance of identifying the CO_2 emissions trade patterns in China's 30 provincial construction sectors. First, the chapter utilizes the concept of HEM to recategorize the construction industry's CO_2 emissions intensities at the national decomposition level. The chapter quantifies the total CO_2 emissions linkages at the industry's national and individual provincial levels through the modified HEM. The effects of local population density on CO_2 emissions linkages are also discussed. Second, the modified HEM second-order decomposition of CO_2 emissions (explained in Chapter two) identifies the critical provincial construction sectors contributing the most to the national CO_2 emissions profile. Third, the chapter traces the directional usage and sources of transferred CO_2 emissions in each of the 30 provincial construction sectors decomposed to determine the dependence on other provinces, with corresponding CO_2 emissions policy reduction strategies proposed.

6.2 Sectoral Classifications

There are 42 sectoral classifications in the Chinese economic structure used in this study (Appendix Table A1). The CO_2 emissions data, on the other hand, were presented in the aggregated form of 45 sectoral classifications (Appendix

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[2] This chapter of the thesis was published in Sustainability as Ogungbile, A. J., Shen, G. Q. P., Xue, J., & Alabi, T. M. (2021). A Hypothetical Extraction Method Decomposition of Intersectoral and Interprovincial CO_2 Emission Linkages of China's Construction Industry. Sustainability, 13(24), 13917. Retrieved from https://www.mdpi.com/2071-1050/13/24/13917.

Table A2). To resolve the structural classification difference, we reclassified the 42 sectors into eight distinct blocks similar to the classification in Wang et al. (2013). We established the classification of the emission intensities potentials of each sector of the economic structure. Sectors with similar intensities were aggregated together and categorized in Table 6.1.

Table 6.1. Total and Direct CO_2 Emissions of China's Economic Sectoral Structure

Categories	**Blocks**	**Sectors**	**Average Direct Emissions intensity ($t/10^4$Yuan)**			**Average Total Emissions intensity ($t/10^4$Yuan)**		
			2012	**2015**	**2017**	**2012**	**2015**	**2017**
High-carbon Industry	B1: Energy Industries	All primary energy sectors, e.g., Power sectors, Water sectors	9.89	7.95	8.51	14.87	12.11	12.45
	B2: Construction Industry	Construction Industry.	6.42	4.88	4.85	8.95	7.13	6.19
	B3: Transportation Industry	Transportation and Transportation Ancillaries.	1.15	0.90	0.84	2.50	2.03	1.74
Medium-carbon Industries	B4: Basic Industries	Non-fossil fuels; Chemical; mining; minerals; metal; and non-metal industries.	0.81	0.75	0.76	2.62	2.34	2.09
	B5: Agriculture industry	All related agricultural industries (crops, hunting, fisheries etc.).	0.18	0.14	0.15	0.91	0.82	0.49
Low-Carbon Industries	B6: Light industries	Food, beverages, timber, leather, textile, and other manufacturing sectors.	0.09	0.06	0.06	0.63	0.60	0.33
	B7: Service Industries	Retail and catering, real estate, and other service industries.	0.07	0.07	0.05	0.84	0.77	0.47
	B8: Information and Communication Technology Industries	Electronic, internet, and communication sectors.	0.05	0.05	0.05	1.05	1.02	0.61

To adequately understand the nature of CO_2 emissions in the construction industry in China, we calculated the direct and the total CO_2 emission intensities for the three years. The results of the calculated CO_2 emissions intensities of the sector are compared with other blocks within the economic structure. For the classification in Table 6.1, industrial blocks with direct CO_2 emission intensities values equal to or greater than one is classified as high-carbon industries, and those with values less than one but greater than 0.1 as medium-carbon industries. In contrast, those with lower values are classified as low-carbon industries.

As presented in Table 6.1, the construction industry's CO_2 emission intensities in the three years are second to the emissions intensities in the energy industry block. The construction industry is categorised as high-carbon industrial blocks based on the direct CO_2 emission intensities. The total CO_2 emission intensities were not used as a basis of classification. Suh (2006) indicated that total CO_2 emission intensities could be increased in sectoral blocks (especially in low-carbon industries) because of diluted overall monetary intensities based on value-added additions from other sectoral inputs. Nonetheless, the direct CO_2 emission intensities of the construction sector in China exhibit the features of a high-carbon industrial sector. The results of the CO_2 emission intensities (total and direct) contradict many opinions inferring the construction industry as a low-carbon industry. Therefore, we establish the importance of studying the critical paths of CO_2 emissions relating to the construction sector.

The contradictions in reporting the emission classification of the construction industry stem from the various aggregation systems available. In some classification systems, construction sectors are classified as buildings and civil engineering works, while other industry products in different sectors of the economic system are left out. Some industry classification system boundaries exclude emissions from the building life's final use and demolition stages. In some classification systems, the cement industry is not considered part of the construction sector. The World Green Building Council provided a basic classification system for the building and construction sector (Ahmed Ali, Ahmad, & Yusup, 2020). These classification system discrepancies play roles in the contradictions of the sector's categorization as a low, medium- or high-carbon sector. For this study, we categorized the sector as a high-carbon sector considering the system boundary in Giesekam, Barrett, and Taylor (2016), including emissions from the production stage to the end of life of buildings, materials, and all appendixes used in the industry.

*Table 6.*1 shows agriculture and basic industrial blocks as medium-carbon industries, while Light sectors, service industries and ICT industries were classed as low-carbon industrial blocks. Light industries in this study show a significant process improvement from the 2007

classifications of Wang et al. (2013), which categorised the block as a medium-carbon industry. However, the service and ICT industrial blocks remained unchanged in their CO_2 emission intensities potential classifications.

The results show an observable pattern of change in intensities from year to year. Except for service and ICT industries, results show a decrease in intestines in 2015 from the 2012 levels in the eight blocks. The same decreasing trend is observed in the 2017 direct intensities levels, except in energy and basic industrial blocks. The low-carbon industrial block exhibited a relatively stable change throughout the study.

6.3 Total CO_2 Emission Linkages

CO_2 emissions linkages in China's provincial construction sector were calculated, except for Tibet, Taiwan and the Special Administrative Regions of Hong Kong and Macau. Tibet was not included in the study because the environmental and emissions data of the province are not included in the national and regional IO tables available during the research. Taiwan, Hong Kong, and Macau are self-administrating regions with few different economic and energy policies from mainland China. Therefore, they were considered not fit for inclusion in the study. The calculated interactions were based on provincial sectoral outputs presented on the IO tables using equations (3.12) to (3.15). The CO_2 emissions linkages of each construction sector in the 30 provinces vary based on the size, predominant fuel type use, interactions with other sectors (within and outside the province), and energy efficiency.

Using equation (3.12), Figure 6.1(2012) shows the total CO_2 emissions linkages contributions of each of the 30 construction sectors in China. In 2012, the construction industry in China produced 1498.42 $MtCO_2$. The construction industries in Shaanxi province had the largest share of over 134 $MtCO_2$, with Xinjiang's 118 $MtCO_2$ and Shanxi's 94 $MtCO_2$ being the second and third highest. In all the 30 provinces, the construction industry of fourteen provinces has a share of over 50 $MtCO_2$ in total CO_2 emissions. Ten provinces had over 20 $MtCO_2$, with the remaining six provinces producing over 2 $MtCO_2$ each. Guangxi, Heilongjiang, and Jiangxi provinces were the least, with 2.04, 2.86, and 7.21 $MtCO_2$, respectively.

Figure 6.1(2015) shows a visualization of the provinces' CO_2 emissions linkages in 2015. Xinjiang province's construction sector became the highest CO_2 emitting construction sector in China, with 8.2% (127.72 $MtCO_2$) of the national construction sector's CO_2 emissions (1550.98 $MtCO_2$). In 2015, the CO_2 emissions in China's construction sector increased by 52.56 $MtCO_2$ from the 2012 levels. In 2015, Gansu province experienced the most significant increase in CO_2 emissions, with over 51 $MtCO_2$ more than in 2012. The most significant decrease in CO_2 emissions was observed in Shaanxi province, from 134.22 $MtCO_2$ in 2012 to 72.22 $MtCO_2$ in 2015, amounting to a 62% CO_2 emissions decrease. Heilongjiang province exhibited the lowest emissions intensities efficiencies by increasing the CO_2 emissions in the province by an alarming 370% of the 2012 levels, from 2.86 to 13.46 $MtCO_2$. The lowest CO_2 emissions increase was in Tianjin, Yunnan, and Hebei provinces, respectively, with 5%, 6%, and 8%. The most significant CO_2 emissions decrease was in Shandong, Liaoning, Jiangsu, and Shaanxi provinces, with a cutdown of 61%, 51%, 49%, and 46%, respectively. Shanxi province experienced a slight change in CO_2 emissions in 2015, with a 1% decrease from 2012 levels.

Figure 6.1(2017) represents the total CO_2 emissions of the 30 provincial construction sectors in 2017. Xinjiang province contributed 9.1% (181.74 $MtCO_2$) of the total national CO_2 emissions linkages in the construction sector (1999.66 $MtCO_2$). Xinjiang maintained the top spot in the CO_2 emissions source in the construction sector, contributing 181.74 $MtCO_2$ (9.1% of the national construction sector's CO_2 emissions). In 2017, Jilin, Fujian, and Yunnan provinces, with an average of 50 $MtCO_2$ in 2015, became the most CO_2 emissions after

Xinjiang. The increase in CO_2 emissions in these provinces amounted to 88.9%, 67.5%, and 75.8%. The increase indicates a reduction in CO_2 emissions efficiencies in the provinces. Henan, Sichuan, and Xinjiang provinces experienced a CO_2 emissions growth of 68.6% (96.8 $MtCO_2$), 60.9% (77.41 $MtCO_2$), and 54% (181.74 $MtCO_2$), respectively. In contrast, there was a significant reduction in CO_2 emissions in Gansu province in 2017. The CO_2 emissions reduction of 61.7% in 2017 in the region indicates Gansu kept CO_2 emissions in 2017 below the 2012 levels. Also, Ningxia, Liaoning, Anhui, Chongqing, Hainan, and Heilongjiang provinces achieved CO_2 emissions reduction in 2017 below the 2015 levels. Hubei province was the only province that maintained the same CO_2 emissions linkages from 2015 levels (81.88 $MtCO_2$).

The construction sector in China experienced a growth of over 500 $MtCO_2$ of CO_2 emissions linkages from the 30 provinces between 2012 and 2017. The results show a significant reduction in the total CO_2 emissions linkages of the Chinese construction industry when compared with the 2260 $MtCO_2$ reported for 2009 in Zhang, Liu, et al. (2019). The reduction in the CO_2 emissions of the sector was observed more in the more developed provincial construction sectors like Jiangsu, Beijing, Shanghai, and Chongqing. The construction sectors in these regions are more demand-driven as most of the CO_2 emission linkages result from intra-provincial transactions. The total CO_2 emission linkages in some less developed and more remote provinces like Xinjiang, Ningxia, Inner Mongolia, and Qinghai are intensified as more construction-based activities are carried out.

2012


Heilongjiang
2.86
Inner Mongolia
91.91
Jilin
26.26
Lia...
39.53
Xinjiang Uygur
118.30
Gansu
62.53
Sha...
94.03
Sha...
77.39
Qinghai
63.48
134.22
Henan
16.04
Tibet
Sichuan
12.64
88.94
29.85
Hunan
62.95
Jian...
7.21
Gui...
27.53
30.67
Yunnan
40.20
2.04
11.42

2015


Heilongjiang
13.46
Inner Mongolia
101.97
Jilin
44.28
Lia...
19.36
Xinjiang Uygur
127.72
Gansu
113.59
Sha...
92.67
Sha...
30.15
Qinghai
100.53
72.22
Henan
28.21
Tibet
Sichuan
16.52
81.88
49.29
Hunan
56.32
12.84
Gui...
45.80
55.81
Yunnan
42.59
2.53
7.92

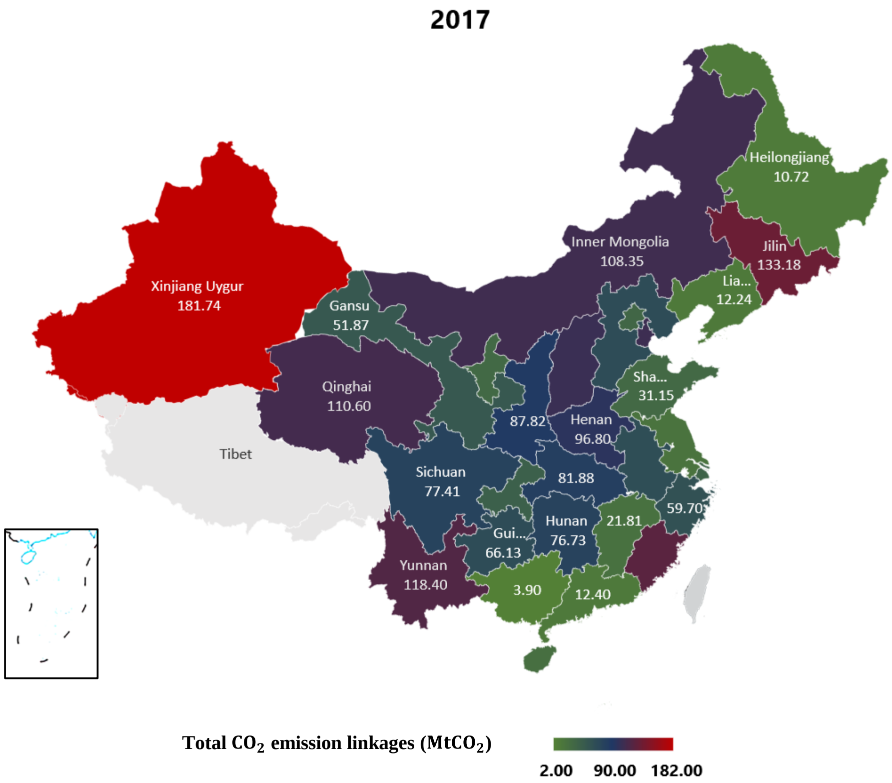


Figure 6.1 Total CO_2 emission linkages of provincial construction sectors in China.

The total CO_2 emission linkages per population density of each province for 2012, 2015, and 2017 indicate the CO_2 emission intensities concerning people and space. The population density in many Chinese regions is high, and many studies suggest it is a primary drive for construction activities and increase CO_2 emission within the provinces (Liu, Gao, & Lu, 2017; Wang, Liu, & Shi, 2019). Figure 6.2 shows relatively stable growth in CO_2 emission linkages in many provinces except four. Gansu, Inner Mongolia, Qinghai, and Xinjiang construction sectors indicate high and growing CO_2 emission linkages per population density. The construction sectors in these provinces show that population density did not necessarily increase construction activities. Instead, demand from other developed and developing provinces' final demand might have caused increasing CO_2 emission linkages in these regions.

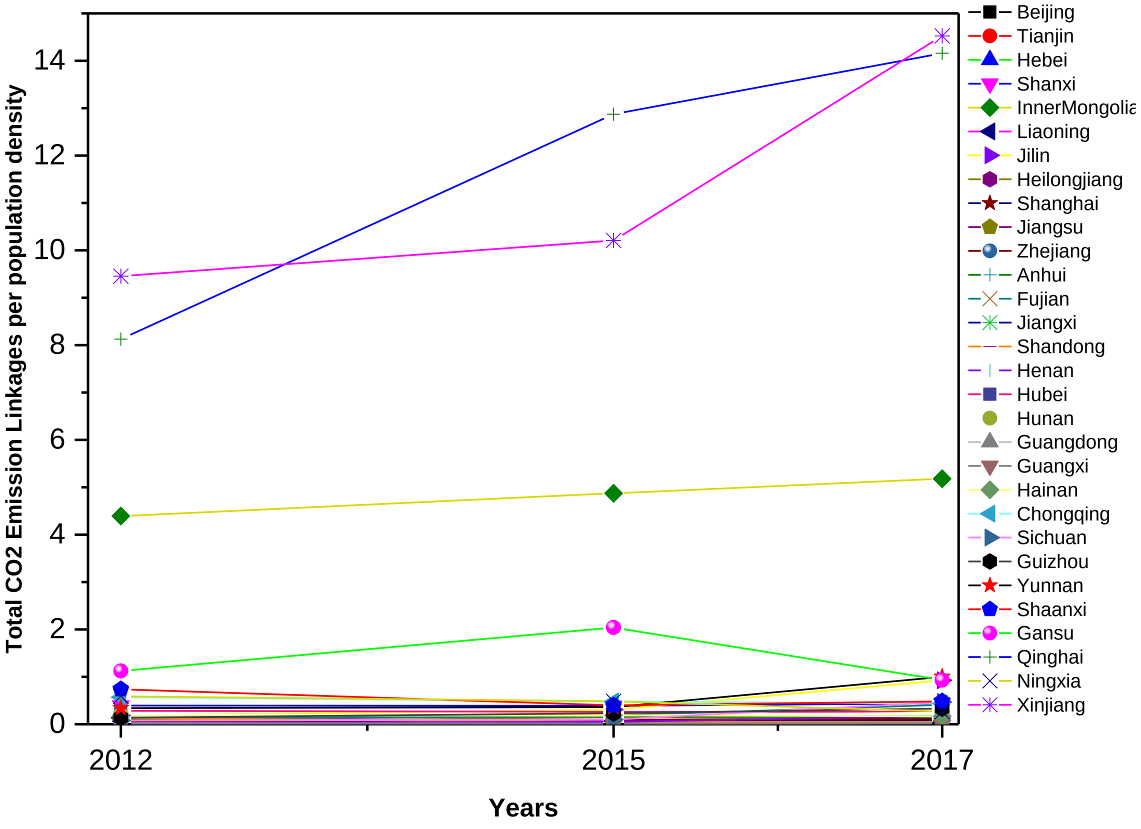


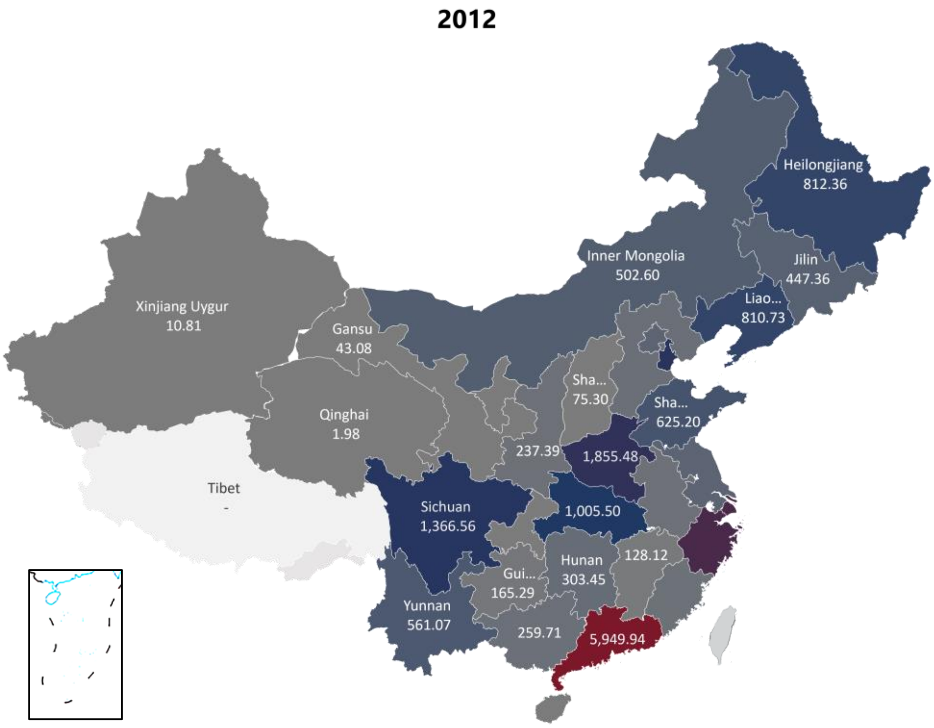
Figure 6.2. Construction Sectors' Total CO_2 Emissions per Population Densities

6.4 Forward and Backward CO_2 Emission Linkages

The first-order decomposition of CO_2 emissions linkages of China's construction industry is the forward and backward CO_2 emissions linkages. These directional decomposition components determine the pull and push effects of the local constructions with other industrial sectors. Figure 6.3 and Figure 6.4 show the backwards and forward effects in China's 30 local construction industries, respectively. The BE of all 30 local construction sectors increased from 24,678.09 tCO_2 in 2012 to 27,910.17 tonnes of CO_2 in 2015. In 2017, there was a slight decrease to 27727.53 $MtCO_2$, amounting to a reduction of 182.64 tonnes of CO_2 from the 2015 levels. Guangxi, Shanghai, Zhejiang, and Henan contributed most to the backwards linkages in 2015 with 24.1%, 13.3%, 12.8%, and 7.5%, respectively. With the addition of Sichuan and Hubei, these provinces had BE above 1,000 tonnes of CO_2, with Guangxi having 5,949.94 tCO_2 (Figure 6.3(2012)). The BE in Guangxi intensified in 2015 with a contribution of 1,940.30

tCO_2 of the total national additions of 3,232.08 tCO_2 (Figure 6.3(2015)). Henan added 1,827.97 tCO_2 to the 2012 levels to have a BE of 3,683.45 tCO_2 in 2015. Shanghai and Tianjin provinces experienced the most significant reductions of over 1,000 tCO_2 from 2012 to 782.38 and 337.99 tCO_2 in 2015. Figure 6.3 (2015) shows that Shandong, Fujian, Chongqing, and Hunan provinces significantly increased BE in 2015.

In 2017, Hubei province maintained the same BE as in 2015 (523.53 tCO_2). While most provinces reduced BE in 2017, Guangxi, Hunan, and Jiangxi significantly increased BE by over 1,000 tCO_2 (Figure 6.3 (2017)). Zhejiang province had over 3,000 tonnes of CO_2 BE in the three years. The most significant BE reduction was observed in Henan, Shandong, Fujian, and Chongqing provinces (2,350.32 tCO_2, 1,240.75 tCO_2, 1,149.67 tCO_2, and 650.36 tCO_2, respectively). 59% of the national BE in 2017 were from Guangxi (34%), Zhejiang (12%), Hunan (8%), and Jiangxi (5%).



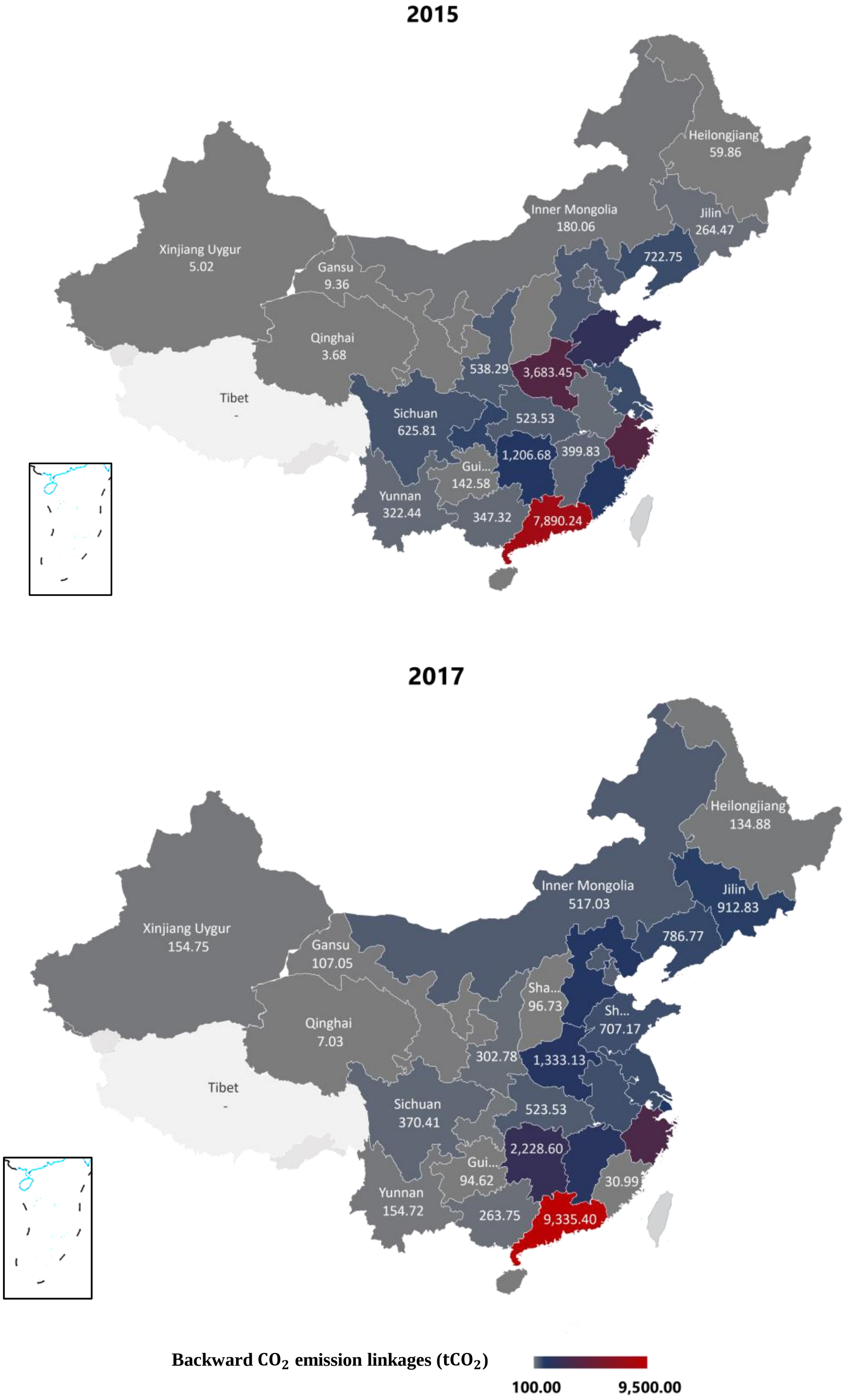


Figure 6.3. Backward CO_2 emission linkages of provincial construction sectors in China.

The forward emission linkages measure the outward emissions from the construction sector to the economic structure of other provinces. The constriction sectors in Xinjiang, Shaanxi, Inner Mongolia, Shanxi, Tianjin, and Qinghai exhibited FE characteristics of the TL. Figure 6.4 shows the primary source of CO_2 emissions in the construction industry is products of the sector. The FE characteristics of local construction sectors in China indicate a high relative ratio with the BE, implying the sectors' dominance in production activities within the economic structure. Overall, the construction sector in China is not a consumption sector as it contributes more to forward emissions than it receives on the backward path (the consumption activities). (Appendix Table A3) gives details of the FE and BE in provincial economic structures in China. The low value of the BE in construction sectors in China indicates the Chinese economic dependence on infrastructural development. The construction industry in China drives the developmental activities of the economy by assuming the core industrial sector of the Chinese economy. Figure 6.4 shows Xinjiang, Shaanxi, Inner Mongolia, Tianjin, and Qinghai as the prominent hidden links of CO_2 emissions in the construction sector in China.

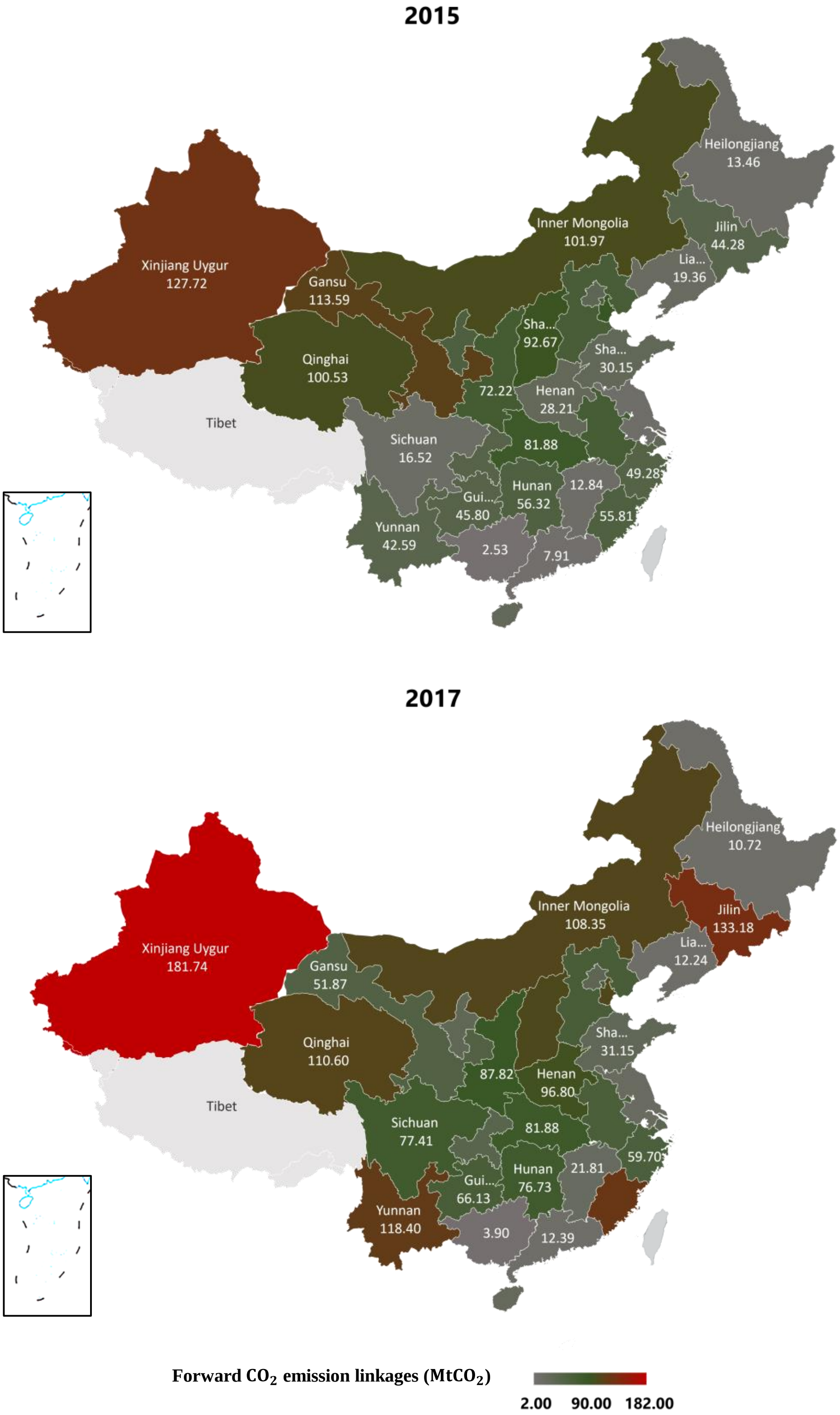


Figure 6.4. Forward CO_2 emission linkages of provincial construction sectors in China.

6.5 Modified Directional Decomposition of CO_2 Emission Linkages

The second-order decomposition of CO_2 emissions linkages of China's construction industry is the decomposition of the BE and FE to understand the dual nature effects of the first-order emission paths. The modified HEM approach disaggregated BE and FE CO_2 emission linkages into sub-components mixed and net CO2 emissions. The net backward linkages indicate the CO_2 emissions inherent in the products of other sectors used in the construction industry. On the other hand, the net backwards linkages indicate the CO_2 emissions generated in products of the construction sector wholly used up in other sectors' production activities. The mixed effects are two-directional features of pull and push CO_2 emissions effects. The mixed forwards effects are CO_2 emissions accrued from products of other sectors used in construction sectors' production and sold back to the economy to satisfy the final demands of different sectors. In contrast, mixed backward effects are CO_2 emissions embodied in products originating from the construction sector, sold to make other sectors' products, and returned to the construction sector to satisfy its final demand.

Table 6.2 presents the mixed and net backward effects of the 30 construction sectors in China. The CO_2 emissions embodied in the intermediate demands of the construction sectors in most of the local construction sectors are unitary directional (NBE). In 2012, only Qinghai, Shanxi, and Gansu had over 10% of CO_2 emissions embodied in dual-directional BE, with Qinghai having 54%. In 2015 and 2017, the trend remained with mixed-backwards linkages in only four provinces that exceeded 10%. Qinghai province had reduced its MBE to 28% by 2017. The NBE in Table 6.2 shows most of the CO_2 emissions in the backward path of the Chinese construction sectors are from goods from other industries and hardy returns to the originating sector. The result implies the construction sector in China is more of a production sector than a consumption sector. The NBE indicates the sectors' large amount of materials intake from other industries and discharging considerable CO_2 emissions back to the economy in its products.

In the same vein,

Table 6.3 presents the directional effects of the FE in provincial construction sectors in China. The mixed directional FE are CO_2 emissions in the construction sector's intermediate products purchased initially as inputs from other sectors. In comparison, the one-directional net FE are CO_2 emissions embodied in products of the construction sector that are sold and fully used in other sectors. The results in

Table 6.3 shows almost all the provincial construction sectors produced CO_2 emissions from outward bounds products of the industry, with little return from other sectors after the intermediate products are converted to final products. All the provincial sectors tend towards more production-based CO_2 emissions sources than demand-based. In 2017, Qinghai (27.7%), Guizhou (15.8%), Hubei (12.7%), Fujian (11.2%), Shanxi (8.5%), Yunnan (8.5%), and Sichuan (6.0%) have mixed FE over 5%. The relative indices in 2017 suggest a sector increasing its dependence on other sectors within the economic structure. Deductively, the construction industry is an overall net exporter of CO_2 emissions in the Chinese economy, with little usage of CO_2 emissions produced from other sectors' final products.

Table 6.2. Mixed and Net Backward CO_2 emission linkages of Construction Sectors

Province	**MBE (tCO_2)**			**NBE (tCO_2)**			**Relative Indices**					
							2012		**2015**		**2017**	
	2012	**2015**	**2017**	**2012**	**2015**	**2017**	**MBE**	**NBE**	**MBE**	**NBE**	**MBE**	**NBE**
Beijing	23.46	13.48	17.41	378.24	332.97	531.23	5.8%	94.2%	3.9%	96.1%	3.2%	96.8%
Tianjin	15.06	19.99	21.08	1483.03	318.00	434.94	1.0%	99.0%	5.9%	94.1%	4.6%	95.4%
Hebei	3.34	7.44	5.27	266.53	557.68	1128.67	1.2%	98.8%	1.3%	98.7%	0.5%	99.5%
Shanxi	8.59	8.36	8.18	66.71	93.70	88.55	11.4%	88.6%	8.2%	91.8%	8.5%	91.5%
Inner Mongolia	20.80	12.02	12.99	481.80	168.04	504.03	4.1%	95.9%	6.7%	93.3%	2.5%	97.5%
Liaoning	17.79	7.47	6.82	792.94	715.27	779.94	2.2%	97.8%	1.0%	99.0%	0.9%	99.1%
Jilin	7.68	12.95	2.72	439.68	251.53	910.11	1.7%	98.3%	4.9%	95.1%	0.3%	99.7%
Heilongjiang	2.55	1.85	0.74	809.81	58.01	134.14	0.3%	99.7%	3.1%	96.9%	0.5%	99.5%
Shanghai	9.86	11.55	6.50	3269.02	770.83	1001.11	0.3%	99.7%	1.5%	98.5%	0.6%	99.4%
Jiangsu	5.73	3.44	1.34	393.09	725.85	736.62	1.4%	98.6%	0.5%	99.5%	0.2%	99.8%
Zhejiang	60.04	97.18	30.41	3095.33	3685.30	3288.66	1.9%	98.1%	2.6%	97.4%	0.9%	99.1%
Anhui	5.95	11.09	12.52	227.66	303.22	682.46	2.5%	97.5%	3.5%	96.5%	1.8%	98.2%
Fujian	8.59	13.04	3.47	242.57	1167.62	27.52	3.4%	96.6%	1.1%	98.9%	11.2%	88.8%
Jiangxi	1.84	5.21	2.44	126.28	394.62	1470.51	1.4%	98.6%	1.3%	98.7%	0.2%	99.8%
Shandong	34.02	35.89	6.81	591.19	1912.03	700.36	5.4%	94.6%	1.8%	98.2%	1.0%	99.0%
Henan	28.35	56.81	8.07	1827.13	3626.64	1325.06	1.5%	98.5%	1.5%	98.5%	0.6%	99.4%
Hubei	30.13	66.65	66.65	975.37	456.88	456.88	3.0%	97.0%	12.7%	87.3%	12.7%	87.3%
Hunan	28.38	57.79	53.77	275.07	1148.89	2174.83	9.4%	90.6%	4.8%	95.2%	2.4%	97.6%
Guangdong	51.87	42.49	3.45	5898.07	7847.75	9331.95	0.9%	99.1%	0.5%	99.5%	0.0%	100.0%
Guangxi	0.60	1.06	0.24	259.11	346.26	263.52	0.2%	99.8%	0.3%	99.7%	0.1%	99.9%
Hainan	0.06	3.35	1.08	0.76	32.00	46.97	7.3%	92.7%	9.5%	90.5%	2.2%	97.8%
Chongqing	0.57	9.57	1.98	21.11	824.70	181.93	2.6%	97.4%	1.1%	98.9%	1.1%	98.9%
Sichuan	62.13	48.15	22.15	1304.43	577.66	348.27	4.5%	95.5%	7.7%	92.3%	6.0%	94.0%
Guizhou	10.17	17.36	14.98	155.12	125.22	79.64	6.2%	93.8%	12.2%	87.8%	15.8%	84.2%
Yunnan	26.67	38.49	13.21	534.40	283.95	141.52	4.8%	95.2%	11.9%	88.1%	8.5%	91.5%

Shaanxi	2.67	3.63	2.49	234.72	534.66	300.29	1.1%	98.9%	0.7%	99.3%	0.8%	99.2%
Gansu	4.61	2.60	4.50	38.46	6.75	102.55	10.7%	89.3%	27.8%	72.2%	4.2%	95.8%
Qinghai	1.07	1.95	1.95	0.91	1.73	5.08	54.0%	46.0%	53.0%	47.0%	27.7%	72.3%
Ningxia	0.55	2.07	1.47	5.63	24.46	60.76	8.9%	91.1%	7.8%	92.2%	2.4%	97.6%
Xinjiang	0.84	0.53	0.61	9.96	4.49	154.14	7.8%	92.2%	10.6%	89.4%	0.4%	99.6%

Table 6.3. Mixed and Net Forward CO_2 emission linkages of Construction Sectors

Province	**MFE ($MtCO_2$)**			**NFE ($MtCO_2$)**			**Relative Indices**					
							2012		**2015**		**2017**	
	2012	**2015**	**2017**	**2012**	**2015**	**2017**	**MFE**	**NFE**	**MFE**	**NFE**	**MFE**	**NFE**
Beijing	0.77	0.84	1.29	46.45	35.21	33.47	1.6%	98.4%	2.3%	97.7%	3.7%	96.3%
Tianjin	3.10	0.76	1.19	81.14	88.10	105.55	3.7%	96.3%	0.9%	99.1%	1.1%	98.9%
Hebei	2.37	3.03	3.45	58.74	62.75	62.59	3.9%	96.1%	4.6%	95.4%	5.2%	94.8%
Shanxi	0.17	0.27	0.57	93.86	92.40	104.15	0.2%	99.8%	0.3%	99.7%	0.5%	99.5%
Inner Mongolia	1.52	1.42	1.34	90.39	100.56	107.02	1.7%	98.3%	1.4%	98.6%	1.2%	98.8%
Liaoning	1.21	1.39	0.64	38.32	17.97	11.60	3.1%	96.9%	7.2%	92.8%	5.2%	94.8%
Jilin	1.53	1.00	13.95	24.74	43.28	119.23	5.8%	94.2%	2.3%	97.7%	10.5%	89.5%
Heilongjiang	0.75	0.25	0.39	2.12	13.20	10.32	26.1%	73.9%	1.9%	98.1%	3.7%	96.3%
Shanghai	1.78	0.68	1.01	35.87	30.23	37.42	4.7%	95.3%	2.2%	97.8%	2.6%	97.4%
Jiangsu	0.85	1.66	4.78	23.66	10.82	14.72	3.5%	96.5%	13.3%	86.7%	24.5%	75.5%
Zhejiang	0.85	1.38	3.13	29.00	47.90	56.57	2.8%	97.2%	2.8%	97.2%	5.2%	94.8%
Anhui	0.83	1.05	0.76	51.69	68.17	63.37	1.6%	98.4%	1.5%	98.5%	1.2%	98.8%
Fujian	0.36	3.56	0.36	30.31	52.25	122.98	1.2%	98.8%	6.4%	93.6%	0.3%	99.7%
Jiangxi	0.34	1.20	4.15	6.87	11.63	17.66	4.7%	95.3%	9.4%	90.6%	19.0%	81.0%
Shandong	0.68	1.04	0.96	76.70	29.11	30.19	0.9%	99.1%	3.4%	96.6%	3.1%	96.9%
Henan	1.78	3.90	2.22	14.25	24.31	94.58	11.1%	88.9%	13.8%	86.2%	2.3%	97.7%
Hubei	0.77	0.33	0.33	88.17	81.55	81.55	0.9%	99.1%	0.4%	99.6%	0.4%	99.6%
Hunan	0.40	0.88	1.70	62.55	55.44	75.03	0.6%	99.4%	1.6%	98.4%	2.2%	97.8%
Guangdong	2.08	2.27	1.59	9.34	5.65	10.80	18.2%	81.8%	28.6%	71.4%	12.8%	87.2%
Guangxi	0.24	0.38	0.45	1.80	2.15	3.44	12.0%	88.0%	14.9%	85.1%	11.7%	88.3%
Hainan	0.00	0.17	0.29	24.94	26.99	23.96	0.0%	100.0%	0.6%	99.4%	1.2%	98.8%
Chongqing	0.05	0.89	2.02	55.14	45.69	40.60	0.1%	99.9%	1.9%	98.1%	4.7%	95.3%
Sichuan	0.59	0.47	0.63	12.04	16.06	76.78	4.7%	95.3%	2.8%	97.2%	0.8%	99.2%
Guizhou	0.31	0.24	0.17	27.22	45.56	65.96	1.1%	98.9%	0.5%	99.5%	0.3%	99.7%
Yunnan	0.47	0.19	0.20	39.73	42.40	118.20	1.2%	98.8%	0.4%	99.6%	0.2%	99.8%
Shaanxi	1.36	2.12	3.26	132.86	70.09	84.56	1.0%	99.0%	2.9%	97.1%	3.7%	96.3%

Gansu	0.42	0.18	0.24	62.11	113.41	51.63	0.7%	99.3%	0.2%	99.8%	0.5%	99.5%
Qinghai	0.01	0.03	0.09	63.46	100.50	110.52	0.0%	100.0%	0.0%	100.0%	0.1%	99.9%
Ningxia	0.12	0.33	0.68	70.90	57.92	31.60	0.2%	99.8%	0.6%	99.4%	2.1%	97.9%
Xinjiang	0.17	0.08	0.80	118.13	127.64	180.95	0.1%	99.9%	0.1%	99.9%	0.4%	99.6%

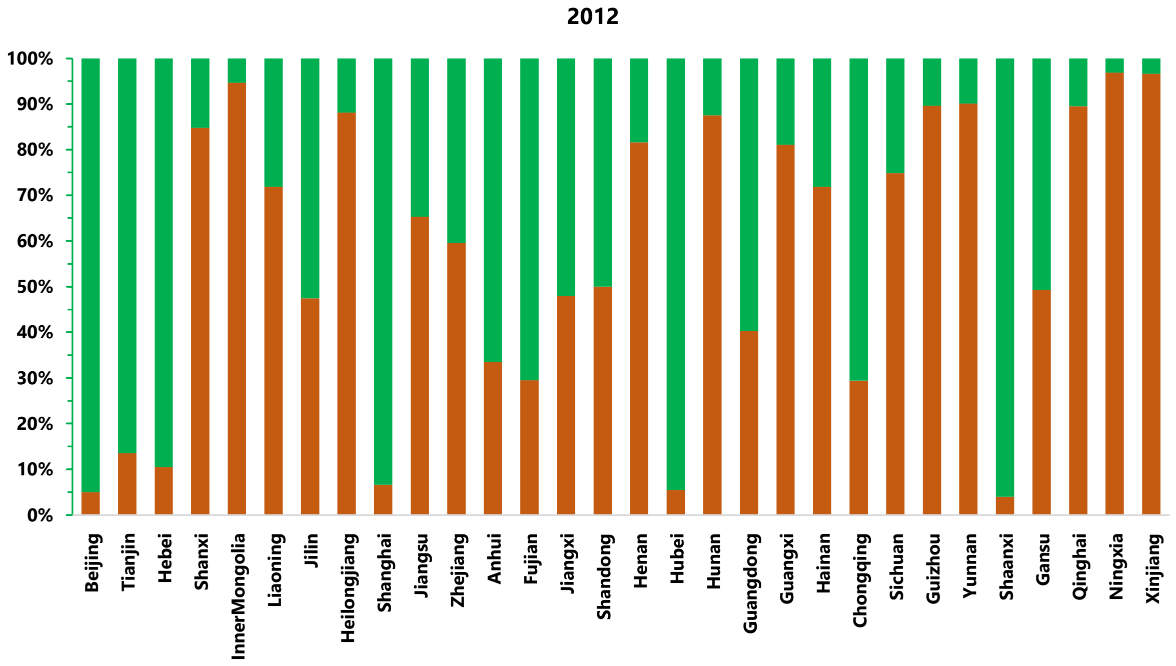
6.6 Transferred CO_2 Emission Linkages Sources and Destinations

This section measured the domestic and inter-provincial paths of CO_2 emissions interaction among the 30 construction industries and other sectoral blocks within and outside the provinces. The domestic exchanges (DNBE and DNFE) are CO_2 emissions of the construction sector with other industrial blocks within the same province. On the other hand, the inter-provincial linkages (INBE and INFE) are CO_2 emissions interactions of the construction industry with other industrial blocks in different regions in China. Due to the dual-directional features of the mixed linkages, only the net linkages are suitable for further decomposition to understand the sources of the emissions. Appendix (Table A4) shows the domestic and inter-provincial CO_2 emissions distribution.

6.6.1 Net Backward CO_2 Emission Linkages Sources

The DNBE are CO_2 emissions resulting from trades of the local construction industry with other sectoral blocks within the same provinces. In contrast, the INBE are CO_2 emissions sourced in trade transactions of the local construction with other sectors from other provinces. Figure 6.5 shows the percentages of CO_2 emissions caused by intra-provincial exchanges in the 30 provinces in China for 2012, 2015, and 2017. In 2012, seventeen of the 30 provinces had over 50% of their net backward CO_2 emissions accruing from transactions within their provinces, while the remaining thirteen had more CO_2 emissions from inter-provincial trades. Beijing had almost absolute CO_2 emissions sources from interprovincial exchanges with over 97% of the net backward CO_2 emissions. Guangdong and Hebei provinces had similar CO_2 emissions sourced from inter-provincial transactions (94%) (*Figure 6.5*(2012)). Ningxia, Xinjiang, Inner Mongolia, Yunnan, Guizhou, and Qinghai are more domestic consumption provinces, with at least 90% of their CO_2

emissions originating from domestic sources. In 2015, 19 local construction sectors had over 50% of net backward CO_2 emissions resulting from trades within their provinces (*Figure 6.5*(2015)). In 2017, the number dropped to 17 (*Figure 6.5*(2017)). Overall, Beijing, Hebei, Shaanxi, Shanghai, Hubei, Chongqing, and Guangdong construction sectors sourced over 75% (on average) of their backward CO_2 emissions from inter-provincial trades. These provinces are some of the most developed in China. These results show that the construction sectors in many developed areas are net consumption provinces, depending on products from other provinces to satisfy their final local demands. On the other hand, construction sectors in less developed provinces like Ningxia, Xinjiang, Guizhou, and Hainan consume more locally produced goods within their provincial boundaries as their final demands.



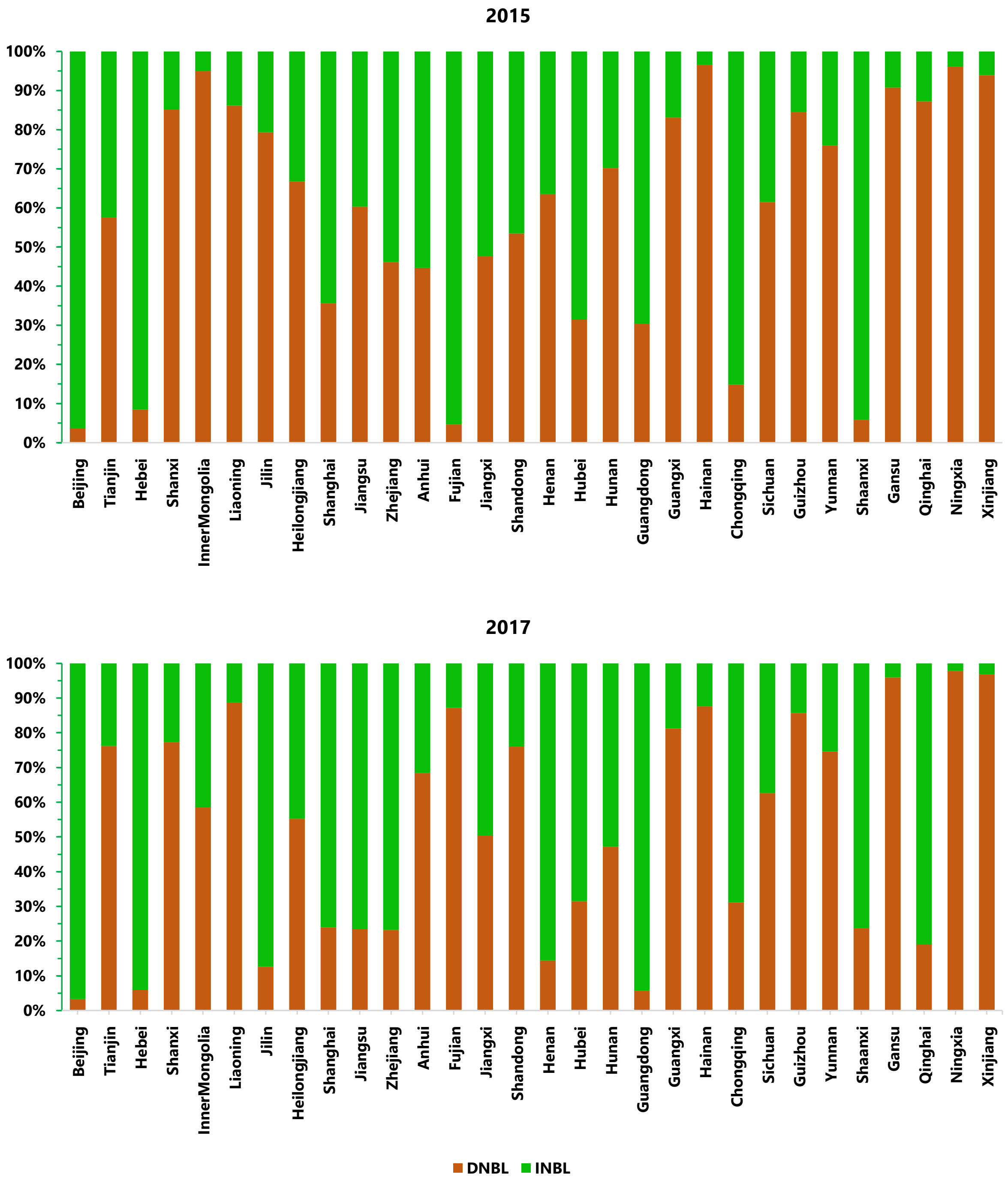
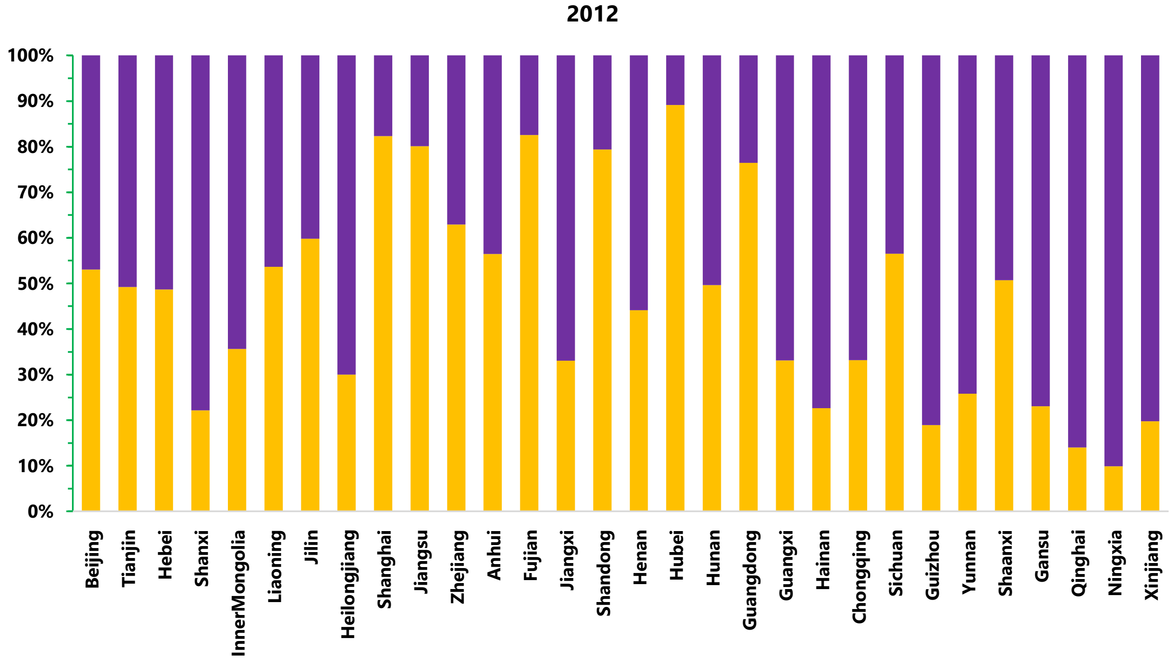


Figure 6.5. Transferred backwards CO_2 emission linkages

6.6.2 Net Forward CO_2 Emission Linkages Sources

In the same vein as the net backward CO_2 emissions linkages, we decomposed the net forward linkages into domestic and inter-provincial paths. We traced the eventual destinations of CO_2

emissions generated in each local construction sector in China. Over the years of investigation, Xinjiang, Ningxia, Qinghai, and Gansu construction sectors are China's largest net exporters of CO_2 emissions. These provinces sold over 80% of CO_2 emissions outflows in trades to other industries in different provinces, while local sectors bought up the remaining 20% to satisfy their final demands (Figure 6.6). Likewise, Shanxi, Jiangsu, Heilongjiang, Hainan, and Guizhou construction sectors had over 70% of CO_2 emissions outflows embodied in interprovincial products. Some developed provinces like Beijing, Chongqing, Hunan, and Hebei had their CO_2 emissions outflows almost divided equally between domestic and inter-provincial destinations. However, most developed provinces like Shanghai, Hubei, Jiangsu, Zhenjiang, Guangdong, and Shandong, with significant population density, have most of the CO_2 emissions outflows embodied within their provinces with small fractions embodied in inter-regional trades.



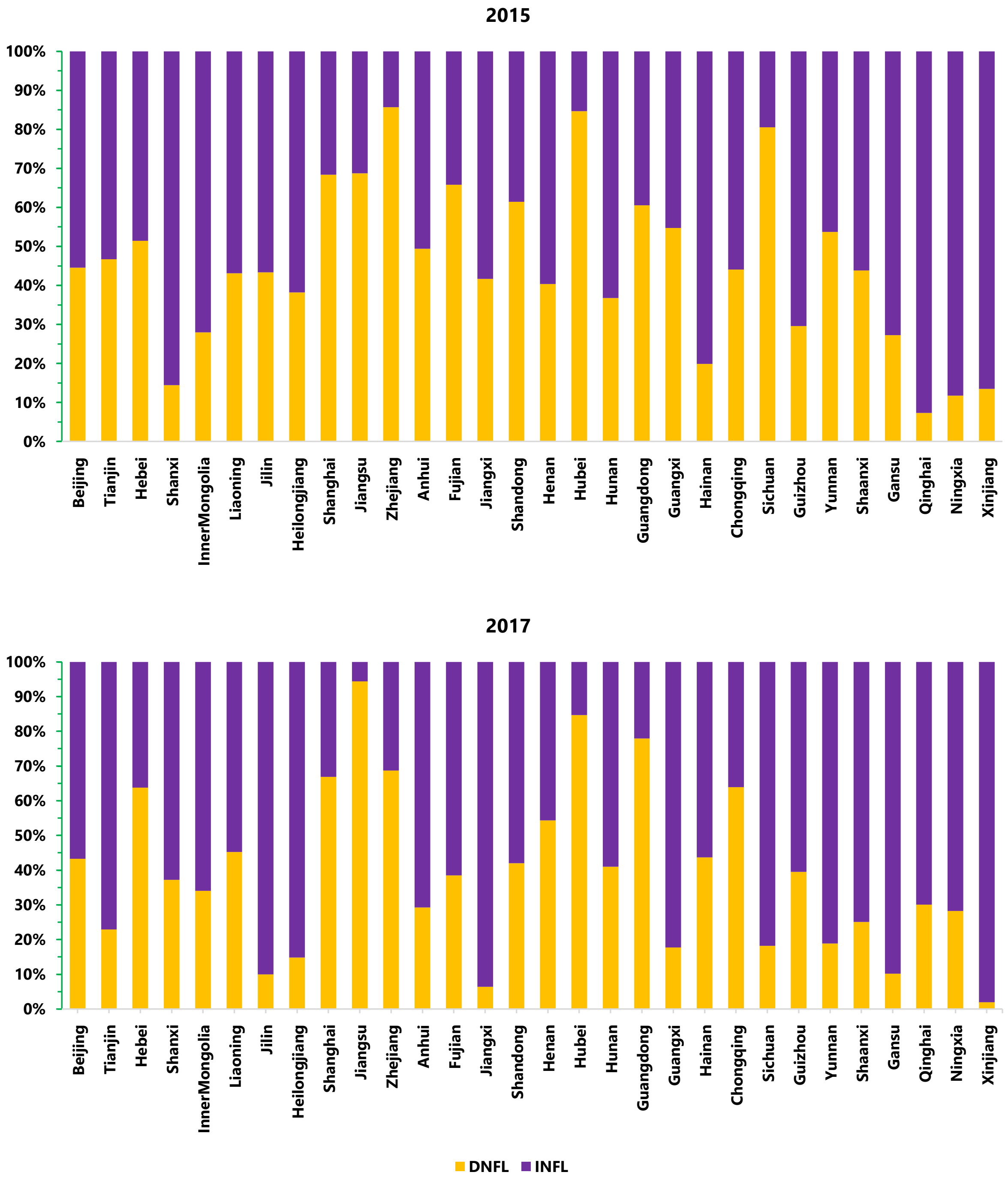


Figure 6.6. Transferred forward CO_2 emission linkages

6.7 Discussion of Findings in Objective Two

The results from the analysed data of the study indicate some exciting and essential observations regarding the criticality and influence of different provincial construction industries on the overall

CO_2 emissions of China. This section of the chapter discusses the implications of the results and possible policy implications of the results in the following sub-headings:

6.7.1 Classification of China’s Construction Industry Carbon Intensity

Contrary to the previous categorization of the construction industry in China as a low-carbon industry (Wang et al., 2013), this study’s results classed the sector as a high-carbon industry with high CO_2 direct intensities. The sector is only second to energy industries as China's top CO2 intensified sectoral blocks. The average CO_2 direct intensity of the sector increased from less than 0.5 t/10^4 Yuan in 2007 (Wang et al., 2013) to 4.85 t/10^4 Yuan in 2017. The implication means the construction sector in China have more significant tendency to emit more CO_2 than most industrial sectors currently receiving more attention in terms of sustainable policy changes. In addition, it could indicate the CO_2 emission efficiency of the industry in China is low compared to other industrial sectors in the country. Investing in enhanced technology to improve the sector's carbon efficiency could be a more feasible route to achieving net-zero carbon emissions in China.

6.7.2 CO_2 Emissions Linkages of China’s Construction Sector

The total CO_2 emissions linkages of the provincial construction sectors combined showed a significant increase from 1,498 $MtCO_2$ in 2012 to 2000 $MtCO_2$ in 2017. With the observed increasing trend in CO_2 emission flow in and out of the construction industry, the construction sector in the 30 provinces has exhibited itself as an essential sector with significant economic and emissions interactions with other sectors. However, the total CO_2 emission linkage compared with the population density of most of the provinces showed a reasonable correlation except in Xinjiang, Qinghai, Inner Mongolia, and Gansu, with relatively high construction activities, more than what is needed to satisfy population demands in the provinces. The results from the study indicate the nature of construction activities in these provinces tends toward production for consumption in other regions. The four provincial construction sectors are net producers and exporters of CO_2 emissions, affecting the final demands of different areas in direct trade with these provinces. The study identified the four provincial construction sectors as the most critical industry.

Developed provinces bear responsibility for the emissions taking place for developmental purposes within their borders, making them more demand driven. The more remote provinces in China should aim to move away from behaving as net exporters of emissions to demand-driven sectors. Akan et al. (2017) suggested the development of emission-reducing technologies focused on less developing areas as a better way to help these regions achieve a better emission behavioral pattern. In addition to technological improvements in the provinces, tax incentives could be introduced to areas with critical emission indications and encouragement of inter-provincial knowledge transfer.

6.7.3 Directional Push and Pull Effects of Provincial Construction Sectors' CO_2 Emission

The study results showed significant deficits in the CO_2 emissions balance between the provinces' BE and FE. The FE far outweighs the BE of the provincial construction sectors, indicating a tilt towards a net emitting sector in the upstream rather than a downstream position in most provincial construction industries. The results imply the construction sectors contribute more CO_2 emission outflows through trade to other economic sectors and do not, in turn, absorb CO_2 emissions in goods from those sectors. Further decomposition of the sectoral linkages of the 30 construction sectors further proved the sector as a net one-directional forward CO_2 emission emitting sector. Both BE indicators (NBE and MBE) show extremely negligible values compared to the two indicators of FE (NFE and MFE). In particular, the minimal value of MBE CO_2 emission in all the 30 provincial sectors indicate the construction sectors have low consumption of its products manufactured from intermediate products used by other sectors to produce their final products. The NBE values indicate the construction sectors consume more products from other sectors to satisfy final demands than intermediate consumption. Also, the small BE means the construction sector provides more products to other industries in the economic structure than it receives, indicating the significant embodied CO_2 emissions in products used in different industries. The NFE, on the other hand, suggests the dependence of other sectors on products of the construction sector. The indicators accentuate the construction sector's pivotal role in developing Chinese technology and industrialization and the need to have more focused sustainability strategies. There is a need to focus on China's construction and concrete industries as an essential sector for climate change just as the energy, transportation, and manufacturing industries. More attention should be given to decompartmentalizing construction products to enable dual usage rather than only being valuable as goods for satisfying final demand in other sectors.

6.7.4 Transferred CO_2 Emissions Linkages of China’s Provincial Construction Sectors

The research revealed the sources and destinations of CO_2 emissions in the provincial construction sectors of China's 30 provinces. The findings revealed that most CO_2 emissions in raw materials in the local construction sectors are sourced within and outside their respective provinces. The observed pattern suggested some developed provinces like Beijing, Shanghai, and Chongqing averagely had more CO_2 emissions inflows from inter-provincial sources. In contrast, many provinces, especially less developed provinces such as Xinjiang, Ningxia, Gansu, and Inner Mongolia, have the most BE CO_2 emissions embodied in products purchased within their provinces. In addition, the destinations of CO_2 emissions in FE suggest that a good part of CO_2 emissions from the construction industry are transferred to different sectors within the same provinces. 43% of CO_2 emissions from the 30 provincial construction sectors combined were transferred to other sectors within the same province, and 56% in inter-provincial trades. The implication suggests products from construction sectors play vital developmental roles within and outside their provinces of origin, indicating a reasonable balance in the inter-sectoral and inter-provincial trades of the construction sector in China. However, Hubei, Jiangsu, Shanghai, Zhejiang, and Guangdong provinces have more CO_2 emissions in inter-sectoral trade than inter-provincial trades. While Xinjiang, Ningxia, and Qinghai contributed more CO_2 emissions in inter-provincial transactions.

6.8 Chapter Summary

The chapter focused on the calculations of CO_2 emissions inflows and outflows in 30 provincial construction sectors in China, using a well-established HEM model combined with the constructed extended MRIO tables for 2012, 2015, and 2017.

The chapter underlines the need for specific sectoral CO_2 emission mitigation plans to consider the different province's emission characteristics rather than a generic approach. More importantly, the materials used for construction require improved process innovations to achieve better CO_2 emission intensities. Improved construction sector CO_2 emissions policies in developed provinces like Shanghai, Beijing, and Jiangsu show a significant change in the behavior of these regions. The more developed provinces' construction sectors have shifted towards being demand-driven. At the same time, the less developed regions serve as net exporters of construction products to the entire economic system, resulting in imbalanced CO_2 interactions between the provinces. Thus, increasing the CO_2 linkages originating from the less developed provincial construction sectors. Therefore, to achieve a reduction in CO_2 in the industry, improving the technical level, especially in less developed provinces like Xingjian, Ningxia, and Inner Mongolia, will benefit the entire construction sector’s CO_2 emissions mitigation drive. Lastly, the construction sector in China needs to invest more into independent, innovative low-carbon research to reduce the industry’s process dependence on fuel and make non-renewable energy the primary energy source. An absolute and urgently increased share of low carbon energy in provincial construction sectors will substantially achieve the national carbon reduction target and reach zero carbon by 2060.

CHAPTER SEVEN: DRIVING FORCES OF CO_2 EMISSIONS IN CHINA'S CONSTRUCTION SECTOR

7.1 Introduction

In this chapter of the thesis, Structural Decomposition Analysis (SDA) was combined with logarithmic mean Divisia method I (LMDI I) to trace the driving forces of CO_2 emissions at national, regional, and provincial levels of the Chinese construction sector. The forces considered in the chapter are the Final Demand Effect (FDE), Final Demand Structure Effect (FDSE), the Leontief Structure Effect (LSE), and Direct Carbon Emissions Intensity Effect (DCEIE). The chapter aimed to: (1) identify the change in the Chinese construction sector CO_2 emissions linkages from base year level (2012) and reference years levels (2015 and 2017). (2) determine the directional trend of the change in CO_2 emissions linkages in the sector at national, regional, and provincial levels. (3) identify the most critical driving force affecting the CO_2 emissions linkages of the sector and suggest relevant policy indications and recommendations towards reducing the influence of the factors on CO_2 emissions. The approach adopted in the chapter takes a cue from the HEM assumptions and principles in previous chapters. The framework for the chapter is presented in Figure 7.1.

In previous chapters of the thesis, we established the backward linkages of the construction industry to be negligible compared with the forward linkages accruing from the industry. For a reminder, the FL are CO_2 emissions embodied in all intermediate goods and services originating in the construction sector and used up by the downstream sectors of the national economic structure. In contrast, the BL are CO_2 emissions embodied in the opposite direction as the FL. They are CO_2 emissions embodied in intermediate inputs from other downstream sectors of the economic structure consumed in the construction sector. Due to the small amount of BL in the

Chinese construction sector determined in Chapter Six, we limit this chapter's scope to decompose the effects of the driving forces on Total CO_2 emissions linkages in the Chinese construction sector. In other words, this chapter focuses on production-based carbon emissions embodied in the construction sector of China.

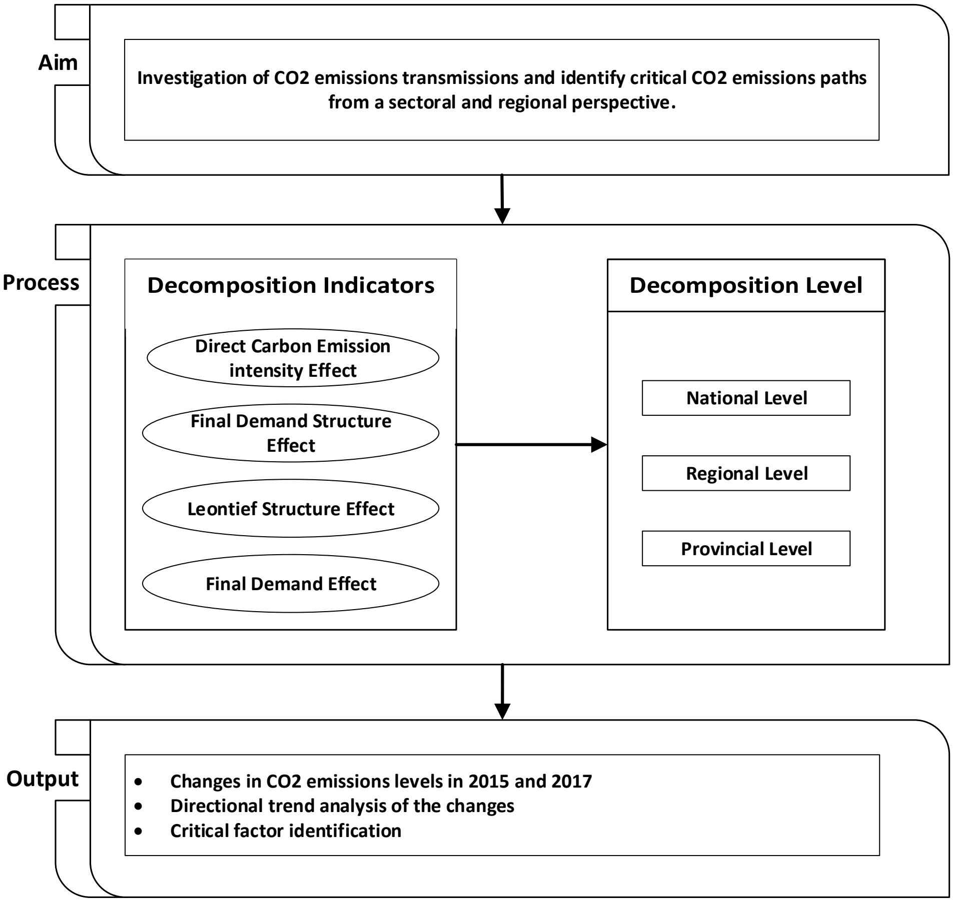


Figure 7.1 Chapter Framework

7.2 National Level Decomposition of the Driving Forces

Table 7.1 presents the change in CO_2 emissions reference years (2015 and 2017) from the base year (2012) in the national Chinese construction sector. The difference in 2015 showed an addition of over 690 Mt of CO_2 emissions shared between the four driving factors compared to the just above 506 Mt addition in 2017. The result indicates a difference of 192.11 Mt of carbon emissions reduction in 2017 production of the sector. Theoretically, the decrease in carbon emissions intermediate injections from the construction sector on the national economic scale indicates a reduction in the sector's goods and services requirements. However, the theory of demand and supply may not necessarily determine the reduction experienced in the second reference year. Therefore, we decomposed the total change in production-based carbon emissions interjections into the four driving forces to understand the pattern and direction of change.

In 2015, three of the four change indicators positively influenced carbon emission changes from 2012 levels. Results showed direct carbon emissions intensity amounted to negative change, indicating a reduction in the total CO_2 emissions linkages between the construction sector and other downstream sectors of the Chinese economy. Table 7.1 shows the final demand had the most significant change in CO_2 emissions linkages in 2015 with over 500 Mt. LSE had 255 Mt additional, while the least positive influencing factor is the FDSE with 25 Mt.

Correspondingly, the influence pattern of the driving forces observed in 2015 is consistent in 2017. The difference in the two reference years is the influence of the FDSE sector with a negative change against the positive change in 2015. Although the 2017 level showed lower influences in the factors than in 2015, FDE remained the most critical driving force of CO_2 emissions linkages in production-based infusions of the sector with 463 Mt. In 2017, a significant difference in the LSE was observed with a 172 Mt reduction from 2015 levels. The LSE maintained the second most critical factor in 2017, while the DCEIE had the third most influence on CO_2 emissions linkages in the sector. However, the DCEIE in 2017 levels increased by 46 Mt compared to 2015. The result indicates a reduction in carbon intensity efficiency in the sector in 2017. Nationally, the four driving forces influenced production-based CO_2 emissions linkages of the construction sector by 1205 Mt in 2015 and 2017 combined. While the final demand and LSEs increased CO_2 emissions linkages between the industry and other downstream sectors of the Chinese economy, the reduced direct carbon emissions intensity indicates a favorable rate of change in emission efficiency of the industry.

Table 7.1. Driving Forces Effects on Change in Total CO_2 Emission Linkages (MCO_2)

Reference Years	**Direct carbon emissions intensity**	**Leontief structure**	**Final demand**	**Final demand structure**	**Total Change in Reference Year**
2015	-81.93	255.34	500.40	25.10	**698.91**
2017	-35.35	83.13	463.90	-4.88	**506.80**
Total Change	**-117.28**	**338.47**	**964.30**	**20.22**	**1205.71**

7.3 Regional Level Decomposition of the Driving Forces of Production-Based CO_2 emissions

The change in production-based carbon emissions in the construction sector in China consists in different regions and provinces. A regional level deposition analysis was conducted to understand better the decomposition distribution of the driving forces and its influence on national economic structure. The national construction sector was divided into six regions: North, Northeast, East, Southcentral, Southwest and Northwest China. Figure 7.2 and Figure 7.3 show the distribution of the four driving factors' effects in China's six regional construction sectors in 2015 and 2017, respectively. This section aims to identify the most critical region in production-based CO_2 emissions.

7.3.1 2015 Levels Change Decomposition

As established in the national construction decomposition in 2015, the FDE had the most influence out of the four driving forces in the sector, with the final demand structure having the least impact. The FDE in 2015 peaked in the Southcentral region with 230 Mt, amounting to 46% of the total CO_2 emissions linkages resulting from the FDE. The result indicates the considerable size of the construction product market in the region compared to the Northwest region with 1.94 Mt (0.39%) of FDE magnitude. East China's FDE had the second most influential share with over 23% (119.37 Mt). the other three regions had less than 12% share influence in the FDE in 2015. As a result, Southcentral and East China demonstrated to be the two most critical regions influencing the FDE CO_2 emissions linkages share in China's construction industry with a combined influence of almost 70% of total production-based CO_2 emissions change.

Results of the SDA in Table 7.2 showed the LSE as the second most critical production-based CO_2 emissions after the FDE. Aggregating the LSE into regional decomposition showed Southcentral as the most critical LSE region with over 50% (130 Mt) contribution, and Northwest had 14.59 Mt (5.7%). The Southwest region LSE in 2015 level is 87.36 (34.2%), East and North regions had 40 Mt and 34.77 Mt respectively. All the regions (except the Northeast region) LSE contributions increased production-based CO_2 emissions by 306.85 Mt, indicating the importance of the negative impact of Northeast LSE. The LSE in the Northeast region reduced production-based CO_2 emissions by over 51 Mt, causing overall LSE to be 255.34 Mt. The reduction in the Northeast region had an impact of -16.78% on overall LSE in 2015.

The FDSE in Figure 7.2 shows five of the six regions had increased impacts on production-based CO_2 emissions in 2015. The most significant change was in the Southcentral region with 33.55 Mt, while the North had 6 Mt change. The Southwest and Northwest regions had a combined change of 4 Mt. However, as observed in LSE, the Northeast region contributed to reducing the production-based CO_2 emissions from FDSE by -32.6 Mt. The reduction in the Northeast region caused a decrease of 56.5% production-based CO_2 emissions in the Chinese construction sector in 2015.

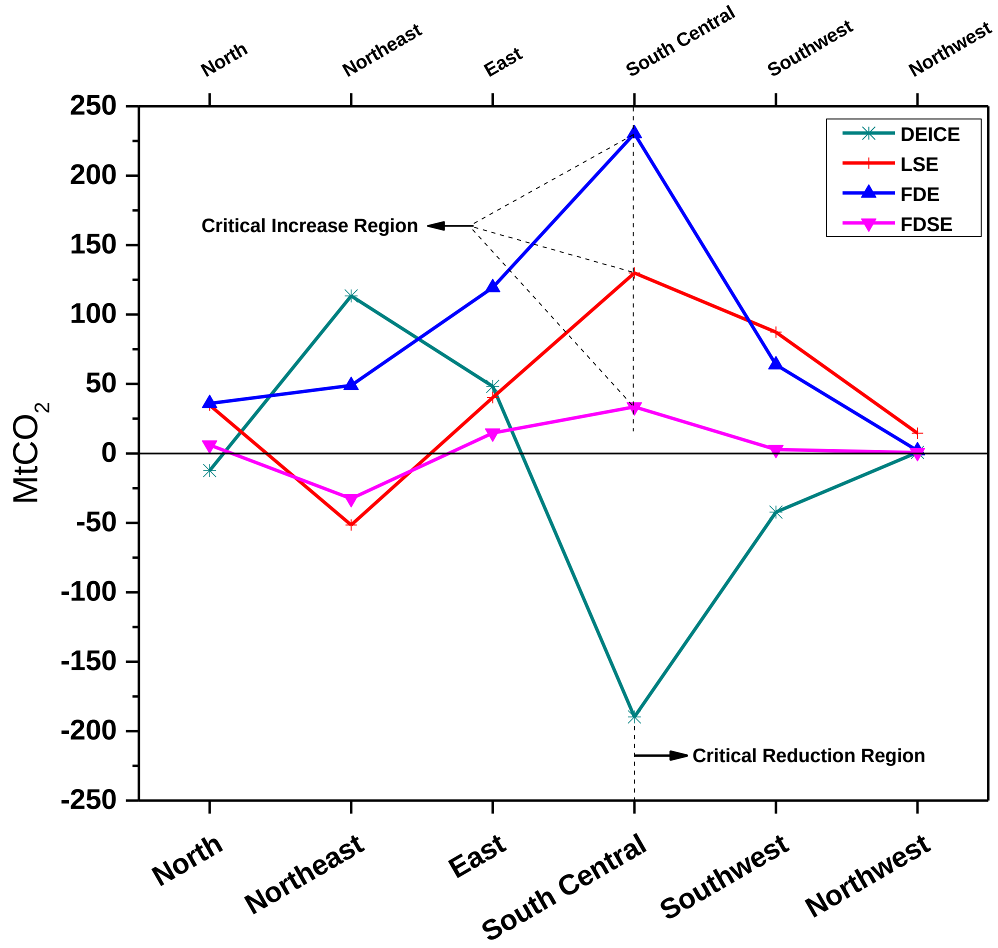


Figure 7.2 Driving Forces of CO_2 Emissions in Regional Construction in 2015

On the other hand, the change distribution of DCEIE varied in directional magnitude from region to region. Three regions negatively impacted production-based CO_2 emissions linkages, while the other three increased the CO_2 emissions linkages in the construction sectors. The Southcentral region had the most significant impact - maintaining consistency with the other driving forces. However, the magnitude of change in DCEIE is negative. DCEIE reduced production-based CO_2 emissions by 189.75 Mt, while the Southwest and North had a reduction impact of 42.24 and 12.33 Mt, respectively. DCEIE resulted in a change of 113.42 Mt in the Northeast, making the region the most critical addition to production-based CO_2 emissions linkages in the construction sector in 2015. Overall, Figure 7.2 shows the Southcentral region's critical directional magnitude for reducing and adding the four driving forces in 2015.

Table 7.2. Regional production-based CO_2 emissions changes by driving forces in 2015

Region	**DEICE**	**LSE**	**FDE**	**FDSE**	**Total**
North China	-12.33	34.77	35.93	6.10	**64.47**
Northeast China	113.42	-51.51	48.93	-32.60	**78.23**
East China	48.25	40.23	119.37	14.63	**222.47**
Southcentral China	-189.75	129.90	230.33	33.55	**204.02**
Southwest China	-42.24	87.36	63.90	2.75	**111.77**
Northwest China	0.74	14.59	1.94	0.68	**17.94**
Total	**-81.93**	**255.34**	**500.40**	**25.10**	**698.91**

Table 7.2 shows the aggregated changes caused by each driving force in the six regional construction sectors in 2015. FDE and LSE were the critical driving forces in the increased production-based CO_2 emissions, contributing 755 Mt between them. However, DCEIE showed positives by helping to reduce CO_2 emissions by 82 Mt. The distribution of the change in CO_2 emissions in the sector indicated that all six regional construction sectors contributed to the increased production-based emissions. The critical regions from the results are East, Southcentral, and Southwest in the order, contributing 77% of the total CO_2 emissions from production-based linkages from the sector to other downstream industries in the economic spectrum of China. The Northwest regional construction sector demonstrated an environmental sustainability characteristic with only 18 Mt contribution in 2015.

7.3.2 2017 Levels Change Decomposition

For 2017 level changes, Table 7.3 shows the change distribution from the base year, 2012, for the four driving forces in the six regional construction sectors. Just as in 2015, the most significant change occurred with the FDE, with an over 460 Mt increase from the 2012 levels. East and southcentral regions contributed 147 Mt and 112 Mt, respectively, making them the most significant contributors in 2017. FDE changes in the six regions indicated additions to CO_2 emissions. The result suggests a positive change growth in the demand for final products of the industry in all regions of China in 2017. The increased demand could result from the increased urbanization rates experienced in the country, with the industry at the heart of all industrial and residential growth.

Also, following the change observed in 2015, the LSE had the second most significant change in CO_2 emissions in 2017. However, in 2017, the rate of increase reduced significantly compared with the CO_2 emissions addition in 2015. The Southcentral region was most critical in the increased CO_2 emissions changes of LSE in 2017, with a 41 Mt contribution. Northwest and North regions had additional 22 and 26 Mt contributions, respectively. The slightest additional increase was recorded in the Southwest region, with a 1 Mt contribution. Meanwhile, while other regions increased CO_2 emissions in the sector, the Northeast region reduced LSE in 2017.

Table 7.3. Regional production-based CO_2 emissions changes by driving forces in 2017

Region	DEICE	LSE	FDE	FDSE	Total
North China	-26.99	26.41	35.19	-24.74	9.87
Northeast China	87.47	-27.30	39.43	59.85	159.44
East China	11.08	18.84	147.71	-8.64	169.00
Southcentral China	-68.71	41.24	112.82	41.24	126.60
Southwest China	-47.99	1.29	61.84	-19.52	-4.38
Northwest China	9.79	22.65	66.91	-53.08	46.27
Total	**-35.35**	**83.13**	**463.90**	**-4.88**	**506.80**

DEICE varies in the six regions, with CO_2 emissions reduction in three regions and addition in the other three regions. The most significant increase in DEICE occurred in the Northeast region with an additional effect of 87 Mt compared with a little below 10 Mt contribution from the Northwest region. The most significant reduction in CO_2 emissions results from DEICE in the Southcentral, Southwest, and North regions, with -68, -47, and -27 Mt, respectively. Compared to the two previously discussed driving forces, the DEICE resulted in CO_2 emissions reduction in more regions with a combined reduction of -35.35 Mt to the sector's national CO_2 emissions stock. Similarly, the combined resultant influence of the FDSE in the six regional construction sectors reduced CO_2 emissions by -4.88 Mt. Overall effects of the driving forces in the six regions in Table 7.3 indicate three significant regions in the increasing trend of CO_2 emissions in China's construction sector in 2017. East, Northeast, and Southcentral regions contributed over 89% of the total CO_2 emissions increase in the industry in 2017 reference levels.

Figure 7.3 illustrates the influence of each driving force on the six regional construction's CO_2 emissions. The distribution of the effects shows the East region is most critical in CO_2 emissions increase in FDE. Although the southcentral region contributed the most to reducing CO_2 emissions on DEICE, the region's influence is also significant on the FDE.

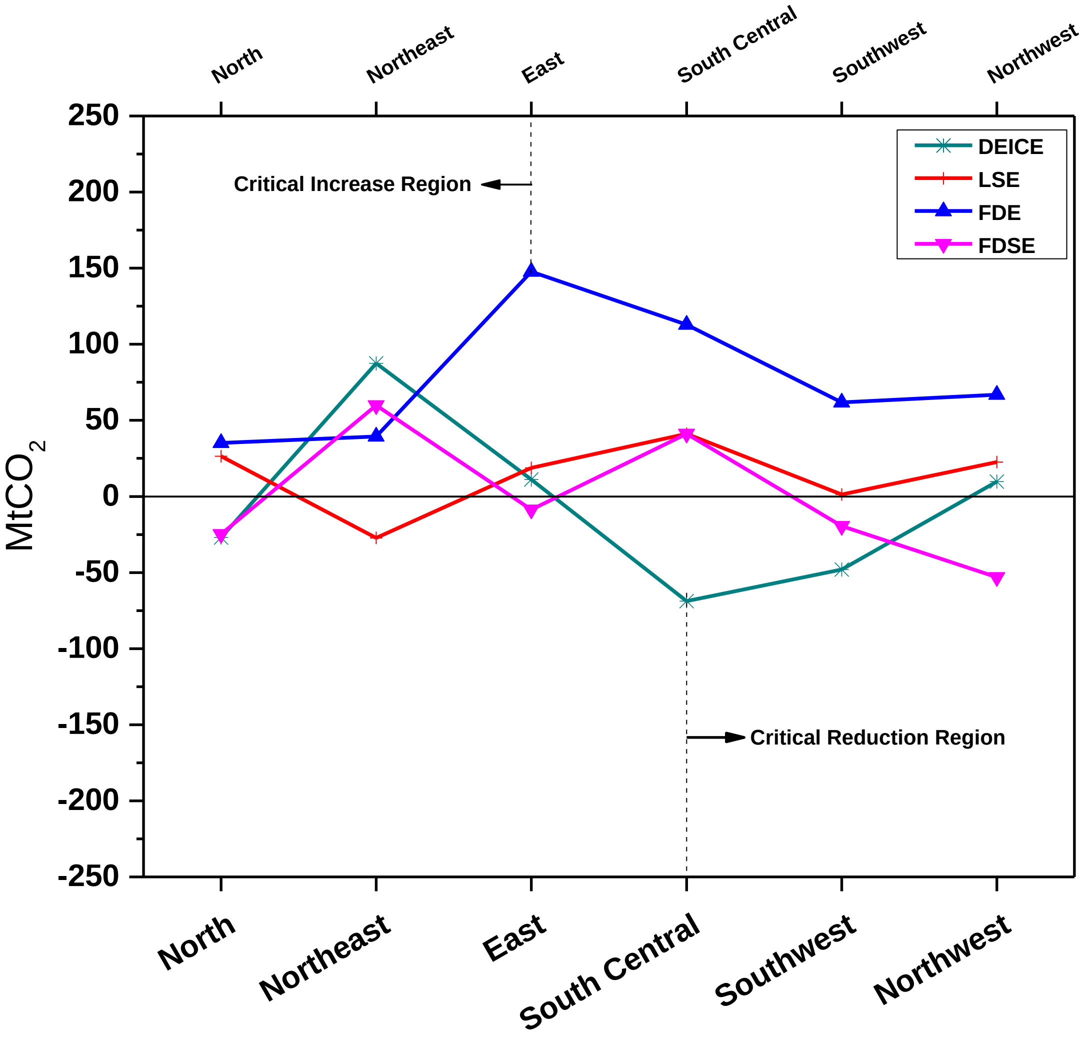


Figure 7.*3* Driving Forces of CO_2 Emissions in Regional Construction in 2017

7.3.3 Combined Regional Effects of Driving Forces in Reference Years

The cumulative effects of the change in CO_2 emissions in the reference years caused by the four driving forces are shown in Table 7.4. The results show FDE, and LSE had the most significant addition to CO_2 emissions, with an additional joint effect of 1302 Mt (greater than the net CO_2 emissions increase by the four factors). Compared to the emissions level in the base year (2012), the six regions combined added 1205 Mt CO_2 emissions in production-based linkages over the two reference years. Cumulatively, the FDSE added only 20 Mt CO_2 emissions to the production-based linkages in the sector in reference years, denoting a low significance of the driving forces in regulating CO_2 emissions generated in the industry. However, unlike the other three driving forces, DEICE had a negative drive on CO_2 emissions in the industry. The resultant implication of the negative force by DEICE is a contributing reduction in CO_2 emissions by -117 Mt.

The reduction caused by DEICE indicates an improvement in technology and emissions intensity efficiency in the industry in the reference years, reflecting the introduction of new technological innovations, optimization of supply chain management, and the drive to achieve better sustainability in the sector. However, as the construction process and technical optimization drive the industry to achieve better CO_2 emissions intensity efficiency, the final demand for the industry and its products increased, as seen in the massive leap in FDE throughout the investigation period. The LSE increase is best described as the increased interconnection between the Chinese economy's construction sector and other economic sectors. The construction sector has been at the heart of China’s globalization and civilization drive over the few decades, causing an increase in the resultant upward drive of CO_2 emissions originating from the industry in other economic sectors.

Table 7.4. Aggregated Production-Based CO_2 emissions Changes by the driving forces

Region	**DEICE**	**LSE**	**FDE**	**FDSE**	**Total**
North China	-39.33	61.18	71.12	-18.64	**74.34**
Northeast China	200.88	-78.81	88.35	27.25	**237.67**
East China	59.33	59.07	267.08	6.00	**391.47**
Southcentral China	-258.46	171.13	343.16	74.79	**330.62**
Southwest China	-90.23	88.66	125.74	-16.78	**107.39**
Northwest China	10.52	37.25	68.85	-52.40	**64.21**
Total	**-117.28**	**338.47**	**964.30**	**20.22**	**1205.71**

The distribution in Table 7.4 shows the critical regions with more significant CO_2 emissions effects in the industry over the two reference years. The decreasing sides of the drive indicate a resultant reduction in CO_2 emissions, while the positive movement suggests the addition of CO_2

emissions in production-based linkages. On the increasing side, the results show FDE in the Southcentral region had the most significant cumulative change in CO_2 emissions over the two reference years. The change in CO_2 emissions recorded in the region alone is more than the incremental change caused by the next driving force (LSE) in the six regions combined. The effect is better illustrated in Figure 7.4, indicating the region as the most critical increase region. The second most significant regional force drive is observed on the same driving force (FDE) in the East region, with an addition of 267 Mt CO_2 emissions. The Northeast region had a massive share of addition to CO_2 emissions in DEICE against the general deduction recorded by other regions in the same driving force. The trend observed in the Northeast region over the two reference years suggests CO_2 emissions intensity of the region is a critical increase drive in the industry.

As presented in Figure 7.4, the southcentral region has a critical reduction in CO2 emissions significantly on the DEICE force over the reference years. The results indicated a decrease of over -258 Mt, negating the addition recorded in the East region FDE. The accumulation of the effects of the four driving forces in each region shows four of the regions contributed a minimum increase of 100 Mt CO_2 emissions over the reference years. However, the results indicate the East, the Southcentral, and the Northeast region as the most critical regions to CO_2 emissions increase in the industry over the reference years. Notably, the east region is considered critical in driving CO_2 emissions increase due to having the most contribution and being the only region with additions in all four driving forces. Unlike the Southcentral region, where the DEICE helped reduce CO_2 emissions, the East region had additions in all four driving forces.

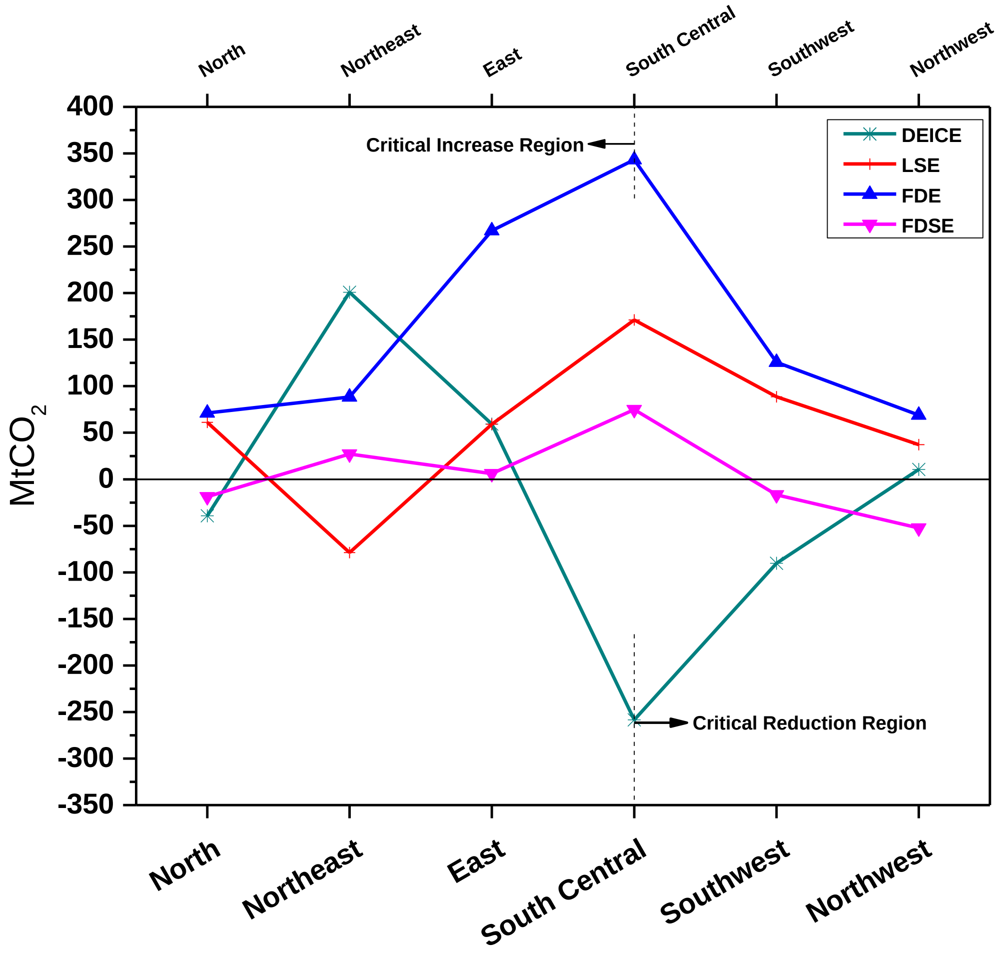


Figure 7.4 Cumulative Effects of Driving Forces of CO_2 emissions in Reference Years

7.4 Provincial Level Decomposition of the Driving Forces

This section further breaks down the directional effects of the four driving forces of CO_2 emissions in the 30 provinces used in the study. The discussions in this section aimed to indicate the most critical provincial threats in CO_2 emissions increase over the reference years and underline the provinces with improvements in 2017 levels compared with the 2015 CO_2 emissions levels. Although, due to the limited availability, the trend may not be established. However, the amount of production-based CO_2 emissions in the reference years in each of the 30 provinces is quantified. The tables are organised in ranks to depict the highest to the lowest contributing province to production-based CO_2 emissions linkages.

The effects of the four driving forces on CO_2 emissions in the provinces in Table 7.5 show the distribution across the 30 provinces in 2015 reference year levels. In 2015, Henan province had the most increased CO_2 emissions change from its base year CO_2 emissions, with a cumulative 158 Mt. The distribution for the province indicated the four driving forces having positive directional impacts on the changes compared to Jiangsu, with DEICE acting as a reduction force. With the second most CO_2 emissions change in 2015 levels, Jiangsu province had a 71 Mt difference from the Henan province. Shanghai and Jilin provinces ranked next to Henan and Jiangsu to complete the four provinces with cumulative change effects greater than 50 Mt in 2015. The four provinces combined had a change effect of 55% of the total CO_2 emissions increase from the base year levels. Figure 7.5 indicates that these four provinces fall within the critical increase provinces of CO_2 emissions in the industry in 2015 reference year levels.

The results in Table 7.5 show that 14 of the 30 provinces had over 10 Mt incremental changes in CO_2 emissions in the first reference year. The cumulative effects of these first 14 provinces resulted in 93.8% of the total CO_2 emissions changes in 2015 reference year levels. Shandong, Hunan, Guangxi, Anhui, Yunnan, and Ningxia combined contributed less than 0.25% of the total CO_2 emissions in production-based linkages, with less than 1 Mt additions each. The results indicate these provinces as not very critical to CO_2 emissions in the production-based supply chain of the industry.

Table 7.5 Driving Forces of Provincial CO_2 emissions Production-Based Linkages, 2015.

Province	DEICE	LSE	FDE	FDSE	Total	Rank
Henan	27.96	48.06	74.23	8.40	158.65	1
Jiangsu	-5.05	45.97	42.05	4.85	87.82	2
Shanghai	-22.85	30.72	68.48	7.10	83.46	3
Jilin	22.63	6.88	21.56	4.56	55.64	4
Chongqing	-52.75	37.37	56.28	6.03	46.93	5
Tianjin	-41.53	34.52	39.74	7.80	40.53	6
Hubei	-92.62	51.34	67.77	9.68	36.17	7
Guizhou	16.07	-16.30	33.68	2.69	36.14	8
Jiangxi	27.20	-6.30	6.85	1.19	28.93	9
Sichuan	-5.20	63.07	-23.71	-5.60	28.55	10
Liaoning	69.44	-41.96	26.49	-37.71	16.26	11
Hebei	-4.12	9.25	6.26	3.92	15.31	12
Zhejiang	-1.15	-11.95	19.61	4.42	10.93	13
Fujian	76.82	-37.29	-24.50	-4.47	10.56	14
Xinjiang	-11.49	11.16	6.77	2.12	8.56	15
Heilongjiang	21.34	-16.43	0.88	0.55	6.34	16
Inner Mongolia	17.18	-1.67	-5.65	-3.55	6.31	17
Qinghai	-2.17	2.86	4.47	0.90	6.06	18
Hainan	-5.90	7.25	2.74	0.68	4.77	19
Guangdong	-20.58	12.45	10.40	1.41	3.68	20
Gansu	-6.92	14.58	-4.92	-0.74	2.01	21
Shaanxi	22.32	-14.14	-5.15	-1.76	1.26	22
Beijing	9.04	-4.12	-2.96	-0.80	1.16	23
Shanxi	7.10	-3.22	-1.46	-1.27	1.15	24
Shandong	-21.70	15.37	5.74	1.21	0.62	25
Hunan	-98.49	11.19	74.54	13.29	0.54	26
Guangxi	-0.12	-0.40	0.65	0.08	0.21	27
Anhui	-5.02	3.71	1.14	0.33	0.15	28
Yunnan	-0.36	3.23	-2.35	-0.37	0.15	28
Ningxia	-1.01	0.13	0.76	0.16	0.05	30

Critical provinces are identified in Figure 7.5, contributing the most to overall CO_2 emissions in the reference year. The criticality of the provinces in Figure 7.5 is double-directional. The negative directional provincial effects are provinces with a significant reduction in CO_2 emissions, while the positive directional effects are the driving provinces of CO_2 emissions in the industry. Hubei and Hunan are important reduction provinces, with Chongqing and Tianjin also contributing to CO_2 emissions reduction in 2015. It is, however, noticed that most reduction provinces were made on DEICE.

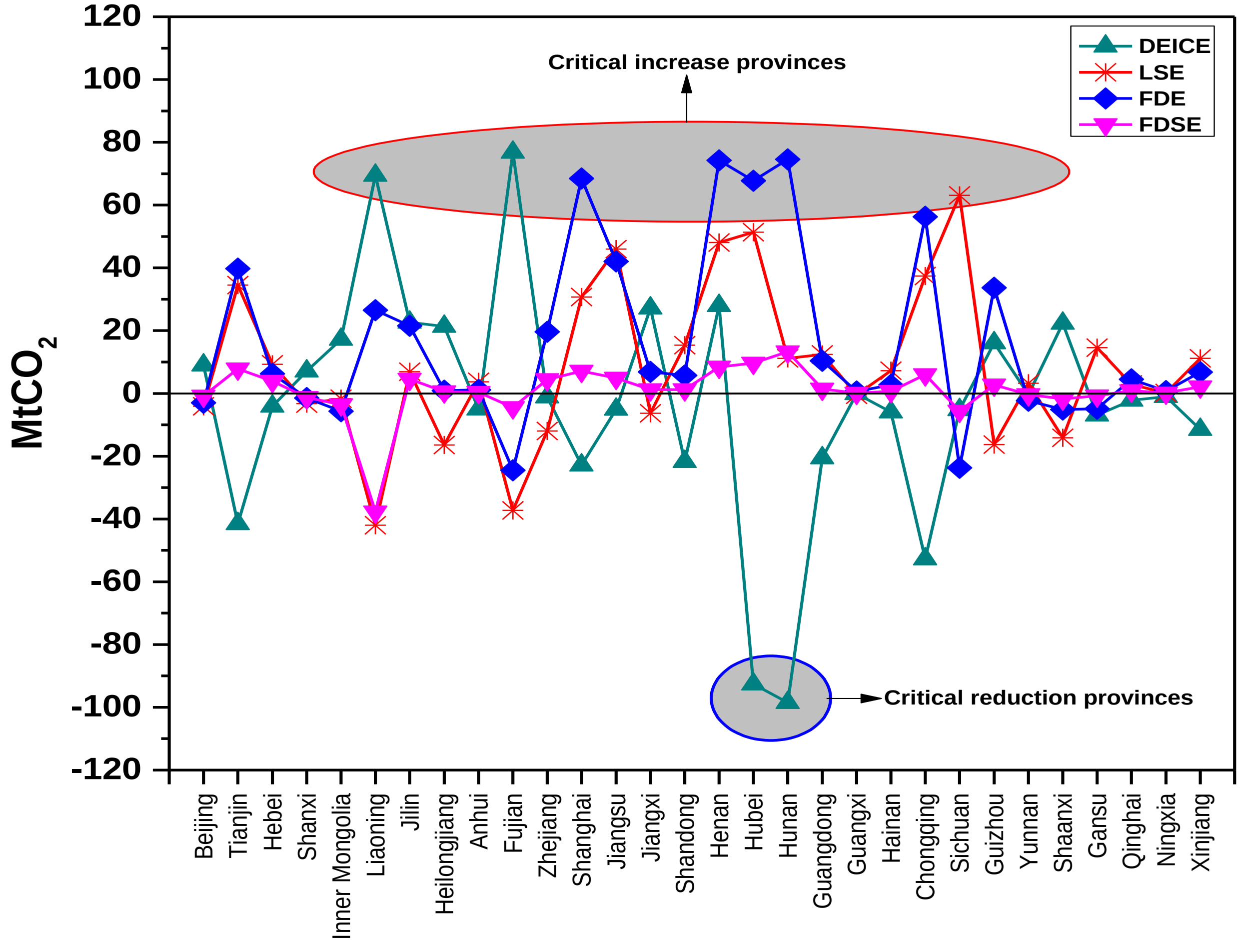


Figure 7.5 Provincial Distribution of Driving Forces Changes in 2015 Reference Levels

For 2017, in Table 7.6, Henan province was the third most contributing province after Shanghai and Liaoning. The biggest contributing province had 138 Mt, almost 20 Mt less than the most contributing province in 2015 reference levels. The industry's sustainability drive in 2017 levels is evident in the number of provinces with a reduction in CO_2 emissions. 14 of the 30 provinces recorded a reduction in CO_2 emissions levels in production-based linkages compared with 2012 aggregated levels. Although there was a drop in CO_2 emissions levels in most provinces, the distribution identified FDSE as the most significant factor in reducing CO_2 emissions levels in 2017. As shown in Figure 7.6, Fujian, Shandong, and Chongqing are critical to reducing the CO_2 emissions in 2017 reference levels. While most regions optimized CO_2 emissions in 2017, Shanghai and Liaoning increased emissions, especially FDSE.

Table 7.6 Driving Forces of Provincial CO_2 emissions Production-Based Linkages, 2015.

Province	DEICE	LSE	FDE	FDSE	Total	Rank
Shanghai	6.12	-10.88	52.44	90.42	138.11	1
Liaoning	41.53	-8.70	20.13	47.36	100.32	2
Henan	-6.99	23.04	67.42	10.13	93.60	3
Jiangsu	-8.17	-7.73	46.23	52.29	82.62	4
Hunan	-20.57	-7.82	32.64	46.62	50.88	5
Jilin	29.23	-7.90	16.64	11.02	49.00	6
Guizhou	-13.17	-4.49	27.24	39.12	48.69	7
Xinjiang	9.62	0.04	30.70	-0.50	39.86	8
Inner Mongolia	-4.37	17.36	6.98	8.52	28.48	9
Qinghai	4.26	-1.95	19.27	6.18	27.77	10
Zhejiang	8.67	6.18	22.25	-18.16	18.94	11
Jiangxi	6.78	-1.75	0.85	9.19	15.07	12
Heilongjiang	16.70	-10.71	2.66	1.47	10.12	13
Sichuan	-11.81	-3.44	5.84	18.91	9.51	14
Tianjin	-11.26	-3.22	-1.11	20.68	5.09	15
Hebei	7.00	4.64	4.91	-16.25	0.30	16
Guangxi	7.88	-0.38	-9.23	1.52	-0.21	17
Gansu	-0.05	2.88	3.44	-8.66	-2.38	18
Guangdong	-9.03	-1.97	-3.20	9.80	-4.40	19
Hubei	-45.62	39.15	30.95	-30.81	-6.33	20
Hainan	5.62	-10.78	-5.77	3.98	-6.95	21
Ningxia	7.08	4.53	9.21	-28.36	-7.53	22
Anhui	-6.93	2.12	3.24	-6.67	-8.23	23
Beijing	-10.01	3.17	17.31	-20.21	-9.74	24
Shaanxi	-11.13	17.15	4.28	-21.75	-11.45	25
Shanxi	-8.35	4.47	7.10	-17.48	-14.26	26
Fujian	22.11	22.54	16.82	-83.91	-22.44	27
Yunnan	11.79	5.08	-11.62	-34.75	-29.49	28
Chongqing	-34.80	4.13	40.37	-42.80	-33.09	29
Shandong	-17.51	8.35	5.89	-51.78	-55.06	30

The change in Figure 7.6 depicts the overall reduction in Final demand of most provinces with a consistent reduction trend in LSE. However, the trend on DEICE showed a drop in direct emission intensity efficiency of most of the provinces in 2017 reference levels.

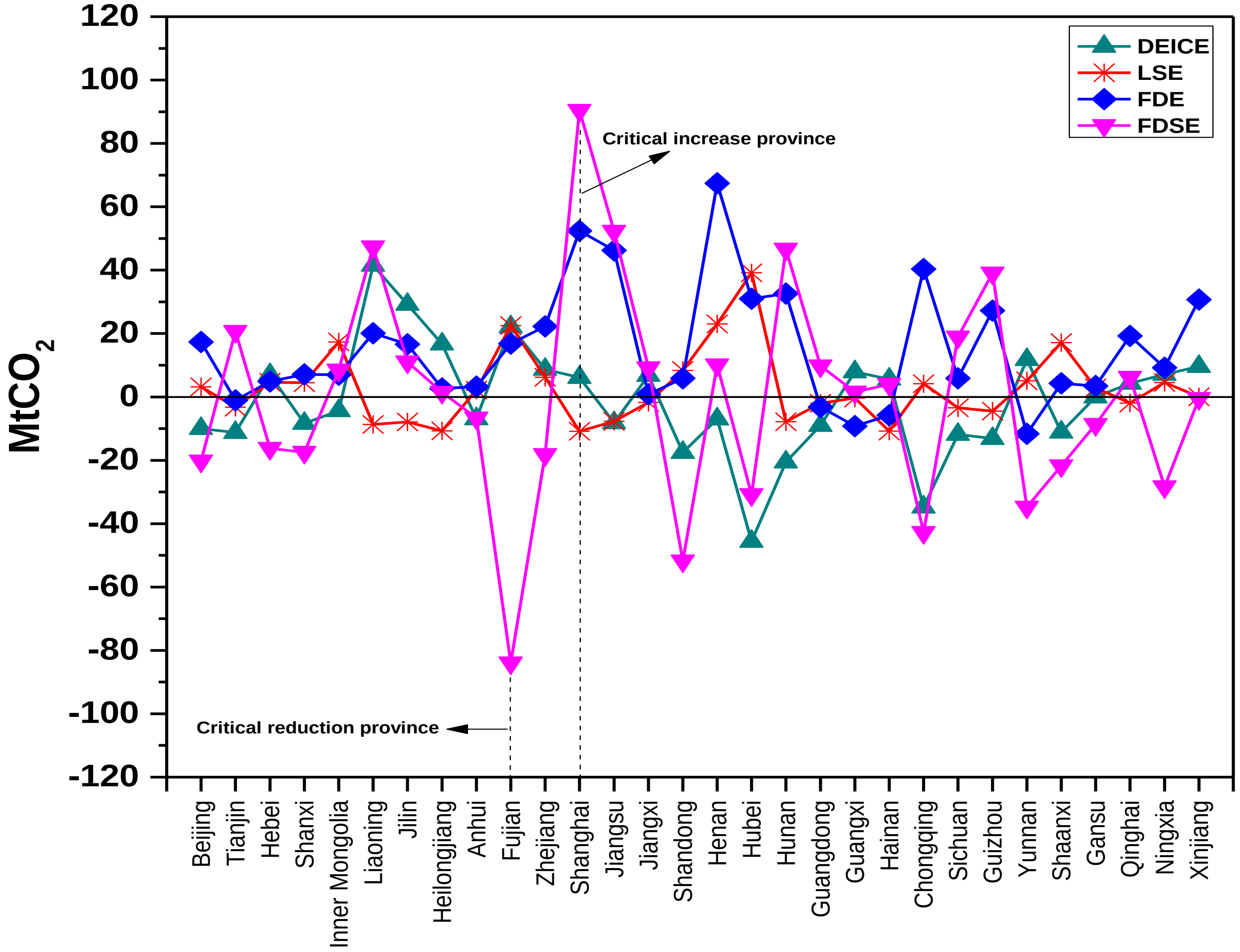


Figure 7.6 Provincial Distribution of Driving Forces Changes in 2017 Reference Levels

Table 7.7 presents the cumulative effects caused by the driving forces in both reference years, 2015 and 2017. The cumulative effects are calculated by adding both years' CO_2 emissions change from the 2012 base year. The addition results are the changes that occurred in CO_2 emissions in the production-based supply chain of the construction sector of the 30 provinces in China over 2015 and 2017 combined. Arranged in order of significance, Table 7.7 shows that 19 of the 30 provinces in China contributed to increased CO_2 emissions in the construction sector. The remaining 11 provincial construction sectors contributed to a reduction in CO_2 emissions in the industry during the reference years.

Cumulatively, there was an incremental change of 1352 Mt in the industry's production-based CO_2 emissions in 2015 and 2017. Henan and Shanghai regions had the most significant changes with 252 and 221 Mt. The addition of the changes in these two provinces (473 Mt) amounted to 35% of CO_2 emissions from the 18 provinces that caused increased CO_2 emissions in the reference years. Jiangsu, Liaoning and Jilin provinces caused an increase of over 391 $MtCO_{2,}$ amounting to 28.9% of CO_2 emissions increase in the reference years. From the results, the combined forces in the first five top provincial contributions amount to 64% (865.5 Mt) of all CO_2 emissions increase in 2015 and 2017 combined.

On the other hand, the cumulative reduction in CO_2 emissions by the remaining 11 provincial construction sectors amounted to -146 Mt. Notably, 57% (-84%) of the reduction effects are in Shandong (37%) and Yunan (20%). In contrast, the other nine provinces contributed a decrease of -62 Mt. Thus, Shandong and Yunan provinces could be noted as the critical provinces in CO_2 emissions reduction in the sector, as shown in Figure 7.7.

Table 7.7 Cumulative Driving Forces Effect on Provincial CO_2 emissions

Province	DEICE	LSE	FDE	FDSE	Total	Rank
Henan	20.97	71.10	141.65	18.53	252.25	1
Shanghai	-16.72	19.85	120.92	97.52	221.57	2
Jiangsu	-13.22	38.24	88.28	57.14	170.44	3
Liaoning	110.97	-50.66	46.62	9.65	116.58	4
Jilin	51.87	-1.01	38.19	15.59	104.63	5
Guizhou	2.90	-20.79	60.91	41.81	84.83	6
Hunan	-119.06	3.37	107.19	59.92	51.41	7
Xinjiang	-1.87	11.20	37.46	1.62	48.42	8
Tianjin	-52.80	31.30	38.62	28.48	45.61	9
Jiangxi	33.98	-8.05	7.69	10.38	44.00	10
Sichuan	-17.01	59.63	-17.87	13.31	38.06	11
Inner Mongolia	12.81	15.69	1.33	4.97	34.80	12
Qinghai	2.09	0.91	23.74	7.08	33.83	13
Zhejiang	7.52	-5.77	41.86	-13.74	29.87	14
Hubei	-138.24	90.49	98.72	-21.13	29.85	15
Heilongjiang	38.04	-27.14	3.54	2.01	16.46	16
Hebei	2.87	13.89	11.18	-12.33	15.61	17
Chongqing	-87.55	41.50	96.66	-36.77	13.84	18
Guangxi	7.75	-0.78	-8.58	1.61	0.01	19
Gansu	-6.96	17.47	-1.47	-9.40	-0.37	20
Guangdong	-29.61	10.48	7.20	11.22	-0.72	21
Hainan	-0.28	-3.53	-3.03	4.66	-2.18	22
Ningxia	6.07	4.66	9.98	-28.19	-7.48	23
Anhui	-11.95	5.83	4.38	-6.34	-8.08	24
Beijing	-0.97	-0.95	14.35	-21.01	-8.58	25
Shaanxi	11.19	3.00	-0.87	-23.51	-10.19	26
Fujian	98.94	-14.76	-7.68	-88.39	-11.88	27
Shanxi	-1.24	1.25	5.64	-18.75	-13.10	28
Yunnan	11.43	8.31	-13.97	-35.12	-29.34	29
Shandong	-39.22	23.72	11.63	-50.57	-54.44	30

Apart from indicating the critical provinces in CO_2 emissions changes in the sector, Figure 7.7 shows the illustrative extent of change in both reference years. The standard deviation of the changes in both reference years shows the most significant value in Liaoning and Chongqing. Henan, Shandong, Shanghai, Hunan and Hubei also experienced a substantial leap in 2017 compared with 2015's. However, compared with other provinces with considerable changes in deviation values, Shandong is the only province with a resultant reduction in CO_2 emissions force over the reference years. With the dynamism experienced in CO_2 emissions changes in Shandong province in the reference years, the province is considered the most sustainable construction sector in China. The standard deviation of provincial construction CO2 emissions changes in 2015 and 2017 are presented in Table 7.8.

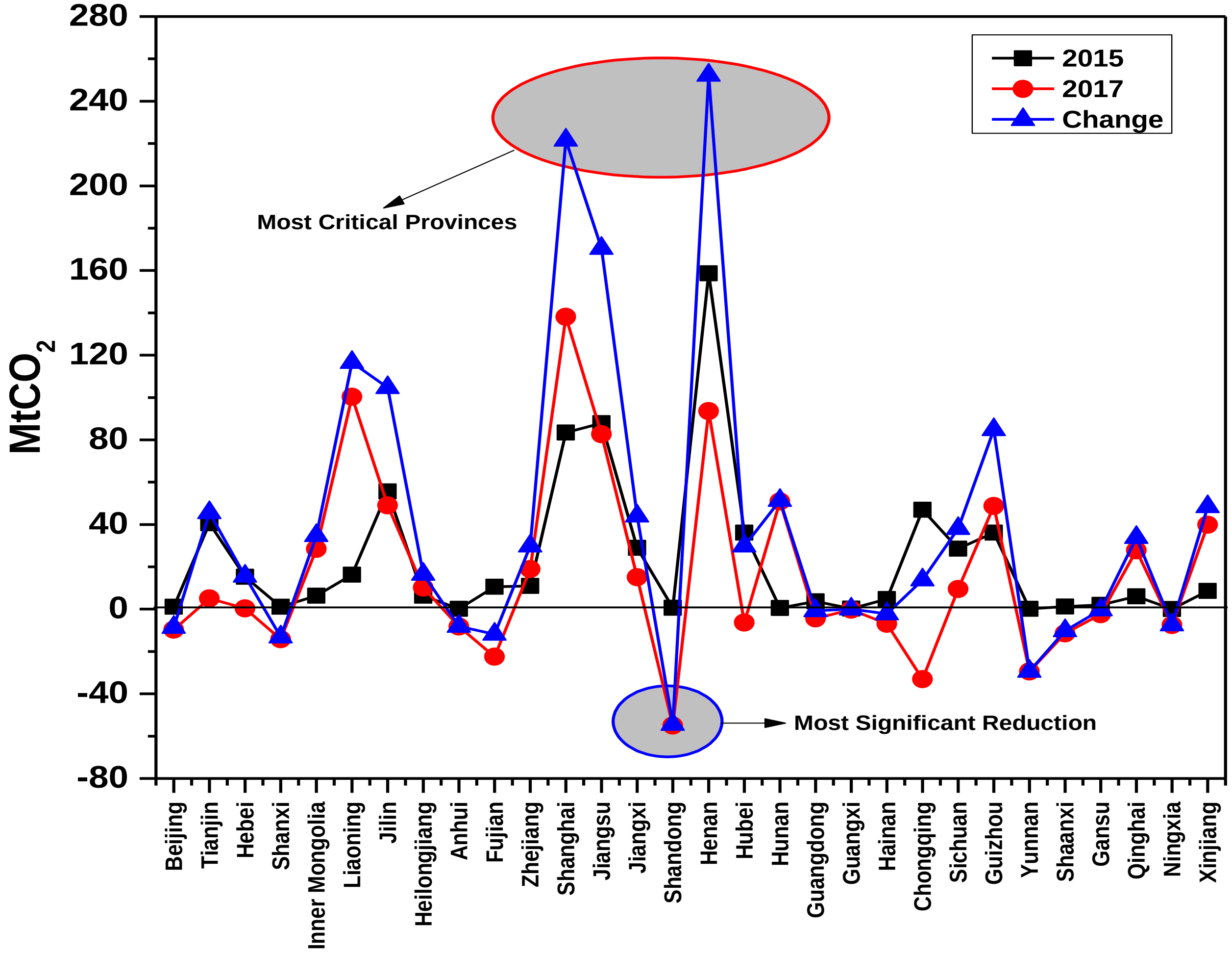


Figure 7.7 Provincial Distribution of Driving Forces Cumulative Changes in Reference Years

The relative CO_2 emissions change consistency in the provinces could be explained by sectoral saturation and low final demand change in construction products. Table 7.8 shows the five categorised zones of the 30 provincial construction sectors based on the change in CO_2 emissions in the 2015 and 2017 reference years. The first group are the provinces with volatile CO_2 emissions zones. In this zone are Liaoning and Chongqing provinces have the most significant deviations in

CO_2 emissions changes in 2017 and 2015. The considerable deviations in both reference years showed a significantly growing CO_2 emission produced in these provinces. The significant growth in CO_2 emissions could result from many indications, including a lack of technological improvement in process change of the industry and substandard sustainability practices in the sectors.

The second category is the significant change zone. This zone consists of five provinces, including Henan, Shandong, Shanghai, Hunan, and Hubei. Amongst the five provinces in this category, Shanghai and Hunan exhibited an incremental change, while the other three experienced a reductional change in CO_2 emissions. The third category is the sizeable change zone, including Tianjin, Fujian, Xinjiang, and Yunnan. Only Xinjiang exhibited an incremental change in this category.

The fourth category is the semi-saturated change zone. This zone depicts the provinces with a significant consistency between the changes in CO_2 emissions in both reference years. Most of the provincial construction sectors fall into this category. A total of fourteen provinces are in this category, out of which only four are CO_2 emissions incremental provinces: Inner Mongolia, Qinghai, Guizhou, and Zhejiang. The fifth category is the saturated change zone consisting of five provinces: Jilin, Jiangsu, Gansu, Heilongjiang, and Guangxi. These provinces in this category signify a relatively stable change in CO_2 emissions in the reference years of this study. Only Heilongjiang exhibited an incremental change in value in CO_2 emissions in this zone. As shown in Table 7.8, the most consistent province over the change period of investigation is Guangxi. Heilongjiang, Gansu, and Jiangsu provinces also recorded a significant consistency in CO_2 emissions generation between 2015 and 2017.

Cumulatively, the construction sector in China exhibited an average of -ve 18.132 change magnitude, implying a directional reduction in CO_2 emissions from 2015 levels in the 2017 reference year. With the value, the overall Chinese construction industry exhibits the characteristics of a semi-saturated change zone CO_2 emissions.

Table 7.8 Directional Change Magnitude of Provincial CO_2 emissions in Reference Years

Province	**2015**	**2017**	**Change**	**SD**	**+ve/-ve Magnitude**	**Change Category**
Liaoning	16.262	100.319	116.581	59.437	**+ve**	**Volatile Change Zone**
Chongqing	46.931	-33.094	13.838	56.586	**-ve**	
Henan	158.654	93.600	252.254	46.000	**-ve**	**Significant Change Zone**
Shandong	0.622	-55.057	-54.436	39.371	**-ve**	
Shanghai	83.460	138.106	221.566	38.640	**+ve**	
Hunan	0.535	50.878	51.414	35.598	**+ve**	
Hubei	36.173	-6.325	29.848	30.051	**-ve**	
Tianjin	40.529	5.085	45.614	25.062	**-ve**	**Sizeable Change Zone**
Fujian	10.559	-22.442	-11.883	23.335	**-ve**	
Xinjiang	8.561	39.862	48.422	22.133	**+ve**	
Yunnan	0.147	-29.491	-29.344	20.957	**-ve**	
Inner Mongolia	6.313	28.484	34.796	15.677	**+ve**	**Semi-Saturated Change Zone**
Qinghai	6.056	27.770	33.826	15.354	**+ve**	
Sichuan	28.550	9.513	38.063	13.462	**-ve**	
Shanxi	1.154	-14.257	-13.104	10.897	**-ve**	
Hebei	15.307	0.301	15.608	10.610	**-ve**	
Jiangxi	28.931	15.068	43.999	9.802	**-ve**	
Shaanxi	1.262	-11.449	-10.188	8.988	**-ve**	
Guizhou	36.142	48.692	84.834	8.874	**+ve**	
Hainan	4.768	-6.952	-2.183	8.287	**-ve**	
Beijing	1.164	-9.740	-8.576	7.710	**-ve**	
Anhui	0.155	-8.232	-8.077	5.931	**-ve**	
Guangdong	3.682	-4.399	-0.717	5.714	**-ve**	
Zhejiang	10.927	18.938	29.865	5.665	**+ve**	
Ningxia	0.054	-7.530	-7.476	5.363	**-ve**	
Jilin	55.635	48.996	104.631	4.695	**-ve**	**Saturated Change Zone**
Jiangsu	87.820	82.617	170.437	3.679	**-ve**	
Gansu	2.008	-2.378	-0.370	3.102	**-ve**	
Heilongjiang	6.336	10.123	16.459	2.678	**+ve**	
Guangxi	0.212	-0.205	0.006	0.295	**-ve**	

7.5 Critical Placement Analysis of the Driving Forces Changes of CO_2 Emissions

The results in previous sections of this chapter indicate the scaler categorization of the driving forces in regions and provincial levels in the base and reference years. To get a more objective classification of the criticality of the provinces according to the results of change in CO_2 emissions in the reference years, a critical placement analysis (CPA) was conducted. The CPA is based on individual provincial influencing impact factors (IFs) on CO_2 emissions in the production-based links of the industry. The IFs are defined using a percentile range from least to highest interquartile percentile achievable by each province. The percentile is expressed as multiples of tenth Mt of CO_2 emissions. The corresponding IF value of each percentile class is shown in Table 7.9. The SI method is adopted by (Chiang, Liu, & Bock, 2017).

Table 7.9 Percentile Impact Factor Ratings for CPA

Percentile	Description	Impact Factor
1st	<10Mt	1
2nd	10-19Mt	2
3rd	20-29Mt	3
4th	30-39Mt	4
5th	40-49Mt	5
6th	50-59Mt	6
7th	60-69Mt	7
8th	70-79Mt	8
9th	80-89Mt	9
10th	>90Mt	10

The severity index (SI) is calculated based on the corresponding class values of IF in each province. The total CO_2 emissions change in each reference year is computed as expressed in Equation (7.1).

$$S.I. = \left(\frac{p_n^r IF_n}{\sum_{n=1}^{30} P}\right) * 100 \tag{7.1}$$

Where p_n^r is the CO_2 emissions change in province n in the reference year, r; IF is the impact factor, and P is the total CO_2 emissions change in the 30 provinces in the reference year. The CPA graph was constructed by plotting the provincial CO_2 emissions (emission intensity) against the SI in the reference years, using the criteria in Table 7.10. The CPA graph was plotted for 2017 and the cumulative change in the two reference years to determine the critical provinces in the Chinese construction sector. The CPA was plotted on a graph of 300 on both Y and X-axis to maintain equal directional magnitude. 300 was chosen as the upper boundary for the graph because the maximum value on both intensity and severity index are less than 300 and, if rounded up to the next hundred, would be 300. Also, 300 would enable an equal division of the plot area into the hundredth equal spaces on both axes and directions. With the plot area division in both axes and directional magnitude, the first and lowest quadrant is the ‘low’ region, the middle quadrant is the ‘medium’ region, and the last quadrant is the ‘high’ region. The plotting area of the graph is color-coded in angular directional movement. Starting from green to red, the color intensity determines the placement criticality of each province on the CPA graph.

The green region indicates provinces with low CO_2 emissions contributions. The green region could be regarded as provinces with better sustainable practices, while the yellow region represents provinces exhibiting characteristics of a low critical region. The red region is the high and volatile critical region with more tendencies to affect the increasing trend of CO_2 emissions. Following the conventional color coding of criticality, the green regions need to be monitored to keep at the current or reduce the rate of CO_2 emissions. On the other hand, the yellow region exhibits the potential risk of increasing the rate of CO_2 emissions in industry. Thereby, the need to reduce the emissions in the yellow region to a level of the green region. In contrast, the red zone requires the highest level of attention and effort to reduce the rate of CO_2 emissions. The provinces in the red zone are essential to the overall CO_2 emissions in the industry. Therefore, the need to introduce aggressive control systems in the provinces to drastically reduce emissions in the region.

Table 7.10 Critical Placement Analysis Criteria for Reference Years and Cumulative Change

Code		2015			2017			Change		
	Province	$MtCO_2$	I.F	S.I	$MtCO_2$	I.F	S.I	$MtCO_2$	I.F	S.I
P1	Anhui	0.15	1	0.0222	-8.23	1	-1.6244	-8.08	1	-0.6699
P2	Beijing	1.16	1	0.1666	-9.74	1	-1.9219	-8.58	1	-0.7113
P3	Chongqing	46.93	5	33.5745	-33.09	4	-26.1197	13.84	2	2.2953
P4	Fujian	10.56	2	3.0215	-22.44	3	-13.2847	-11.88	2	-1.9712
P5	Gansu	2.01	1	0.2874	-2.38	1	-0.4693	-0.37	1	-0.0307
P6	Guangdong	3.68	1	0.5268	-4.40	1	-0.8680	-0.72	1	-0.0595
P7	Guangxi	0.21	1	0.0303	-0.21	1	-0.0405	0.01	1	0.0005
P8	Guizhou	36.14	4	20.6849	48.69	5	48.0383	84.83	9	63.3241
P9	Hainan	4.77	1	0.6822	-6.95	1	-1.3717	-2.18	1	-0.1811
P10	Hebei	15.31	2	4.3801	0.30	1	0.0595	15.61	2	2.5890
P11	Heilongjiang	6.34	1	0.9065	10.12	2	3.9950	16.46	2	2.7302
P12	Henan	158.65	10	227.0024	93.60	10	184.6881	252.25	10	209.2163
P13	Hubei	36.17	4	20.7026	-6.33	1	-1.2481	29.85	3	7.4266
P14	Hunan	0.54	1	0.0766	50.88	6	60.2351	51.41	6	25.5852
P15	Inner Mongolia	6.31	1	0.9033	28.48	3	16.8608	34.80	4	11.5439
P16	Jiangsu	87.82	9	113.0877	82.62	9	146.7156	170.44	10	141.3585
P17	Jiangxi	28.93	3	12.4182	15.07	2	5.9465	44.00	5	18.2462
P18	Jilin	55.64	6	47.7617	49.00	5	48.3388	104.63	10	86.7799
P19	Liaoning	16.26	2	4.6537	100.32	10	197.9459	116.58	10	96.6911
P20	Ningxia	0.05	1	0.0078	-7.53	1	-1.4858	-7.48	1	-0.6200
P21	Qinghai	6.06	1	0.8665	27.77	3	16.4382	33.83	4	11.2220
P22	Shaanxi	1.26	1	0.1805	-11.45	2	-4.5183	-10.19	2	-1.6899
P23	Shandong	0.62	1	0.0889	-55.06	6	-65.1824	-54.44	6	-27.0890
P24	Shanghai	83.46	9	107.4738	138.11	10	272.5064	221.57	10	183.7646
P25	Shanxi	1.15	1	0.1651	-14.26	2	-5.6265	-13.10	2	-2.1736
P26	Sichuan	28.55	3	12.2550	9.51	1	1.8770	38.06	4	12.6276
P27	Tianjin	40.53	5	28.9942	5.09	1	1.0034	45.61	5	18.9159
P28	Xinjiang	8.56	1	1.2249	39.86	4	31.4615	48.42	5	20.0805
P29	Yunnan	0.15	1	0.0210	-29.49	3	-17.4574	-29.34	3	-7.3014
P30	Zhejiang	10.93	2	3.1269	18.94	2	7.4736	29.87	3	7.4310

The CPA in Figure 7.8 depicts the severity and intensity of the 30 provinces in the Chinese construction sector in the 2015 reference year. On the emission intensity classification, all the provinces but P12 fall within the first quadrant classification – low emission intensity. Only Henan province (P12) exhibits the characteristics of a medium emission intensity zone. The severity quadrant placements of the provinces distinguished the characteristics of the 30 provinces in the three levels of classification. From Figure 7.8, only three of the 30 provinces fall outside the low severity zone. Shanghai (P24) and Jiangsu (P16) fall within the medium severity zone. On the other hand, Henan (P12) is the only province with a high zone severity placement in 2015.

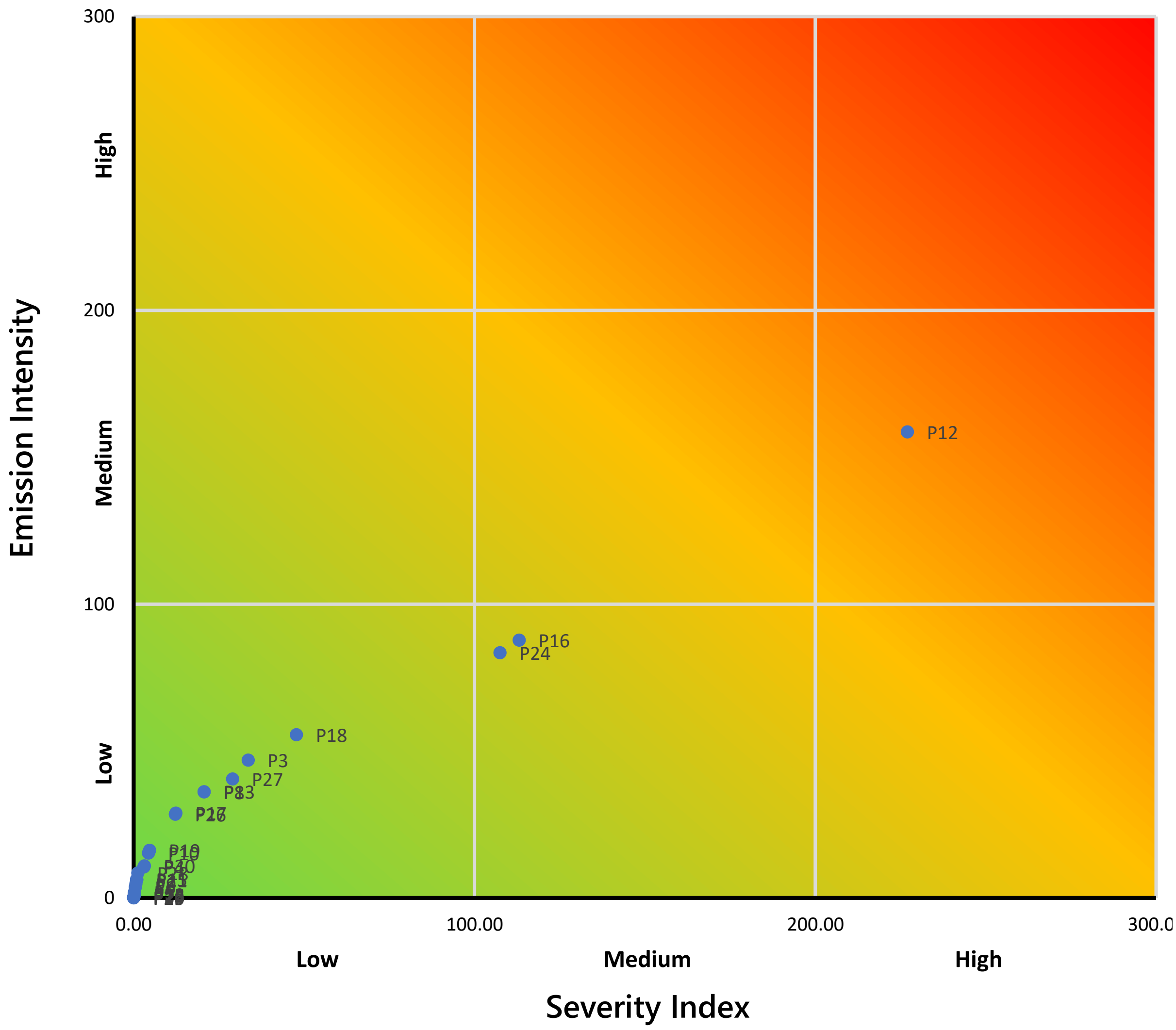


Figure 7.8 CPA of Change in CO_2 Emissions in 2015

In Figure 7.9, the distribution shows an improvement in the overall CO_2 emissions of many of the provinces in the 2017 reference year. The emission intensity and severity of the nine provinces reduced to the negative low quadrant compared to the 2015 levels. The implication of the negative placement of these provinces is the drive towards sustainability of the construction sectors by reducing CO_2 emissions generation in 2017 compared to the base year. The placements in Figure 7.9 show Shandong province had the most reduction effects in 2017 compared to other provinces' change from CO_2 emissions levels in 2012. However, Figure 7.9 shows a cluster of many other provinces around the neutrality points of the CPA, indicating a balanced in emission generation and severity probability of the provinces' construction sectors. Jiangsu (P16) maintained the same placement zone as in 2015 levels, while Henan (P12) experienced a reduction in placements in 2017. Liaoning (P19) and Shanghai (P24) experienced a burst in placement in 2017, with the latter placing in the medium-high quadrant.

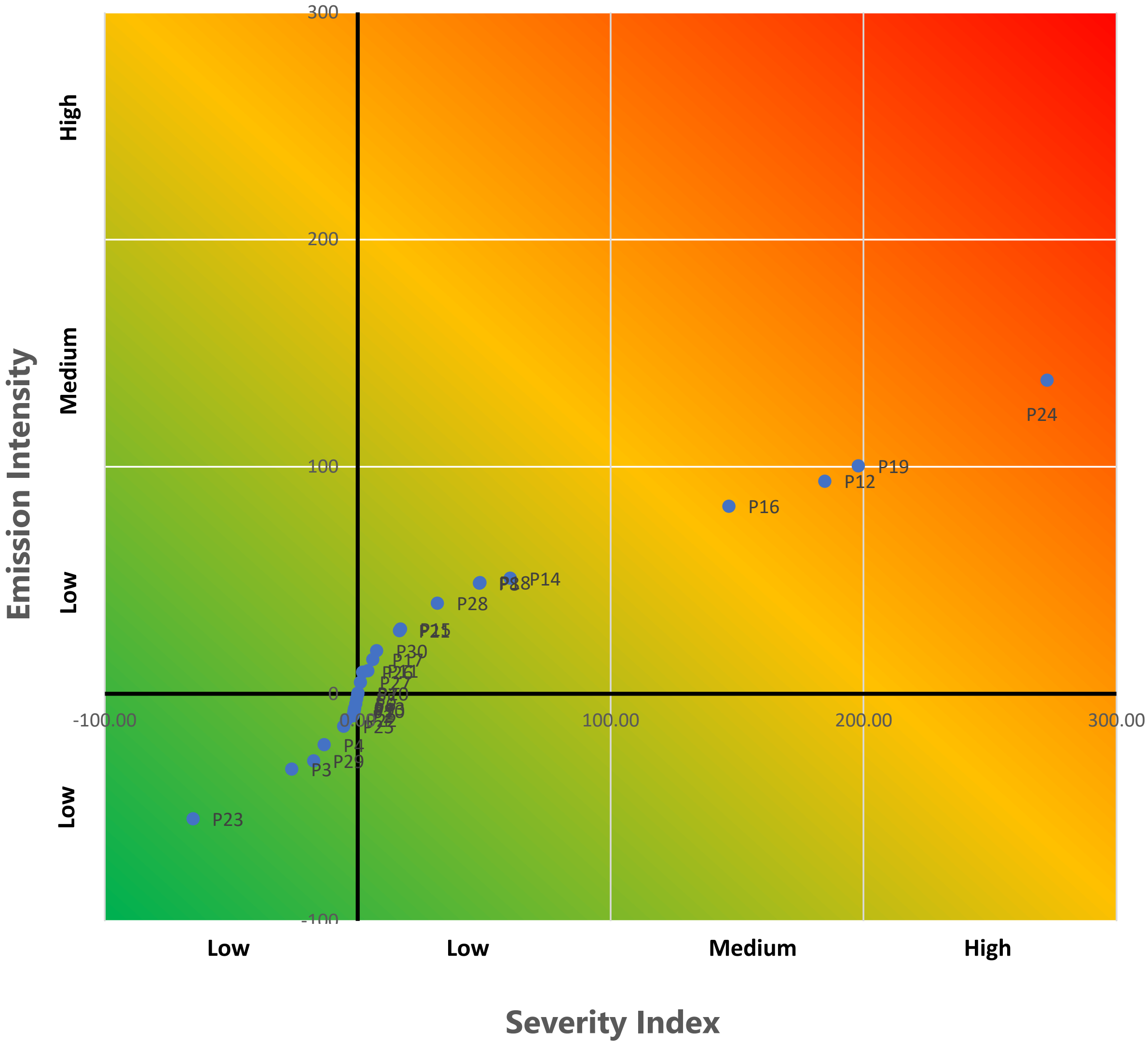


Figure 7.9 CPA of Change in CO_2 Emissions in 2017

In Figure 7.10, the cumulative effects of CO_2 emissions changes in both reference years indicate the final spread of the provinces across the CPA graph. Most of the provinces clustered around the low-low quadrants. P23 (Shandong) remained a vital province in reducing CO_2 emissions. From the color coding in Figure 7.10, three provinces fall within the highly critical quadrants – Henan (P12), P24 (Shanghai), and P16 (Jiangsu). These provinces are defined as the main drivers of the CO_2 emissions increase in production linkages of the construction industry in China.

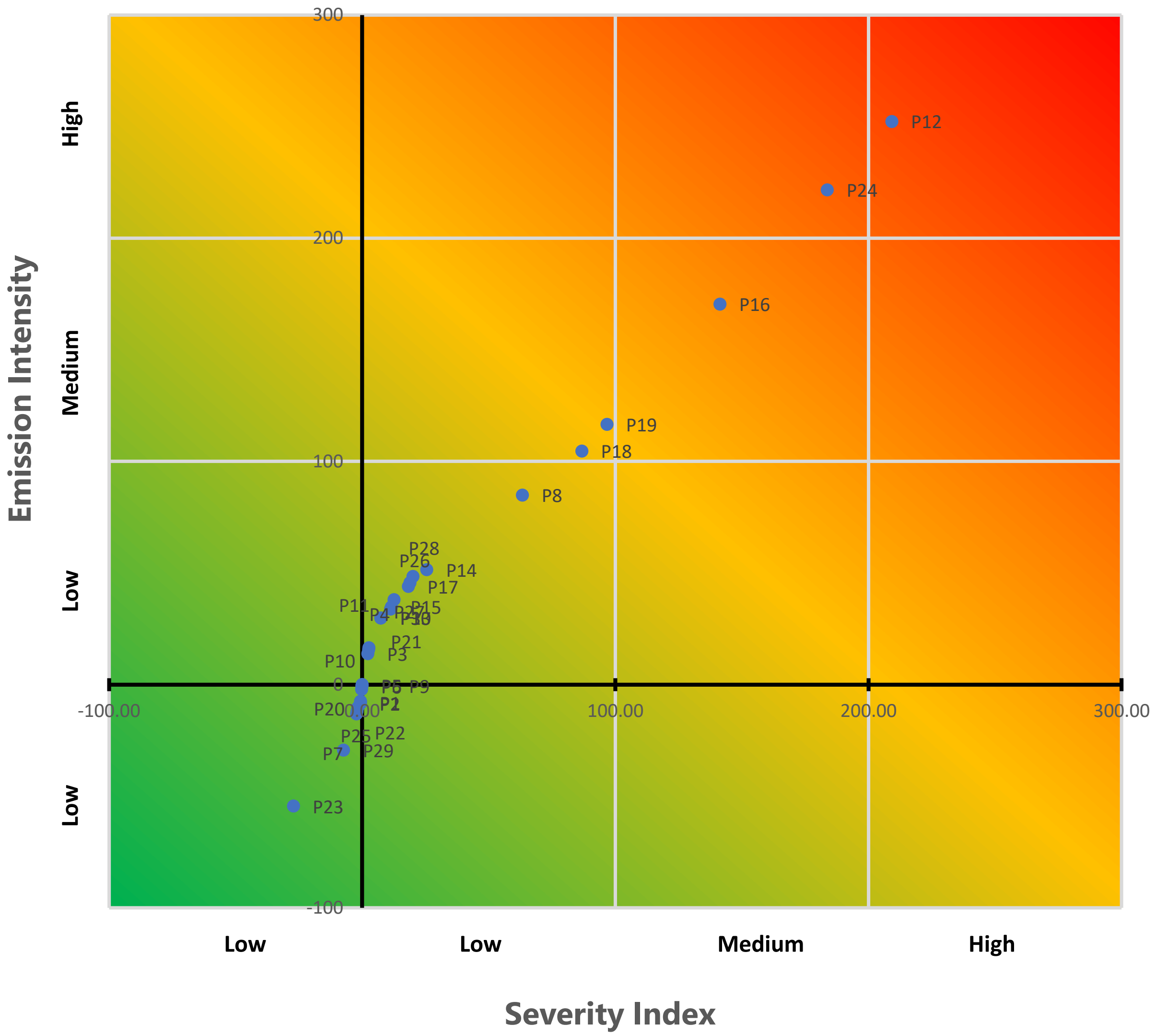


Figure 7.10 CPA of Cumulative Change in CO_2 Emissions in Reference Years

7.5 Discussion of Findings in Objective Three

7.5.1 Driving Forces of CO_2 Emissions in China's Construction Industry

The study of decomposing the driving forces of CO_2 emissions in China shows the main contributing factor as the effects of final demand on production-based inter-regional interactions. The final demand in the study is defined in terms of the consumption, investments, and exports originating from the construction sector to satisfy the demand of other sectors. The result further proves the claim of the active role the construction sector plays in developing other sectors in the entire economic spectrum of China. The final demand for the industry's products in other sectors plays a leading role in driving its CO_2 emissions outlook. The rise in final demand effect CO_2 emissions is explained by the increase in China's housing stock and industrialization requirements evident in the East and Southcentral regions of the country (Wen & Li, 2020). In recent years, the Southcentral region's development plans have shown a rapid development of more extensive industrial economies policies, like the Eastern block of China. The developments in provinces like Hunan, Shanghai, and Jiangsu are examples of increasing contribution to final demand CO_2 emissions change in the industry. With the results, factors of population and migration could be responsible for the increasing Final demand CO_2 emissions in some of the provinces in China. Wen and Li (2020) suggested improved industrial developments in the Southcentral and Eastern regions of China could be a pulling force for migration and population growth, which will drive further the effects of final demand on the upward movement of CO_2 emission.

On the other hand, the carbon emission intensity effect effectively reduced CO_2 emissions in the industry. The result shows improvements in the industry's energy utilization per GDP efficiency and encouraged technological innovation development. The Carbon emission intensity is the CO_2 emissions based on the amount of fuel combusted per GDP of the provinces. Most of the reduction effects are from the southcentral region of China's construction sector, especially Hunan and Hubei provinces. Zheng et al. (2019) described the gains in emission reduction plans in these provinces resulting from provincial policies on fuel mix ratio and a shift from heavy industrial intensive to light industry. Reducing dependence on high-carbon and optimizing effective use of intermediate products of the industry could be an efficient way to improve carbon emission intensity and CO_2 emissions contribution.

As for Leontief Structure and Final Demand Structure effects, the former showed a significant contribution to CO_2 emissions change in the industry than the latter. However, both effects increase CO_2 emission changes, unlike carbon emission intensity with a decreasing effect. The positive change in CO_2 emissions caused by Leontief Structure results from imbalanced backward trades of the industry with other economic sectors. The outflows from the industry outweigh the inflows, negatively affecting the industry's carbon emission utilization. The results indicate the importance of imports for regional production and consumption activities to balance directional trades of the industry. Such import assumptions can apply to international and inter-regional imports (Su & Ang, 2016). Although the effects of the Final Demand Structure are limited in this study, it is essential to note that the key to resolving current carbon emissions predicaments depends more on the Final Demand Structure. The Final Demand Structure is determined by the spread of growth of final domestic demand, carbon emissions produced by local residence energy consumption, income distribution of regional and urban residents' consumption, fixed capital and inter-regional exports (Deng, Zhong, & Xiang, 2019). However, it is important to keep track of the increasing trend of the sector’s Final Demand Structure in policy-making decisions to keep carbon emissions in check.

The study further shows that, unlike what was observed in similar research, the driving forces analysis of the Chinese construction industry is not urbanization driven. There is an observable spread between the rural and urban provinces regarding CO_2 contribution to the national emissions profile. However, a few developed provinces like Shanghai and Jiangsu contributed more to the increasing trend of carbon emissions in the sector. The increasing abilities of these regions could result from the provinces’ economic importance to national growth and the upstream and downstream sectors increasing trade demand on the construction sector. However, compared to developed countries, the Leontief structure effects in China’s construction sector contributed the second most significant role in China’s increasing carbon emissions trend. The result shows a lack of improvement in balancing the various economic and construction sectors’ input-output relationships. The problem could be termed an optimization problem as the nation is still undergoing extensive economic development. The final demand structure’s effects are consistent with developed economies with a minimal impact on the increasing trend of carbon emissions in China’s construction sector. Whilst the other three driving forces indicate increasing carbon emissions trends, the direct carbon emission intensity shows a decreasing impact. The implication of the decreasing trend signifies the positive effects of various government policies to address climate change on the construction industry and energy usage in China.

7.5.2 Regional and Provincial Changes in CO_2 Emissions in China’s Construction Industry

The study shows the change in CO_2 emissions according to the originating provinces and regions. The results show the most critical of the 30 provinces, subsequently the regions with the most crucial effects on CO_2 emissions in the construction sector. Henan, Shanghai, and Jiangsu provinces had the most contributions to CO_2 emissions changes in the industry. These provinces are in China's Eastern and Southcentral regions, with intensive developmental policies in recent times. However, Northeast China shows a significant potential to increase CO_2 emissions over the next few years. Zheng et al. (2019) identified it is better to continue with the advantages of transformation and upgrading in the Southwest while improving on the setbacks in the East, Northeast and Southcentral regions.

The study further classified the provinces based on the rate of changes over the reference years in terms of deviations for investigation. The classification showed Liaoning and Chongqing as volatile provinces for change in CO_2 emissions. However, while Liaoning had the most volatile addition to CO_2 emissions, Chongqing had a volatile reduction effect in CO_2 emissions. The gains in Chongqing can be related to the sustainable policy drive of the province to beat down carbon emissions through the implementation of two low-carbon road transportation policies and a mixed policy (Tan et al., 2020). While most of the provinces are categorised as semi-saturated change zones, notably Guangxi, Heilongjiang, Gansu, Jiangsu, and Jilin, with a saturated change in CO_2 emissions over the study period. These saturated change zones exhibited characteristics of consistent CO_2 emissions changes.

In addition, the study further categorised the provinces in terms of CO_2 emissions change criticality using a CPA. The categorization showed that most provinces fall within the low-low addition zone while a few are within the low-low reduction zone. However, with Henan, Shanghai, Jiangsu, Liaoning, and Jilin classified above the safe zone defined within the low-low zone, there was a significant imbalance of CO_2 emissions changes in the industry.

7.6 Chapter Summary

The chapter focused on calculating the driving forces of production-based CO_2 emissions changes in the construction sector in China in 2015 and 2017. SDA models were used in analysing the changes of four driving forces, namely direct carbon emissions intensity effects, final demand effects, final demand structure effects, and Leontief structure effects. In addition, the impact of the driving forces was aggregated on national, regional and provincial levels. Critical driving forces and provinces were identified using a CPA approach.

The study identified FDE as the most significant driver of the increasing trend of CO_2 emissions changes in the construction sector, with LSE and FDSE also having a significant positive drive. Direct carbon emissions intensity effects, on the other hand, are significant to reduction strategies of the industry. Henan, Shanghai, Jiangsu, Liaoning, and Jilin provinces were identified as the critical provincial zones to increase CO_2 emissions in the industry. In contrast, Shandong served as a vital reduction province in the industry. However, while many provinces exhibited a rather semi-consistent rate of change in CO_2 emissions, Liaoning and Chongqing provinces showed volatile change characteristics in both directions. The stable provinces with a mild difference in CO_2 emissions over the study period are identified as Guangxi, Heilongjiang, Gansu, Jiangsu, and Jilin, with a consistent rate of change over the two reference years.

CHAPTER EIGHT: CONCLUSIONS, POLICY IMPLICATIONS AND LIMITATIONS OF STUDY

8.1 Introduction

The chapter contains the main findings in the form of a summary of the study, the recommendations deduced from the study results, the limitations of the study, and suggestions for future research. The key findings are presented as a review of the study's objectives and how they have been achieved. Research recommendations are presented in the form of policy implications and theoretical and practical contributions of the study. The study's limitations are summarized in this chapter and led to some of the directions for future research.

8.2 Summary of the Study's Objectives

While the conversation around climate change and its environmental consequences continues to be a hot topic worldwide, China's contribution to the reduction and increase in GHGs remained a subject of importance. The focus of emissions studies in China's construction sector, considered a significant stakeholder in emission generation in the country, is concentrated around the operational phase use of the industry. By implication, many studies aggregated at sectoral and provincial levels of the sector are methodologically inept at investigating and determining the hidden linkages of emissions embedded in trans-sectoral and inter-provincial trades of the entire economic structure. Therefore, the study aimed to use a multi-regional and multi-scale assessment methodology to quantify the direct and indirect embodied CO_2 emissions in China's construction sector at the national, provincial, and project levels to determine the aggregated hidden linkages of CO_2 emissions embodied in trans-sectoral and inter-provincial upstream trades of the industry. Three specific objectives were identified to achieve the study's aim. The objectives are: (1) to quantify the direct CO_2 emissions embodied in China's construction sectors (National and regional levels), (2) to investigate embodied CO_2 emissions linkages from a sectoral and provincial perspective, and (3) to investigate the driving forces of embodied CO_2 emissions interactions among provincial construction sectors from a multi-regional perspective. The study, therefore, used a combination of trending and modified complex structural models to achieve these objectives. Presented in the following sub-headings are the main findings of each objective and the methodological approach used in achieving the objectives.

8.2.1 Objective 1: To Quantify the Direct CO_2 Emissions Embodied in China's Construction Sectors

Direct carbon emission quantifications in China's construction sector are uneven, with a variety of standards and methods utilized over time. This objective identified a factor preventing complete quantification as the failure to consider China-specific technologies and datasets. Using a hybrid framework of economic and environmental data, the study quantified direct CO_2 emissions in business at national and regional levels. In the 30 provincial construction sectors, the quantification framework was created utilizing nineteen (19) sets of fossil fuel and electricity data from provincial energy yearbooks between 1997 and 2015. Furthermore, the study developed regression models for each of China's six regional construction industries by combining the findings with three sets of econometric data: total annual construction output, cement consumption, and steel consumption.

The study identified the North and East China regions as the primary source of direct CO_2 emission with over 50%, while Southeast China contributed the least. While there is a gradual shift to other energy sources, the study identified coal and diesel oil as the industry's primary energy sources. Cement and steel data exhibited a significant predictive relationship with CO_2 emissions in five regional construction industries. The study identified the need to have policies tailored to technological improvements to enhance renewable energy generation and usage in the industry. The models developed in this study could generate initial quantifications of carbon emissions in construction industries with similar carbon-emitting characteristics for carbon tracking and fast-tracked energy decision-making purposes.

8.2.2 Objective 2: To Investigate Embodied CO_2 Emissions Linkages from a Sectoral and Provincial Perspective

Understanding the intricate CO_2 emissions in the construction industry's inter-sectoral and interregional linkages is critical to China's long-term sustainability. Many prior studies concentrated on aggregating CO_2 emissions from the building sector on a national scale, overlooking provincial differences and interconnections. Using expanded environmental input-output tables, the objective decomposed CO_2 emissions linkages in 30 provincial building sectors using a hypothetical extraction method combined with extended environmental multi-regional input-output tables for 2012, 2015, and 2017 data. The recategorization of China's construction sector as a high-carbon-intensity industry was founded on province carbon emissions data from a whole system boundary.

The interprovincial interaction results show relatively small backward CO_2 emissions linkages compared to forward CO_2 emissions linkages depicting the industry’s significant role in China’s economic growth and an essential target in CO_2 emissions reduction plans. The provinces exhibited different directional push-pull impacts, with less developed provinces having one-way directional effects. The more developed provincial sectors behaved more like demand-driven industries creating an overall imbalance in CO_2 emissions interaction between the sectors in interregional emission trades. The results identified Gansu, Xingjian, Ningxia, and Inner Mongolia as the most critical construction sectors with more significant CO_2 emissions linkages than other provinces. Improving the technical level in less developed provincial construction sectors, considering provincial characteristics in policy formulation, and a swift shift to renewable energy as a primary energy source would aid in reducing the emissions intensities in the construction sector, especially in the less developed provinces, and achieving China's quest to reach a CO_2 emissions peak by 2030.

8.2.3 Objective 3: To Investigate the Driving Forces of Embodied CO_2 Emissions Interactions among Provincial Construction Sectors from a Multi-Regional Perspective

The increasing trend of CO_2 emissions emanating from the construction industry in China was investigated to determine (1) the critical driving forces of CO_2 emissions in production-based industrial linkages and (2) the critical contributing region and provinces to CO_2 emissions in the industry. The three-year datasets from objective two were adopted to investigate the change and change magnitude in CO_2 emissions between a base year and reference years. 2012 was used as the base year in this objective, while 2015 and 2017 were the reference years. The change in CO_2 emissions in production-based years depicts the increase or decrease in production linkages in the industry from 2012 levels. The driving forces considered in the objectives are (1) direct carbon emissions intensity effects, (2) Leontief structure effects, (3) final demand effects and (4) final demand structure effects. The methodology of the objective combined SDA and LMDI I in the investigation.

Results show that three of the four driving forces had positive cumulative changes in CO_2 emissions in the industry in both reference years. Direct carbon emission effects are the only driving force with a CO_2 emissions reduction capacity in the investigated period. Final demand effects were the most significant forces, with Leontief structure effects following in second place. Final demand structure effects contributed only 20Mt addition, regarded as low significant compared with other forces. The regional distribution of the effects placed East and Southcentral China as the most significant contributors to CO_2 emissions in the industry, with the Northeast closing in with a substantial effect. Production-based CO_2 emissions change is minimal in the North region with a combined effect of less than the total additional changes in the Northeast region. Henan, Shanghai, Jiangsu, and Liaoning provinces were identified as the critical provinces contributing to the increasing trend of CO_2 emissions in the Chinese construction sector. On the other hand, Shandong, Yunnan, Shanxi, Fujian, and Shaanxi provinces were points of CO_2 emissions reduction. Overall, the distribution of the change in CO_2 emissions in production-based linkages of the sector indicated an imbalanced distribution over the reference years.

8.3 Recent Trends in Carbon Emissions of the Chinese Construction Sector

As discussed in different chapters of the thesis, the study was limited in data availability and recency. The study adopted data up to 2017 for the reportage in the thesis and further policy suggestions made. It is worth noting that recent data released in 2021 was not merged with the study's findings based on many reasons described in the limitations and suggestions for the future research section of the thesis. However, it is appropriate for the thesis not to ignore the existence of the data and briefly discuss the industry's more recent carbon emissions situation and relate the study findings to some indicators observed from recent data and literature. Thus, the need for this section of the thesis. The section focused on changes in the interregional carbon emissions linkages and the driving forces of these changes from 2017 to 2020.

The observed indicators from the construction sector showed the demand-side linkage path (consumption-based CO_2 emissions as referred to in the thesis) is much lesser than the supply-side linkages (the production-based CO_2 emissions) (Wang, Wang, Peng, Li, & Wei, 2020). The composition of the combined influence of the construction sector on CO_2 emissions in China is felt in many industries, including power, non-metal minerals, smelting and metal, and service industries. The linkages have been considered relatively stable over the past few released data years with the ever-improving Chinese technological advancements (Chen, Song, & You, 2022; Wang et al., 2020). Chen et al. (2022) reported the construction sector's CO_2 emissions increased from 981Mt in 2002 to 3,763Mt in 2019. The study demonstrated the most significant contributing factor is the final demand effect having an increase of 192.3%, followed at a distance by the Leontief structure effect with an 81.9% increase, and the energy intensity effect amounted to a cumulative -70% decrease over the period. The indicators in the study resonate with the findings from Zhu, Feng, Li, and Zhang (2020) and Zhang et al. (2020), in which predictions were made for future CO_2 emissions trends in the construction sector of China based on the 2017 data. The increasing urbanization rate could explain China's increasing final demand effect. The urbanization rate in China grew by over 0.83% in 2022 (NBS, 2022), which is a very significant growth rate compared with other countries in the world.

However, the energy intensity effect's reduction influence on CO_2 emissions in the industry shows an improving industry's technology and the resulting behavioral changes in the end-user energy usage pattern. The nexus of continued innovations within the construction industry's practices and the systems put in place to better educate stakeholders in the sector is yielding much effect on CO_2 emissions. The effectiveness of China's CO_2 emissions mitigation policies is gradually taking center stage, especially in the construction industry, helping reduce carbon emissions generated due to a lack of advanced technology and human-related behaviors.

The results from the above-discussed studies are in tandem with this study's findings and subsequent recommendations. Just like the CO_2 emissions linkages in the Chinese construction sector were found to be on an increasing trend, the studies showed a further increase in the more recent data. Fundamentally, similar scenarios still affect the Chinese construction sector as of recent. The recent real estate crash in the country didn’t stop the increasing trend of CO_2 emissions; instead increased the embodied carbon emissions through the non-usage of vacant buildings and the opportunity cost of installing the more advanced new carbon reduction technologies in these unoccupied buildings. Embodied CO_2 emissions are also released from these buildings with their lack of proper maintenance since they remain empty. The final demand effect increase in the sector could result from the low quality of materials and the very low average lifespan of buildings in China of about 30 to 40 years. Compared with other countries where the average lifespan of buildings is between 60 to 100 years, the Chinese construction industry needs to, by means of urgency, investigate reducing final construction product demands by improving the quality of materials and building stocks to prolong the building lifespan. On the other hand, the gains recorded in the sector through reducing CO_2 emissions through increased efficiency of energy intensity effects need to be encouraged and further improved.

Juxtaposing the findings of the study with the evidence from a study based on more recent data, it is safe to conclude that CO_2 emissions remained on an increasing trend mainly due to the growing demand for the sector’s final products and the inefficiency in the technical coefficients and production structure of the industry.

8.4 Recommendations

From the study’s conclusions, there are practical recommendations to different stakeholders in the construction industry. These recommendations are discussed in terms of stakeholders in the construction sector.

The Government and Policy Makers

Prior to the release of the recent 14th five-year plan (2021-2025), where the National People’s Congress (NPC) set out a plan to a renewed focus on the accelerated fourth industrial revolution and to make China an advanced manufacturing superpower, the goal of achieving global competitiveness has come with a climate prize. Emissions in China have increased over a few decades, becoming the largest net exporter of carbon globally. Countering the outreaching effects of increased emissions in the country made the government and policymakers focus on some heavy industrial sectors through more research and emission cap policies. However, the construction sector is generally overlooked as a secondary emission sector. With the results of this study, policymakers can re-evaluate their stance on the importance of the construction sector in emission profiling and its contributing effects to achieving the earlier set long-term emission cap by 2035 and the carbon neutrality goal of 2060.

The Clients

Construction clients play a significant role in the final designs and modalities of construction products. The behavior of clients and end-users of the industry’s products is critical in reducing energy consumption and increasing carbon efficiency. Therefore, continuous client engagement and education for carbon reduction plans are essential to mitigating the rising emissions in the industry. An adequate understanding of the ripple effects of individuals’ excessive and non-functional energy demand in building requirements will help the industry’s drive towards sustainability.

Contractors and Consultants

Contractors and consultants play significant roles in emission management within the sector. Knowledge and design capacities of the professionals during the inception stages of a project are fundamental to eventual emission planning during and after the construction phases of a project and the end-of-life usage. The choice of material, specifications, material recycling, structural efficiency maximization, and new energy management technological choices rest in the hands of the contractors and construction professionals. With their increasing importance in the emission life-cycle flow of the industry, it is, however, essential to keep track of emissions on construction sites and downstream chains of the industry. Research like this gives good insight into trend analysis and understanding of the industry's emission performance.

Suppliers and Construction Materials Manufacturers

The newly released China's 14th FYP for 2021 to 2026 under the "new progress and ecological civilization" goal showed the importance of energy and climate. Dedicating an entire section titled "Establishing a modern energy system" and CO_2 emissions intensity reduction by 18% in the plan indicates the seriousness to be expected over the next few years. This study showed the relationship between construction materials and direct CO_2 emissions in the construction industry. The study shows the industry's importance in China's CO_2 emissions trade train. The need for more sustainable materials and energy supplies is at its most crucial period. Materials manufacturers can use the models in this study to have preliminary predictions of the effects of their products on the industry's CO_2 emissions outlook.

Other stakeholders

The construction sector globally is known to be a complex and multidisciplinary conglomeration. Many parties are involved from inception to project completion and final end-of-life use of construction products. It is, however, crucial to get all stakeholders involved in the management and reduction of CO_2 emissions in the industry. End-users of the products need to understand their inputs in the entire process. Facilities managers and other professionals not directly involved during construction stages also need to know their duties in maintaining a low CO_2 emissions profile. Active research like this will enable trend analysis and conclusions drawn from results on achieving a better CO_2 emissions profile in the sector.

In conclusion, reducing CO_2 emissions in China's construction sector is the duty of the many professionals, contractors, policymakers, the government, and every other party involved in the industry's entire supply chain. Therefore, the implementation of research such as this should not be limited to only policymakers, but inclusiveness of other stakeholders is vital in achieving sectoral sustainability.

8.5 Policy Implications

8.5.1 Increased Focus on the Construction Sector

The Chinese construction industry has received underwhelming attention in emissions inventory studies and policy drives. Many government policies focus on heavy industries such as manufacturing, oil, gas, and other sectors believed to have higher carbon intensities. However, the construction industry has significant input on the country's emissions. In quantifying CO_2 emissions originating from the Chinese construction sector, many researchers have focused on the downstream sectors of the Chinese economy, with little detail on the direct CO_2 emissions from construction activities. To fully understand the nature of emissions in the construction industry in China, emphasis needs to be placed on regular quantifications of emissions generated directly on construction sites in China. The study recommends construction-industry-focused policies to guide the emissions emanating from construction processes in China as obtainable in other parts of the world. While emission reductions are focused on the construction industry, it is, however, critical that geospatial considerations are made in GHGs policy formulations for the construction industry to help mitigate climate change. The study presents a comprehensive yet straightforward approach to generating preliminary direct CO_2 emissions in the construction sector for fast checking and indications of the needed carbon efficiency improvement strategies.

8.5.2 Redistribution of Uneven Energy Sources in Chinese Regions

Energy resource generation and distribution in the industry need to be extensively studied with enhanced policy motivational drive. The alarming reliance of some regional construction industries on coal and fossil fuels is because of the high concentration of such fuel types in the region, especially in North and Northeast China, with significant coal and oil deposits. The uneven distribution of energy sources in the areas threatens to disrupt sustainability goals in the regions. On a national level, China needs mega-projects to redistribute energy resources between the regions to forestall absolute dependence on the most abundant energy resources in the regions, solving the uneven energy distribution problem.

8.5.3 Construction Materials Improvement and Increased Renewable Energy Use

Globally, emission reduction, technology innovations, energy conservation, and renewable energy dependence have been proposed in construction. The construction industry in China needs to focus more on material-improving technologies, as most emissions in the sector are material-originated. Cement and steel consumption composition needs to be technologically enhanced to reduce their carbon contents. There is a need for continuous process change to shift from fossil-fuel- and electricity-driven machinery to renewable energy use. Increased renewable energy use would alleviate dependence on primary energy sources, reducing the industry's environmental risks.

8.5.4 Classification of China's Construction Industry Carbon Intensity

Contrary to the previous categorization of the construction industry in China as a low-carbon industry (Wang et al., 2013), this study's results classed the sector as a high-carbon industry with high CO_2 direct intensities. It is essential to recognize the sector's downstream and supply chain in determining the carbon categorization of the industry. Classifying the carbon potential of the industry based on segregated sectoral classes would fail to indicate the significance and the tendencies of the sector in increasing carbon growth in China. The sector is only second to energy industries among China's top CO_2 intensity sectoral blocks. The average CO_2 direct intensity of the sector increased from less than 0.5 t/10^4 Yuan in 2007 to 4.85 t/10^4 Yuan in 2017. The construction sector in China has a more significant tendency to emit CO_2 than most industrial sectors, currently receiving more attention in terms of sustainable policy changes. In addition, it could indicate the CO_2 emission efficiency of the industry is low compared to other industrial sectors in China. Investing in enhanced technology to improve the sector's carbon efficiency could be a more feasible route to achieving net-zero carbon emissions in China. In addition, from the study and observations from previous studies, most global policies are not reflective of the whole but fractions of the sector. Therefore, carbon emissions policies in the construction sector, especially in China, need to follow robust boundary definitions to prevent inadequate representation of the sector's emitting potential.

8.5.5 CO_2 Emissions Linkages of China's Construction Sector

The total CO_2 emissions linkages of the provincial construction sectors combined showed a significant increase from 1498 $MtCO_2$ in 2012 to 2000 $MtCO_2$ in 2017. With the observed increasing trend in CO_2 emission flow in and out of the construction industry, the construction sector in the 30 provinces exhibited itself as an essential sector with significant economic and emissions interactions with other sectors. Cheng, Lu, Zhu, and Xiao (2022) attributed this significance to rapid urbanization in China. However, the total CO_2 emission linkage compared with the population density of most of the provinces showed a reasonable correlation except in Xinjiang, Qinghai, Inner Mongolia, and Gansu, with relatively high construction activities that are more than what is needed to satisfy population demands in the provinces. The results from the study indicate the nature of the construction activities in these provinces tends toward production for consumption in other regions. The trend is consistent with (Chi, Liu, Wang, Zhang, & Wei, 2021). The four provincial construction sectors are net producers and exporters of CO_2 emissions, affecting the final demands of other areas in direct trade with these provinces. The study identified the four provincial construction sectors as the most critical industries.

Developed provinces bear responsibility for the emissions taking place for developmental purposes within their borders, making them more demand driven. The more remote provinces in China should aim to move away from behaving as net exporters of emissions to demand-driven sectors. Akan et al. (2017) suggested the development of emission-reducing technologies focused on less developing areas as a better way to help these regions achieve a better emission behavior pattern. In addition to technological improvements in the provinces, tax incentives could be introduced to areas with critical emission indications and encourage inter-provincial knowledge transfer.

8.5.6 Directional Push and Pull Effects of Provincial Construction Sectors' CO_2 Emission

The study results showed significant deficits in the CO_2 emissions balance between the provinces' BE and FE. The FE far outweighs the BE of the provincial construction sectors, indicating a tilt towards a net emitting sector in the upstream rather than a downstream position in most provincial construction industries. Forward linkages are much higher than backward linkages in all provincial construction sectors in China, indicating the industry operates as an upstream industrial position in the economic chain of China. With the upstream role of the industry, other sectors of the economic chain significantly depend on inputs from the industry for their survival. With the suggestion that final demands from different economic sectors drive the industry's production, the industry serves as a net exporter of embodied CO_2 emissions in inter-sectoral trades with a meagre significant return in backward CO_2 emissions.

The results imply the construction sectors contribute more CO_2 emission outflows through trade to other economic sectors and do not, in turn, absorb CO_2 emissions in goods from those sectors. The observation is related to the global construction carbon emissions study's characteristics (Gao, Liu, Sun, Liu, & Xu, 2021). Further decomposition of the sectoral linkages of the 30 construction sectors further proved the sector as a net one-directional forward CO_2-emitting sector. Both BE indicators (NBE and MBE) show extremely negligible values compared to the two indicators of FE (NFE and MFE). In particular, the minimal value of MBE CO_2 emission in all the 30 provincial sectors indicate the construction sectors have low consumption of products manufactured from intermediate products used by other sectors to produce their final products.

The NBE values indicate the construction sectors consume more products from other sectors to satisfy final demand than intermediate consumption. The small BE also means the construction sector provides more products to other industries in the economic structure than it receives, indicating the significant embodied CO_2 emissions in products used in different industries. The NFE, on the other hand, suggests the dependence of other sectors on products of the construction sector. The indicators accentuate the construction sector's pivotal role in developing Chinese technology and industrialization and the need to have more focused sustainability strategies. There is a need to focus on China's construction and concrete industries as an important sector for climate change, like energy, transportation, and manufacturing. In agreement with (Zhang et al., 2020), more attention should be given to compartmentalizing construction products to enable dual usage rather than only being valuable as composite goods for satisfying final demand in other sectors.

8.5.7 Transferred CO_2 Emissions Linkages of China's Provincial Construction Sectors

The study showed the sources and destinations of the CO_2 emissions in the provincial construction sectors of the 30 provinces in China. The results showed that local construction sectors' CO_2 emissions embodied in raw materials are sourced from within and outside their corresponding provinces. The observed pattern suggested that developed provinces such as Beijing, Shanghai, and Chongqing on average had more CO_2 emissions inflows from inter-provincial sources. In contrast, many provinces, notably less developed provinces, such as Xinjiang, Ningxia, Gansu, and Inner Mongolia, had the most BE CO_2 emissions embodied in products purchased within their provinces. In addition, the destinations of CO_2 emissions in FE suggest that a good part of CO_2 emissions from the construction industry are transferred to different sectors within the same provinces: 43% of CO_2 emissions from the 30 provincial construction sectors combined were transferred to other sectors within the same province and 56% in inter-provincial trades.

The result suggests products from construction sectors play vital developmental roles within and outside their provinces of origin, indicating a reasonable balance in the inter-sectoral and inter-provincial trades of the construction sector in China. However, Hubei, Jiangsu, Shanghai, Zhejiang, and Guangdong provinces had more CO_2 emissions linkages in inter-sectoral trade than inter-provincial trades. At the same time, Xinjiang, Ningxia, and Qinghai contributed more CO_2 emissions in inter-provincial transactions. The balance in transferred CO_2 emissions observed in many provinces must be maintained while developing policies to tackle the imbalance in the remaining provinces, especially the critical ones, such as Xinjiang, Ningxia, Gansu, and Inner Mongolia, identified in the study.

8.5.8 Drivers of CO_2 Emissions in the Industry

The study shows the gains from various national energy use policies in China, especially on energy consumption with the decreasing trend of direct carbon emissions intensity. However, more needs to be done with the other three driving forces analysed in the study, showing an increasing carbon emissions trend. The imbalance in the input-output relationship raised questions on carbon structure optimization in the industry. The economic growth of many of the provinces is construction and real estate driven. With the high dependence on the construction industry's products for economic development in these provinces, the final demand effects of the industry on carbon emissions will tend to increase. A policy to tone down the need for more construction for economic growth should be encouraged within the entire national economic plan. Aggressive urban renewal and city regeneration policy could help reduce the demand for new construction activities within many provinces. In addition, the green provinces in the study need to be encouraged to improve their cleaner production technology and energy efficiency creating a balance for other provincial outputs on the national scale aggregation.

Also, some more prominent, and populous provinces like Shanghai, Jiangsu, and Henan, need to pay more attention to the environmental damage and resource depletion caused by not optimizing trade resulting from the inter-regionalization of their final demands. By developing policies that promote intra-trading between the construction industry and other sectors within the provinces, the input-output relationships will help drive down the Leontief structure effects in increasing trends of carbon emissions in the industry. In conclusion, the overall push effects of the construction sector are more far-reaching than its pull effects on CO_2 emissions in the industry.

The study showed China's construction sector exhibited more forward linkages than the backward linkages causing a significant deficit in the directional trends of the sector's CO_2 emissions and driving forces. Therefore, it is essential to have more policies focused on the construction sector's downstream activities and trade interactions within the entire national economic structure and its driving forces.

8.6 Research Contributions

With increasing interest in emission studies in global construction research, the usefulness of this study cannot be overemphasized. The study combined approaches not common to emission studies in the construction sector. The methodologies were adopted from energy research, combined with macro-economic models and equations to understand the links and connections of CO_2 emissions in China's construction sector's upstream and downstream economic positions. The study extended the research to micro-economic activities of the construction industry to understand the effect of the sector's demand and supply behavior on carbon emissions in China. Combining the construction industry's macro and micro-economic features is novel to the sector's research outputs. The study systematically introduced a methodology capable of decomposing carbon emissions interaction in the construction industry with other economic sectors. Before now, studies in the sector adopted mostly building and energy consumption data in calculating carbon emissions. However, in this study, both energy consumption data and economic data attributes of the industry were combined to quantify and identify embodied carbon emissions.

The study opens new sets of methodologies not common in the industry to quantify CO_2 emissions at provincial, regional and national levels in China's construction industry. The adjusted methodologies in the study are significant for their applicability to trace and detect CO_2 emissions interdependencies and hidden paths from economic relationships within the national economic spectrum. The study captures all stages of the construction industry with results quantified from all inputs and outputs of the industry.

The study generated a novel hybrid quantification model for the preliminary measurement of direct CO_2 emissions in China's regional construction sectors. The developed model defined in terms of fossil fuel consumption, construction materials, and annual national or regional outputs of the industry can predict the number of carbon injections from the sector to the national carbon profile from series data of the sector's activities. The early indicative knowledge of the impacts of construction activities on national carbon outputs is essential for proper mitigation policy adjustments and planning.

A critical contribution of the study is the re-categorization of China's construction sector as a high-carbon emitting industry. Previous studies in the industry have predicted the increasing influence of the industry on the overall emission profile of China. Few studies have indicated the rise in influence of the Chinese construction sector from the traditional tertiary emission sector in most developing countries to an influence sphere of secondary carbon emission sector, as seen in many developed nations. However, results from this study placed the construction sector in China as a vital sector for development and Chinese global influence and regional dominance. The study showed the Chinese construction sector is a high-carbon emitting industry throughout the investigation as the industry serves as a pillar to the Chinese local and international exports. Therefore, the study indicates the need for better action plans to reduce the emission profile of the industry within the national and global climate change action plans.

In addition, the study completely reaggregated the Chinese construction sector's environmental and economic data to construct the extended CO_2 emissions multi-regional input-output tables upon which the analysis of the study was based. The aggregated constructed tables are useful for further adoption as foundations for advanced GHGs research in the industry.

The study successfully demonstrated the applicability of combining three distinct methodologies to carbon emissions in the construction industry. Combining HEM, SDA, and LMDI methods for multi-provincial CO_2 emissions study in the construction sector is an approach not common to emissions research in the industry. The approach indicated a less dependence on building and energy data for measuring CO_2 emissions in the industry. With this study's approach, the three combined methods can be comprehensively adopted in GHGs qualification within the industry and its linkages with other economic sectors.

Finally, the study presents semi-processed open data and applications of the developed model in MATLAB codes for further decomposition, which can be built upon for future related studies. Overall, the study is essential for providing new and novel knowledge to the existing approaches and nature of emission studies in the construction sector, especially in China.

8.7 Study Limitations and Areas of Further Research

Although the research's objectives were achieved with comprehensively modified methodologies and model formulations for embodied CO_2 emissions in China's construction sector, several limitations influenced the study's outcome. Some of these limitations prevented the study from achieving some initially planned activities during the proposal stages of the study. Understanding and overcoming these shortfalls would improve future related studies.

First, out of the six GHGs identified by IPCC, the study focused on only CO_2 emissions while neglecting the other five GHGs effects and embodied distributions in the industry. Although CO_2 emissions have the most prominent global warming power (GWP) amongst the six GHGs, the impact of others on global climates cannot be underemphasized. In addition to the pollutant considered in the study, the scale does not include the end life and additional use stages of construction products. Demolition and construction dust was not considered in the study since the scope of the study is from gate to cradle stages. An investigation of the complete system boundary of energy consumption phases and the complete GHGs impacts on the construction industry in China would be interesting for future studies.

The study generally suffered from a lack of adequate and recent data availability. The recency and comprehensiveness of time series data available during the investigation period significantly affected the study's outcome. Chinese data are challenging to come by with the available ones not recent. Although towards the completion of the study, a new set of data was released in late 2021. However, the newly released data could not be integrated into the already formulated models and analysis of the study because of many reasons. One of such reasons was the manner of preparation of the data which was not in tandem with the structure of data originally used in the study. The new set of data was prepared on an 88 sub-sectoral aggregation (with basis of the sub-division not expressly defined and made available) against the 44 and 42 sub-sectoral aggregation used in the study. As a result, the new data could not be properly integrated into the existing data set without having to make unnecessary assumptions and data manipulations capable of invalidating the results of the study. In addition, the newly released data set could not be used because it was a stand-alone data. The study used a series data to show a trend analysis using base and reference years to depict a change over a few years. Using the new dataset would imply no reference years could be chosen and negates the aim of the study – tracking carbon emission use in the industry.

It would be interesting to adopt the methodologies in this study on the recent and subsequently released data (when they are available) by first resolving the sub-sectoral aggregation differences, to observe the pattern changes over recent years and further validate the models and methodologies of this study. In addition, native Chinese researchers in the field could consider creating a translated data depository website for easy access to foreign researchers to overcome language barriers.

Although initially planned during the proposal phase of the study, the variance of the discrepancies that exist in the Chinese construction emissions quantification was not evaluated. Largely, the lack of adequate and recent data availability contributed to the non-achievement of the activity. It is however important that future studies consider these discrepancies in relation to this study's results to unify emission quantifications (especially, CO_2 emissions) in the Chinese construction sector. The technological improvements variables should also be integrated into the study to signify China's efforts in tackling emissions over the years.

The study considered the construction sector's linkages primarily at provincial and regional levels. The specific linkages of the construction sector with other individual industries of the enlarged economic structure need to be adequately considered. Such a study would give a clearer understanding of the intricate relationships between the sectors while further suggesting the important emissions trade connections that need urgent attention. Also, a study decomposing emissions linkages of provincial construction sector's trades with non-Chinese economic sectors can be studied in future. This study becomes essential because of the low backward trades that occur within the provincial trade structure in China in this study. The study would aim to establish international linkages of provincial construction sectors in China using integrated multiple multi-regional IO models.

Finally, the driving forces of CO_2 emissions considered in this study were limited to four out of many. More factors such as urbanization, labour, income, energy intensity, population densities, and other macro and micro-factors could be considered to understand the deeper connections of CO_2 emissions. Therefore, further studies should expand the results of this study to more driving forces of CO_2 emissions in the Chinese construction sector.

APPENDICES

Table A1 Original sector classifications of the Chinese MRIO tables.

S/N	**Sector**
1	Agriculture, forestry, animal husbandry, and fishery
2	Mining and washing of coal
3	Extraction of petroleum and natural gas
4	Mining and processing of metal ores
5	Mining and processing of nonmetal and other ores
6	Food and tobacco processing
7	Textile industry
8	Manufacture of leather, fur, feathers, and related products
9	Processing of timber and furniture
10	Manufacture of paper, printing and articles for culture, education and sport activity
11	Processing of petroleum, coking, processing of nuclear fuel
12	Manufacture of chemical products
13	Manufacture of non-metallic mineral products
14	Smelting and processing of metals
15	Manufacture of metal products
16	Manufacture of general-purpose machinery
17	Manufacture of special-purpose machinery
18	Manufacture of transport equipment
19	Manufacture of electrical machinery and equipment
20	Manufacture of communication equipment, computers, and other electronic equipment
21	Manufacture of measuring instruments
22	Other manufacturing and waste resources
23	Repair of metal products, machinery, and equipment
24	Production and distribution of electric power and heat power
25	Production and distribution of gas
26	Production and distribution of tap water
27	Construction
28	Wholesale and retail trades
29	Transport, storage, and postal services
30	Accommodation and catering
31	Information transfer, software, and information technology services
32	Finance
33	Real estate
34	Leasing and commercial services
35	Scientific research
36	Polytechnic services
37	Administration of water, environment, and public facilities
38	Resident repair and other services
39	Education
40	Health care and social work
41	Culture, sports, and entertainment
42	Public administration, social insurance, and social organizations

Table A2. Sectoral classification of CO_2 emissions in China.

S/N	Sector
1	Production and supply of electric power, steam, and hot water
2	Production and supply of gas
3	Production and supply of tap water
4	Transportation equipment
5	Transportation, storage, post, and telecommunication services
6	Coal mining and dressing
7	Petroleum and natural gas extraction
8	Ferrous metals mining and dressing
9	Nonferrous metals mining and dressing
10	Nonmetal minerals mining and dressing
11	Other minerals mining and dressing
12	Petroleum processing and coking
13	Raw chemical materials and chemical products
14	Medical and pharmaceutical products
15	Chemical fibre
16	Rubber products
17	Plastic products
18	Nonmetal mineral products
19	Smelting and pressing of ferrous metals
20	Smelting and pressing of nonferrous metals
21	Metal products
22	Scrap and waste
23	Farming, forestry, animal husbandry, fishery, and water conservancy
24	Logging and transport of wood and bamboo
25	Food processing
26	Food production
27	Beverage production
28	Tobacco processing
29	Textile industry
30	Garments and other fibre products
31	Leather, furs, down, and related products
32	Timber processing, bamboo, cane, palm fibre, and straw products
33	Furniture manufacturing
34	Papermaking and paper products
35	Printing and record medium reproduction
36	Cultural, educational and sports articles
37	Wholesale, retail trade, and catering services
38	Others
39	Construction
40	Ordinary machinery
41	Equipment for special purposes
42	Electric equipment and machinery
43	Electronic and telecommunications equipment
44	Instruments, meters, cultural and office machinery
45	Other manufacturing industry

Table A3. CO_2 emissions result from HEM in 30 provincial construction sectors in China.

Province	**2012**			**2015**			**2017**		
	TL ($MtCO_2$)	**BE (tCO_2)**	**FE ($MtCO_2$)**	**TL ($MtCO_2$)**	**BE (tCO_2)**	**FE ($MtCO_2$)**	**TL ($MtCO_2$)**	**BE (tCO_2)**	**FE ($MtCO_2$)**
Beijing	47.22	401.70	47.22	36.06	346.45	36.06	34.76	548.64	34.76
Tianjin	84.24	1498.09	84.24	88.86	337.99	88.86	106.74	456.02	106.74
Hebei	61.12	269.87	61.12	65.78	565.11	65.78	66.04	1133.94	66.04
Shanxi	94.03	75.30	94.03	92.67	102.06	92.67	104.73	96.73	104.73
Inner Mongolia	91.91	502.60	91.91	101.97	180.06	101.97	108.35	517.03	108.35
Liaoning	39.53	810.73	39.53	19.36	722.75	19.36	12.24	786.77	12.24
Jilin	26.26	447.36	26.26	44.28	264.47	44.28	133.18	912.83	133.18
Heilongjiang	2.86	812.36	2.86	13.46	59.86	13.46	10.72	134.88	10.72
Shanghai	37.66	3278.88	37.65	30.91	782.38	30.91	38.43	1007.61	38.43
Jiangsu	24.51	398.82	24.51	12.48	729.29	12.48	19.50	737.97	19.50
Zhejiang	29.85	3155.37	29.85	49.29	3782.48	49.28	59.70	3319.07	59.70
Anhui	52.52	233.61	52.52	69.22	314.31	69.22	64.13	694.98	64.13
Fujian	30.67	251.16	30.67	55.81	1180.66	55.81	123.34	30.99	123.34
Jiangxi	7.21	128.12	7.21	12.84	399.83	12.84	21.81	1472.95	21.81
Shandong	77.39	625.20	77.39	30.15	1947.92	30.15	31.15	707.17	31.15
Henan	16.04	1855.48	16.04	28.21	3683.45	28.21	96.80	1333.13	96.80
Hubei	88.94	1005.50	88.94	81.88	523.53	81.88	81.88	523.53	81.88
Hunan	62.95	303.45	62.95	56.32	1206.68	56.32	76.73	2228.60	76.73
Guangdong	11.42	5949.94	11.42	7.92	7890.24	7.91	12.40	9335.40	12.39
Guangxi	2.04	259.71	2.04	2.53	347.32	2.53	3.90	263.75	3.90
Hainan	24.94	0.82	24.94	27.16	35.35	27.16	24.25	48.05	24.25
Chongqing	55.19	21.67	55.19	46.58	834.27	46.58	42.62	183.91	42.61
Sichuan	12.64	1366.56	12.64	16.52	625.81	16.52	77.41	370.41	77.41
Guizhou	27.53	165.29	27.53	45.80	142.58	45.80	66.13	94.62	66.13
Yunnan	40.20	561.07	40.20	42.59	322.44	42.59	118.40	154.72	118.40
Shaanxi	134.22	237.39	134.22	72.22	538.29	72.22	87.82	302.78	87.82
Gansu	62.53	43.08	62.53	113.59	9.36	113.59	51.87	107.05	51.87
Qinghai	63.48	1.98	63.48	100.53	3.68	100.53	110.60	7.03	110.60
Ningxia	71.02	6.18	71.02	58.25	26.53	58.25	32.28	62.23	32.28
Xinjiang	118.30	10.81	118.30	127.72	5.02	127.72	181.74	154.75	181.74
National Total	**1498.42**	**24,678.09**	**1498.40**	**1550.98**	**27,910.17**	**1550.96**	**1999.66**	**27,727.53**	**1999.63**

Table A4. Domestic and inter-provincial CO$_2$ source emissions distribution.

Province	2012				2015				2017			
	DNBE (tCO$_2$)	**INBE (tCO$_2$)**	**DNFE (MtCO$_2$)**	**INFE (MtCO$_2$)**	**DNBE (tCO$_2$)**	**INBE (tCO$_2$)**	**DNFE (MtCO$_2$)**	**INFE (MtCO$_2$)**	**DNBE (tCO$_2$)**	**INBE (tCO$_2$)**	**DNFE (MtCO$_2$)**	**INFE (MtCO$_2$)**
Beijing	18.87	359.37	24.65	21.80	12.25	320.72	15.69	19.52	17.56	513.67	14.50	18.98
Tianjin	200.67	1282.36	39.95	41.19	182.87	135.13	41.15	46.96	331.48	103.46	24.19	81.36
Hebei	28.08	238.45	28.59	30.15	47.33	510.34	32.29	30.46	67.59	1061.08	39.92	22.67
Shanxi	56.56	10.16	20.80	73.06	79.85	13.85	13.36	79.05	68.46	20.09	38.74	65.41
Inner Mongolia	456.06	25.73	32.22	58.17	159.53	8.51	28.14	72.42	294.79	209.25	36.45	70.57
Liaoning	569.67	223.27	20.55	17.77	616.44	98.83	7.75	10.22	692.23	87.71	5.25	6.35
Jilin	208.57	231.11	14.79	9.95	199.51	52.01	18.77	24.51	114.75	795.37	11.90	107.33
Heilongjiang	713.46	96.35	0.63	1.48	38.74	19.27	5.05	8.16	74.03	60.11	1.53	8.79
Shanghai	216.14	3052.89	29.53	6.34	274.20	496.63	20.66	9.57	239.66	761.45	25.01	12.40
Jiangsu	256.87	136.22	18.94	4.72	437.92	287.93	7.44	3.38	173.28	563.35	13.89	0.83
Zhejiang	1841.57	1253.76	18.25	10.75	1698.91	1986.39	41.05	6.86	762.46	2526.20	38.85	17.72
Anhui	76.20	151.46	29.17	22.52	135.47	167.76	33.70	34.47	467.23	215.23	18.53	44.84
Fujian	71.48	171.08	25.02	5.28	54.56	1113.06	34.36	17.88	23.99	3.53	47.36	75.63
Jiangxi	60.48	65.80	2.27	4.60	187.87	206.75	4.85	6.78	741.36	729.14	1.13	16.53
Shandong	295.58	295.61	60.89	15.82	1022.47	889.56	17.89	11.22	532.11	168.25	12.68	17.51
Henan	1491.32	335.81	6.29	7.97	2304.05	1322.59	9.81	14.50	191.19	1133.87	51.39	43.19
Hubei	53.71	921.66	78.60	9.57	143.89	312.98	69.04	12.51	143.89	312.98	69.04	12.51
Hunan	240.78	34.29	31.03	31.52	806.20	342.69	20.38	35.06	1025.82	1149.00	30.75	44.29
Guangdong	2378.08	3519.99	7.14	2.20	2378.39	5469.35	3.42	2.23	533.46	8798.49	8.42	2.38
Guangxi	210.02	49.09	0.59	1.20	287.68	58.58	1.18	0.97	214.15	49.36	0.61	2.83
Hainan	0.55	0.21	5.64	19.29	30.89	1.11	5.36	21.62	41.15	5.82	10.47	13.49
Chongqing	6.21	14.89	18.30	36.84	122.29	702.41	20.14	25.55	56.62	125.31	25.94	14.66
Sichuan	976.29	328.14	6.81	5.24	355.30	222.36	12.93	3.13	218.17	130.09	13.98	62.80
Guizhou	139.02	16.10	5.15	22.07	105.83	19.39	13.49	32.07	68.24	11.40	26.03	39.93
Yunnan	481.59	52.81	10.26	29.47	215.80	68.15	22.77	19.63	105.50	36.02	22.33	95.88
Shaanxi	9.41	225.31	67.37	65.50	31.02	503.64	30.72	39.37	70.97	229.32	21.18	63.37
Gansu	18.95	19.51	14.32	47.79	6.13	0.63	30.91	82.49	98.38	4.17	5.24	46.39
Qinghai	0.81	0.10	8.91	54.55	1.51	0.22	7.35	93.15	0.97	4.11	33.23	77.29
Ningxia	5.46	0.18	7.02	63.88	23.52	0.94	6.83	51.09	59.42	1.34	8.92	22.68
Xinjiang	9.63	0.33	23.39	94.74	4.22	0.27	17.21	110.44	149.14	5.01	3.55	177.40
Total	**11,092.09**	**13,112.04**	**657.09**	**815.41**	**11,964.63**	**15,332.06**	**593.66**	**925.29**	**7578.06**	**19,814.17**	**660.99**	**1286.01**

Table A5 Regional Distribution of Driving Forces of CO_2 Emissions in Reference Years

Region	**Direct carbon emissions intensity**	**Leontief structure**	**Final demand**	**Final demand structure**	**Total**
			Reference Year: 2015		
North China	-12.33	34.77	35.93	6.10	64.47
Northeast China	113.42	-51.51	48.93	-32.60	78.23
East China	48.25	40.23	119.37	14.63	222.47
Southcentral China	-189.75	129.90	230.33	33.55	204.02
Southwest China	-42.24	87.36	63.90	2.75	111.77
Northwest China	0.74	14.59	1.94	0.68	17.94
			Reference Year: 2017		
North China	63.38	26.41	35.19	-24.74	100.25
Northeast China	-2.91	7.70	39.43	59.85	104.06
East China	-46.65	18.84	66.91	-8.64	30.46
Southcentral China	-10.98	6.24	61.84	41.24	98.35
Southwest China	-37.99	1.29	112.82	-19.52	56.60
Northwest China	-0.21	22.65	147.71	-53.08	117.07

Table A6 Provincial Distribution of Driving Forces of CO_2 Emissions in Reference Years

Province	**2015**					**2017**				
	Direct carbon emissions intensity	**Leontief structure**	**Final demand**	**Final demand structure**	**Total**	**Direct carbon emissions intensity**	**Leontief structure**	**Final demand**	**Final demand structure**	**Total**
Beijing	9.04	-4.12	-2.96	-0.80	1.16	-10.01	3.17	37.31	-20.21	10.26
Tianjin	-41.53	34.52	39.74	7.80	40.53	29.23	-3.22	-41.11	20.68	5.58
Hebei	-4.12	9.25	6.26	3.92	15.31	17.00	4.64	4.91	-16.25	10.30
Shanxi	7.10	-3.22	-1.46	-1.27	1.15	-4.37	4.47	27.10	-17.48	9.72
Inner Mongolia	17.18	-1.67	-5.65	-3.55	6.31	31.53	17.36	6.98	8.52	64.38
Liaoning	69.44	-41.96	26.49	-37.71	16.26	16.70	11.30	20.13	47.36	95.49
Jilin	22.63	6.88	21.56	4.56	55.64	-11.26	-2.90	8.64	11.02	5.50
Heilongjiang	21.34	-16.43	0.88	0.55	6.34	-8.35	-0.71	10.66	1.47	3.08
Shanghai	-5.02	3.71	1.14	0.33	0.15	-6.93	2.12	14.21	-6.67	2.74
Jiangsu	96.82	-37.29	-24.50	-4.47	30.56	-75.62	22.54	40.70	-83.91	-96.30
Zhejiang	-1.15	-11.95	19.61	4.42	10.93	18.67	6.18	0.97	-18.16	7.66
Anhui	-22.85	30.72	68.48	7.10	83.46	16.12	-10.88	-12.53	90.42	83.14
Fujian	-5.05	45.97	42.05	4.85	87.82	11.83	-7.73	6.31	52.29	62.70
Jiangxi	7.20	-6.30	6.85	1.19	8.93	6.78	-1.75	-7.03	9.19	7.19
Shandong	-21.70	15.37	5.74	1.21	0.62	-17.51	8.35	24.27	-51.78	-36.67
Henan	27.96	48.06	74.23	8.40	158.65	-16.99	-16.96	27.24	10.13	3.42
Hubei	-92.62	51.34	67.77	9.68	36.17	-17.89	34.15	80.37	-30.81	65.83
Hunan	-98.49	11.19	74.54	13.29	0.54	19.43	-7.82	-36.48	46.62	21.76
Guangdong	-20.58	12.45	10.40	1.41	3.68	0.97	-1.97	-5.84	9.80	2.95
Guangxi	-0.12	-0.40	0.65	0.08	0.21	-2.12	-0.38	1.94	1.52	0.96
Hainan	-5.90	7.25	2.74	0.68	4.77	5.62	-0.78	-5.39	3.98	3.43
Chongqing	-52.75	37.37	56.28	6.03	46.93	-14.80	4.13	67.42	-42.80	13.95
Sichuan	-5.20	63.07	-23.71	-5.60	28.55	-41.81	-3.44	30.95	18.91	4.62
Guizhou	16.07	-16.30	33.68	2.69	36.14	-43.17	-4.49	32.64	39.12	24.10
Yunnan	-0.36	3.23	-2.35	-0.37	0.15	61.79	5.08	-18.20	-34.75	13.93
Shaanxi	22.32	-14.14	-5.15	-1.76	1.26	-11.13	17.15	71.72	-21.75	55.98
Gansu	-6.92	14.58	-4.92	-0.74	2.01	-0.05	2.88	16.82	-8.66	11.00
Qinghai	-2.17	2.86	4.47	0.90	6.06	-5.74	-1.95	5.89	6.18	4.38
Ningxia	-1.01	0.13	0.76	0.16	0.05	17.08	4.53	52.44	-28.36	45.70
Xinjiang	-11.49	11.16	6.77	2.12	8.56	-0.38	0.04	0.85	-0.50	0.01

Table A7 List of Fuel and Energies Consumed in the Chinese Construction Industry

S/N	**Fuel/Energy**	**Unit**
1	Raw Coal	10^4 Tn
2	Cleaned Coal	10^4 Tn
3	Other Washed Coal	10^4 Tn
4	Briquettes	10^4 Tn
5	Coke	10^4 Tn
6	Coke Oven Gas	10^8 cu.m
7	Other Gas	10^8 cu.m
8	Other Coking Products	10^4 Tn
9	Crude Oil	10^4 Tn
10	Gasoline	10^4 Tn
11	Kerosene	10^4 Tn
12	Diesel Oil	10^4 Tn
13	Fuel Oil	10^4 Tn
14	LPG	10^4 Tn
15	Refinery Gas	10^8 cu.m
16	Other Petroleum Products	10^4 Tn
17	Natural Gas	10^8 cu.m
18	Anthracite	10^4 Tn
19	Bituminous	10^4 Tn
20	Lignite	10^4 Tn
21	Electricity	10^8 kwh
22	Heat	10^{10} KJ
23	Methanol	10^8 cu.m
24	Nitromethane	10^8 cu.m
25	Hydrogen	10^8 cu.m
26	Other Energy	10^4 TCE

MATLAB codes used for HEM.

```
%%====CO2 Emissions in China (Global Construction CO2 Emissions
%%Linkages)=====

%%===  "T=AT+F=(I-A)^-1*F %===MRIO Model Foundation - Eqtn (2)

%%Hypothetical Extraction Approach
A = xlsread('Intl china.xlsx','2009','BDA7:BDA1458'); %%Final Demand (Fs,F-s)

Ainv = (inv(xlsread('Intl china.xlsx','2009','E7:BCZ1458')+ eye(1452)*1e-3));
filename = ('Inv Intl China.xlsx');
xlswrite(filename,Ainv,'E7:BCZ1458')

T = Ainv * A; %%Eqtn 3
C = diag(xlsread('Intl china.xlsx','2009','BDD7:BDD1458'));
D1 = C * T; %%equation 4 (Total CO2 emissions of all sectors)

clear T
%Equation 5%%
E= inv(eye(1) - xlsread('Intl china.xlsx','2009','E7'));
F = inv(eye(1451) - xlsread('Intl china.xlsx','2009','F8:BCZ1458'));
G = zeros(1,1451);  G1 = zeros(1451,1);
D2 = C *[E G; G1 F] * A;% Equation 5 (Total CO2 emissions of the hypothetical economy
clear C G G1 A
%Equation 6%%
eq6 = (D1 - D2);
clear D1 D2

%===Equation 7%% - China's Construction Industry Total Linkages with the world
%Economy====
China = xlsread('China.xlsx','2009','E1:BCZ1');
EQ7 = China * eq6; %Total CO2 emission linkages of China’s construction sector
Z = xlsread('Intl china.xlsx','2009','E7:BCZ7');
TL = Z * eq6; %Either of the two...Z is coeff, China is the money value
clear eq6

%%=====Backward Linkage of China's Construction Sector========
Es = diag(xlsread('Intl china.xlsx','2009','BDD7'));
E2 = diag(xlsread('Intl china.xlsx','2009','BDD8:BDD1458'));

Rss = Es * ((xlsread('Inv Intl China.xlsx','sheet1','E7') - E));
R2 = Es * (xlsread('Inv Intl China.xlsx','sheet1','F7:BCZ7'));
R3 = E2* (xlsread('Inv Intl China.xlsx','sheet1','E8:E1458'));
R4 = E2 * ((xlsread('Inv Intl China.xlsx','sheet1','F8:BCZ1458') - F));
R = [Rss,R2;R3,R4];
clear E F Es E2

%==all final demands Categories====
Fin1 = xlsread('Intl china.xlsx','2009','BDA7');
Fin2 = xlsread('Intl china.xlsx','2009','BDA8:BDA1458');

%===forward AND backward LINKAGES====
BL = China * [Rss;R3] * Fin1;%Eqtn (8)
FL = China * [R2;R4] * Fin2; %Eqtn (9)
```

```
%OR
BL1 = Z * [Rss;R3] * Fin1;%Eqtn (8)
FL1 = Z * [R2;R4] * Fin2; %Eqtn (9)

%====Modified HEM Decomposition of China's C.S.'s CO2 Emissions====
MBLc = China * [Rss;zeros(1451,1)] * Fin1; %for splitted result make Fchina = F14
NBLc = China * [zeros(1,1);R3] * Fin1; %for splitted result make Fchina = F14
NFLc = China * [R2;zeros(1451,1451)] * Fin2; %for splitted result make Fchina = F14
MFLc = China * [zeros(1,1451);R4] * Fin2; %for splitted result make Fchina = F14
%OR
MBLc1 = Z * [Rss;zeros(1451,1)] * Fin1; %for splitted result make Fchina = F14
NBLc1 = Z * [zeros(1,1);R3] * Fin1; %for splitted result make Fchina = F14
NFLc1 = Z * [R2;zeros(1451,1451)] * Fin2; %for splitted result make Fchina = F14
MFLc1 = Z * [zeros(1,1451);R4] * Fin2; %for splitted result make Fchina = F14
Rv = (MBLc/EQ7); %(repeat for other linkages)==Gc is Percentage Relative value of each linkage
clear Fin1 Fin2 R R2 R3 R4 Rss

%%===Eqtn 16 and 17===Aggregated Inter-Sectoral CO2 Emission Linkages of
%%Global Construction Sector
%NBLst = China * [xlsread('Inv of As','AS1:BCV44');zeros(1408,1408)] * xlsread('(1) F (s,-s) matrix.xlsx','2009','F51:F1458');
%NFLst = China * [zeros(44,44);xlsread('Inv of As','A45:AR1452')] * xlsread('(1) F (s,-s) matrix.xlsx','2009','F7:F50');

%Internationalization of CO2 Emission Linkages of the construction sector
%Basic assumption; China construction, all sectors in China === Domestic AND
%China Construction, all sectors in other countries ===International
DNBLc = China * [zeros(1,32);(diag(xlsread('Intl china.xlsx','2009','BDD8:BDD39')));zeros(1419,32)] * xlsread('Inv Intl china.xlsx','E8:E39') * xlsread('Intl china.xlsx','2009','BDA7');
INBLc = China * [zeros(33,1419);(diag(xlsread('Intl china.xlsx','2009','BDD40:BDD1458')))] * xlsread('Inv Intl china.xlsx','E40:E1458') * xlsread('Intl china.xlsx','2009','BDA7');

DNFLc = China * [(diag(xlsread('Intl china.xlsx','2009','BDD7')));zeros(1451,1)] * xlsread('Inv Intl china.xlsx','F7:AK7') * xlsread('Intl china.xlsx','2009','BDA8:BDA39');
INFLc = China * [(diag(xlsread('Intl china.xlsx','2009','BDD7')));zeros(1451,1)] * xlsread('Inv Intl china.xlsx','AL7:BCZ7') * xlsread('Intl china.xlsx','2009','BDA40:BDA1458');
%OR
DNBLc1 = Z * [zeros(1,32);(diag(xlsread('Intl china.xlsx','2009','BDD8:BDD39')));zeros(1419,32)] * xlsread('Inv Intl china.xlsx','E8:E39') * xlsread('Intl china.xlsx','2009','BDA7');
INBLc1 = Z * [zeros(33,1419);(diag(xlsread('Intl china.xlsx','2009','BDD40:BDD1458')))] * xlsread('Inv Intl china.xlsx','E40:E1458') * xlsread('Intl china.xlsx','2009','BDA7');

DNFLc1 = Z * [(diag(xlsread('Intl china.xlsx','2009','BDD7')));zeros(1451,1)] * xlsread('Inv Intl china.xlsx','F7:AK7') * xlsread('Intl china.xlsx','2009','BDA8:BDA39');
INFLc1 = Z * [(diag(xlsread('Intl china.xlsx','2009','BDD7')));zeros(1451,1)] * xlsread('Inv Intl china.xlsx','AL7:BCZ7') * xlsread('Intl china.xlsx','2009','BDA40:BDA1458');
```

MATLAB Codes for SDA.

```
A = xlsread('SDA data.xlsx','2012','E6:IJ245'); %A-coeff.
I = xlsread('SDA data.xlsx','Iden','E6:IJ245'); %Identity
L = inv(I-A);

filename = ('Leontief.xlsx');%Leontief Inverse matrix for reference
xlswrite(filename,L,'E6:IJ245')

E = diag(xlsread('SDA data.xlsx','2012','IO6:IO245'));
s1 = xlsread('SDA data.xlsx','2012','E6');
s2 = xlsread('SDA data.xlsx','2012','F7:IJ245');

filename = ('Intensity.xlsx');%Emission Intensities for reference
xlswrite(filename,E,'E6:IJ245')

r1 = xlsread('Intensity.xlsx','Sheet1','E6')*(xlsread('Leontief.xlsx','Sheet1','E6')-(inv(eye(1)-s1)));
r2 = xlsread('Intensity.xlsx','Sheet1','E6')*(xlsread('Leontief.xlsx','Sheet1','F6:IJ6'));
r3 = xlsread('Intensity.xlsx','Sheet1','F7:IJ245')*(xlsread('Leontief.xlsx','Sheet1','E7:E245'));
r4 = xlsread('Intensity.xlsx','Sheet1','F7:IJ245')*(xlsread('Leontief.xlsx','Sheet1','F7:IJ245')-inv(eye(239)-s2));
R=[r1,r2;r3,r4];

w=L-R; %change in Leontief inverse
P0 = sum(w);
w0=sum(P0);%inverse change
f0=xlsread('Intensity.xlsx','Sheet1','E6');%intensity
Y0=xlsread('SDA data.xlsx','2012','IM6');%Output
sF0=sum(xlsread('SDA data.xlsx','2012','IL6:IL13'));
S0=Y0/sF0;
sY0=sum(xlsread('SDA data.xlsx','2012','IM6:IM13'));

clear A C C1 C2 E F filename I L r1 r2 r3 r4 s1 s2 v R Y0 P0 sF0
```

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