A STUDY OF EMBODIED ENERGY ASSESSMENT OF CHINA'S CONSTRUCTION SECTOR AND CONSTRUCTION PROJECTS

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CERTIFICATE OF ORIGINALITY

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Abstract

Building-related energy problems are a worldwide concern. Due to its rapid pace of urbanization and industrialization, China is one of the largest primary energy users in the world which accounts for approximately one-fifth of the global total primary energy supply (TPES) and one-fourth of carbon dioxide (CO_2) emissions, facing big challenges in environmental pollution. Therefore, this study chooses China as the jurisdiction within which to investigate the environmental implications of the construction sector because of its extremely high resource consumption and environmental burden.

The primary aim of this research was to systematically quantify the direct and indirect energy transmissions embodied in China's construction sector at the regional and sectoral level, and develop a multi-regional hybrid framework for assessing embodied energy consumption at the project level.

The specific objectives of this research were as follows:

(1) To explore the driving forces behind the increase in energy use of the construction sector and investigate energy consumption trajectory in the past two decades.

(2) To quantify embodied energy use of the construction sector at the regional and sectoral level.

(3) To decompose energy transmissions and identify critical energy paths in the entire supply chain from the sectoral and regional perspectives.

(4) To develop a multi-regional hybrid framework for assessing embodied energy consumption at the project level by integrating regional average data and case-specific process data.

(5) To verify and validate the reliability of the developed framework in real building cases through data from project level.

The study firstly explored the driving forces behind the increase in energy use of China's construction industry from 1990 to 2010 by conducting a structural decomposition analysis (SDA). A multi-regional input-output (MRIO) model was then employed to investigate the hidden linkage and economic network among regional construction sectors by considering region-specific characteristic and technological differences. An optimized algorithm was designed for structural path analysis (SPA) to quantify indirect energy transmissions through the upstream supply chain of the construction sector. Ultimately, a multi-regional hybrid framework for embodied energy assessment of construction projects was proposed by integrating three modules: the region-based sectoral energy intensity module (RBSEIM), the process-based energy intensity module (PBEIM), and the computational structure module (CSM). The hybrid framework was then validated in real cases by conducting comparative and empirical analyses.

The key findings obtained in this study include the following aspects. First, the results of SDA indicate that the energy consumption trajectory of China's construction sector is the result of competition between the effect of increasing final demand and improvement in energy efficiency. Although consistent efforts in structural optimization by the central government had significant positive effects between 2007 and 2010, the potential to reduce much more energy remains dependent on optimization of energy structure, production structure, and final demand structure. Second, the results of MRIO analysis show that the construction sector consumed 793.74 million tons of coal equivalent in 2007, which is equal to 29.6% of China's total national energy consumption. Interregional imports of the construction sector represented a resource-dependent geographical distribution, implying that the energy flows are from resource-abundant areas in the central part of the country to resource-deficient areas on the eastern coast. By contrast, energy exports represent a regional discrete distribution, which exports energy in the form of labor mobility and service supply. Third, the findings from SPA revealed that the first two stages in the upstream production process consumed the highest amount of energy in the supply chain, accounting for approximately 50% of total energy consumption. The regional analysis revealed the self-sufficiency characteristic for energy consumption in the regional construction sectors. The sectoral analysis demonstrated that imports from sectors of “manufacturing of non-metallic mineral products”, “smelting and pressing of metals”, and “transportation, storage, post, and telecommunications” are the most important energy flows in the first stage. The sectors of “chemical industry”, “production and distribution of electric power and heat power”, and mining industries pose significant indirect impact on the energy use of the construction sector. Ultimately, the comparative analyses and empirical studies of the developed hybrid framework indicate that it not only enables us to explore interregional energy transfers but also exhibits ‘hidden’ embodied energy consumption. The framework can also reflect the effects of changes in geographical location, building type, and building structure on the total embodied energy consumption.

This study contributes the sustainable construction at three levels of investigation: national level, regional level, and project level. At the national level, the research explored the driving forces and trajectory of the embodied energy consumption of the construction sector, which revealed the potential areas for improvements in sustainable construction. At the regional level, the inter-regional energy transfers and the indirect energy input through the higher order of upstream supply chain were systematically analyzed and decomposed for the construction sector, which not only enhances our understanding of overall energy flows of the construction sector at the regional level but also reinforces the importance of specific energy-intensive paths. At the project level, the embodied energy assessment system provided valuable information in terms of embodied energy use at the early stage of a construction project, which enables stakeholders to take appropriate actions and formulate effective strategies to reduce energy use embodied in the project.

From an academic point of view, the sectoral and regional analysis of driving forces, energy flows, and the supply chain provided contributions to knowledge regarding SDA, MRIO, and SPA of the construction sector. In addition, recognizing the hidden linkage in the interregional trade of China’s construction sector can help with a holistic understanding of the current energy consumption status of regions and also help policy makers to achieve a fair and equitable energy reduction policy. From the viewpoint of practice, the multi-regional embodied energy assessment framework is an effective tool for pre-estimating embodied energy use at the initial stage of a project, which could provide practitioners with an incentive to develop construction sustainability.

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1. Hong, J., Shen, Q.P., Feng Y., Lau S.T., and Mao C. (2015). Greenhouse gas emissions during the construction phase of a building: a case study in China. *Journal of Cleaner Production*, 103, 249-259.
2. Hong, J., Shen, Q.P., and Guo S. (2015). Energy use embodied in china's construction industry: a multi-regional input-output analysis. *Renewable and Sustainable Energy Reviews,* 53, 1303-1312.
3. Hong, J., Shen, Q.P., Mao C., Li Z.D., and Li K.J. (2016). Life-cycle energy analysis of prefabricated components in buildings: an input–output-based hybrid model. *Journal of Cleaner Production*, 112, 2198-2207.
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Table of Contents

List of Figures

List of Tables

Table of Abbreviations

Abbreviation	Full name	Page of the abbreviation firstly appeared
IEA	International Energy Agency	1
TPES	Total primary energy supply	1
Mtce	Million tons of coal equivalent	1
IPCC	Intergovernmental Panel on Climate Change	1
SRIO	Single-region input–output table	2
RBSEIM	Region-based sectoral energy intensity module	7
PBEIM	Process-based energy intensity module	7
CSM	Computational structure module	7
SDA	Structural decomposition analysis	8
MRIO	Multi-regional input-output model	8
SPA	Structural path analysis	8
GDP	Gross domestic product	24
GHG	Greenhouse gas	26
CDM	Clean Development Mechanism	27
IDA	Index decomposition analysis	50

Chapter 1 Introduction

1.1 Introduction

This chapter outlines the basic research proposition of this study, including research background, research questions, research scope, and research aim and objectives. The overall research design and structure of the thesis are also presented. Finally, the value and significance of the research is highlighted.

1.2 Research Background

Energy and its related problems are a worldwide concern. According to the International Energy Agency (IEA), the total primary energy supply (TPES) reached a historical high of 13.1 billion tons of coal equivalent (Mtce) in 2011, releasing 31.3 billion tons of energy-related CO_2 emissions, which is regarded as the major human cause of global warming (International Energy Agency, 2013). China, as a major contributor, accounts for approximately one-fifth of the global TPES and one-fourth of CO_2 emissions. Energy consumption is related to the process of consuming energy or power. The Intergovernmental Panel on Climate Change (IPCC) reported that the building sector was responsible for 40% of global energy consumption and approximately 25% of global CO_2 emissions (Metz et al., 2007). China is on a path to rapid urbanization and industrialization. As the result of such intensive construction, the growth rate of energy consumption related to construction is more than 10% of that in past decades (Chang et al., 2014b). Being one of society’s primary energy consumers, the construction sector accounted for 16% of total energy consumption in China in 2007 (Chang et al., 2010) and was projected to be 20% in 2015 by Chang et al. (2011). Therefore, as one of the largest primary energy users in the world, China faces big challenges in energy consumption and a huge environmental burden due to its rapid urbanization. According to the 12th Five-Year Plan, the urbanization rate in China is estimated to reach a historic high of 51.5% in 2015, which is certain to produce considerable energy demands. China is therefore the ideal country within which to investigate the environmental implications of the construction sector. Not only does the country generate a significant environmental impact and resource consumption but it also represents a distinctive feature due to its extensive and sizable construction projects.

Therefore, considering the requirement for cleaner energy production in China, it is imperative to holistically investigate the embodied energy use involving the direct energy input from the onsite production process and the indirect energy consumption from the upstream process (Chen and Chen, 2013a). Such investigation could not only facilitate specific policy decisions on energy and environmental issues related to the construction sector but also steer the urbanization process towards more sustainable development. Energy transmission is the process of transferring energy from one point to another in an economic system. In this study, it represents the energy transfer among sectors and regions. However, the indirect energy transmissions with other economic sectors and regions in the supply chain are infinite as it mixes production technology from both domestic and foreign sources. Traditional single-region input–output (SRIO) analysis fails to capture the hidden linkage and economic network among interregional trade flows (Peters and Hertwich, 2006a, b; Wiedmann, 2009; Wiedmann et al., 2007b). It is applied on the assumption that the manufacturing technology in the domestic production process is the same as the technology used in foreign regions. Therefore, the SIRO model is unable to describe these differences in production and economic structure. More importantly, the specific regional characteristics such as the variations in the climate, geographical location, natural resources, and level of the economy directly determine the interregional import and export among different regions. This results in cross-regional environmental shifting. Unfortunately, the environmental pollution caused by interregional trade is commonly ignored. This insufficient understanding of current energy consumption status could result in unfair or irrational policies for the construction industry. Furthermore, although embodied energy assessment tools have been extensively studied at the project level, the effect of regional disparities has been rarely considered during evaluation processes.

This study therefore conducts the systematic analyses based on four steps. First, the driving forces behind the increase in energy consumption were explored for the construction sector. Such analysis is fundamental to provide comprehensive understanding and projections regarding future energy consumption. It seeks appropriate solutions and policy implications regarding the booming property market and the characteristics of the construction sector. Second, the hidden linkage and economic network of the construction sector were examined at the regional and sectoral levels, which provided valuable information on the current energy consumption status of China's construction sector. Third, a systematic structural analysis quantified energy transfers in the upstream process and identified the important paths with the largest potential for energy reduction by tracing the intricate production chain. This provides a sufficient understanding of the correlations in the energy consumption embodied in the interregional trade of China's construction sector such that linkages between consumption and production in the interregional supply chain can be explored, which could help decision makers formulate equitable energy reduction policies at the national or regional level. The fourth and final step was the development of a multi-regional hybrid framework for assessing the embodied energy consumption of construction projects. This framework is capable of providing first-hand energy assessment reports and energy reduction strategies at the initial stage of a specific construction project, which could facilitate embodied energy assessment at the project level.

1.3 Scope of the Study

Since the definition of the construction sector in China is highly aggregated, it is necessary to define the scope of the study. According to the definition of the construction sector in the Chinese I-O table, it is composed of five sub-sectors: building construction, civil engineering construction, building installation, decoration, and other construction related activities that cover the entire range of on-site and off-site construction activities. The services, materials, and techniques that are distinctively present in the "intricate production chain" are also quantified according to the infinite sectoral interactions in the I-O analysis. Therefore, the total economic output of the construction sector contains all the values embodied in the design, extraction of raw materials, manufacturing, transportation, onsite construction, and other construction related processes before completion of building and civil engineering projects.

Because construction processes of buildings and civil engineering projects are distinguished from other forms of production by their multitude of activities, long-term duration, and complex manufacturing process, researchers normally divide the whole life cycle of a construction project into different phases. Based on the scope of the construction sector, the system boundary for this study was the investigation of embodied energy consumption of construction projects from cradle to construction, namely extraction of raw materials, manufacturing, transportation, and onsite construction process.

1.4 Research Questions

The literature regarding energy assessment in the construction practice, from both a micro and macro perspective, suggests that the construction sector plays an important role in alleviating adverse environmental impacts and resource depletion. This necessitates a comprehensive understanding of how direct and indirect construction activities affect China's regional sustainability development. This understanding can be achieved by employing data analysis techniques at the macro level and developing a prototype framework with a consistent computational process for energy assessment at the micro level. More specifically, to fill the identified research gaps in the relevant literature, this study measured direct and indirect energy transmissions embodied in the interregional trade of the construction sector using systematical decomposition and structural analysis. The research then combined regional average data and project-specific process data to shed light on the energy assessment of construction projects within a particular regional context and complete system boundary. Given the research background and identified gaps, this study addressed the following research questions:

(1) What are the driving forces behind the increase in energy use in the construction sector over the past two decades?

(2) How to measure the regional energy consumption and indirect energy transfers due to interregional trade of the construction sector?

(3) How to decompose and quantify the energy transmissions through the entire supply chain of the construction sector at the regional and sectoral level?

(4) How to assess the embodied energy consumption in the construction sector at the project level by taking regional disparities into consideration?

1.5 Research Aim and Objectives

To address the aforementioned research questions, the primary aim of this research was to systematically quantify the direct and indirect energy transmissions embodied in China's construction sector at the regional and sectoral level, and develop a multi-regional hybrid framework for assessing embodied energy consumption at the project level.

The specific objectives of this research were as follows:

(1) To explore the driving forces behind the increase in energy use of the construction sector and investigate energy consumption trajectory in the past two decades.

(2) To quantify embodied energy use of the construction sector at the regional and sectoral level.

(3) To decompose energy transmissions and identify critical energy paths in the entire supply chain from the sectoral and regional perspectives.

(4) To develop a multi-regional hybrid framework for assessing embodied energy consumption at the project level by integrating regional average data and case-specific process data.

(5) To verify and validate the reliability of the developed framework in real building cases through data from project level.

First, a holistic investigation of the driving forces and energy consumption trajectory of the construction sector was conducted (Objective 1), followed by the quantification of the regional construction embodied energy use (Objective 2) and decomposition of energy transmissions of the supply chain associated to regional construction sectors (Objective 3). The first three objectives together provide a theoretical foundation and computational framework for energy consumption assessment at the project level. A multi-regional hybrid framework was then proposed by integrating the region-based sectoral energy intensity module (RBSEIM), process-based energy intensity module (PBEIM), and the computational structure module (CSM) with external case-specific building information (Objective 4). Finally, this developed framework was validated by testing its reliability and feasibility in real construction projects (Objective 5). Based on this framework, regional and sectoral embodied energy analysis and specific energy saving strategies can be provided at the project level, which can contribute towards cleaner production of construction industrial activities in China.

1.6 Research Design

This study aimed to quantitatively measure direct and indirect energy transmissions due to the interregional trade of regional construction sectors at the regional level and establish an energy assessment framework at the project level. To achieve these research objectives, both qualitative and quantitative research approaches were elaborately designed in a logical research process. In general, this research is quantitatively dominant, since quantitative methods were widely adopted to quantify regional energy consumption with solid numeric data. On the other hand, qualitative methods were used to extract research questions, identify research gaps, explain quantitative results, and collect empirical data. More specifically, three types of research methods were adopted to achieve the study's research objectives. They are document analysis, data analysis, and case studies.

Document analysis. Document analysis is normally identified as archival research, which is designed to resolve research problems and questions by investigating recorded information and previous documentations. This is the major qualitative method for in-depth content analysis and reviewing existing data. In this research, document analysis was first conducted to review relevant literature with the aim of identifying and extracting the research barriers and gaps existing in the research field. Second, document analysis was used to serve as a solid reference for the collecting and analyzing of data from public documents, which for the purpose of this research were China's statistical yearbooks.

Data analysis. Data analysis is a process comprising various analytical tools for exploring, transforming, and modeling data, which aims to extract valuable information and make useful conclusions. Both exploratory data analysis and predictive analytics have been used in this research. More specifically, the analytical tools include structural decomposition analysis (SDA) in Chapter 4, multi-regional input-output (MRIO) model in Chapter 5, and structural path analysis (SPA) in Chapter 6.

Case study. Case study is a research method designed for detailed examination of typical cases, representing the basic features and situations of subjects of study in the context of practice. It may involve other research methods such as document analysis, observation, and field survey. This research employed case studies to verify the reliability as well as validate the effectiveness and advantages of the developed framework.

Based on specific methods discussed above, the entire research process is illustrated in Figure 1.1. There are 4 components and 8 steps in the research process, which correspond to the chapters in the thesis from chapter 2 to chapter 8. In the first component - research proposition, by reviewing the recent development of related studies, the research objectives and methodologies were identified, which served as a theoretical foundation for subsequent analyses. In the component 2 and 3, the embodied energy consumption and energy transmissions of the construction sector were analyzed and decomposed at the national and regional level by utilizing data analysis methods. Component 4 is the stage of establishing and validating the multi-regional hybrid framework at the project level.

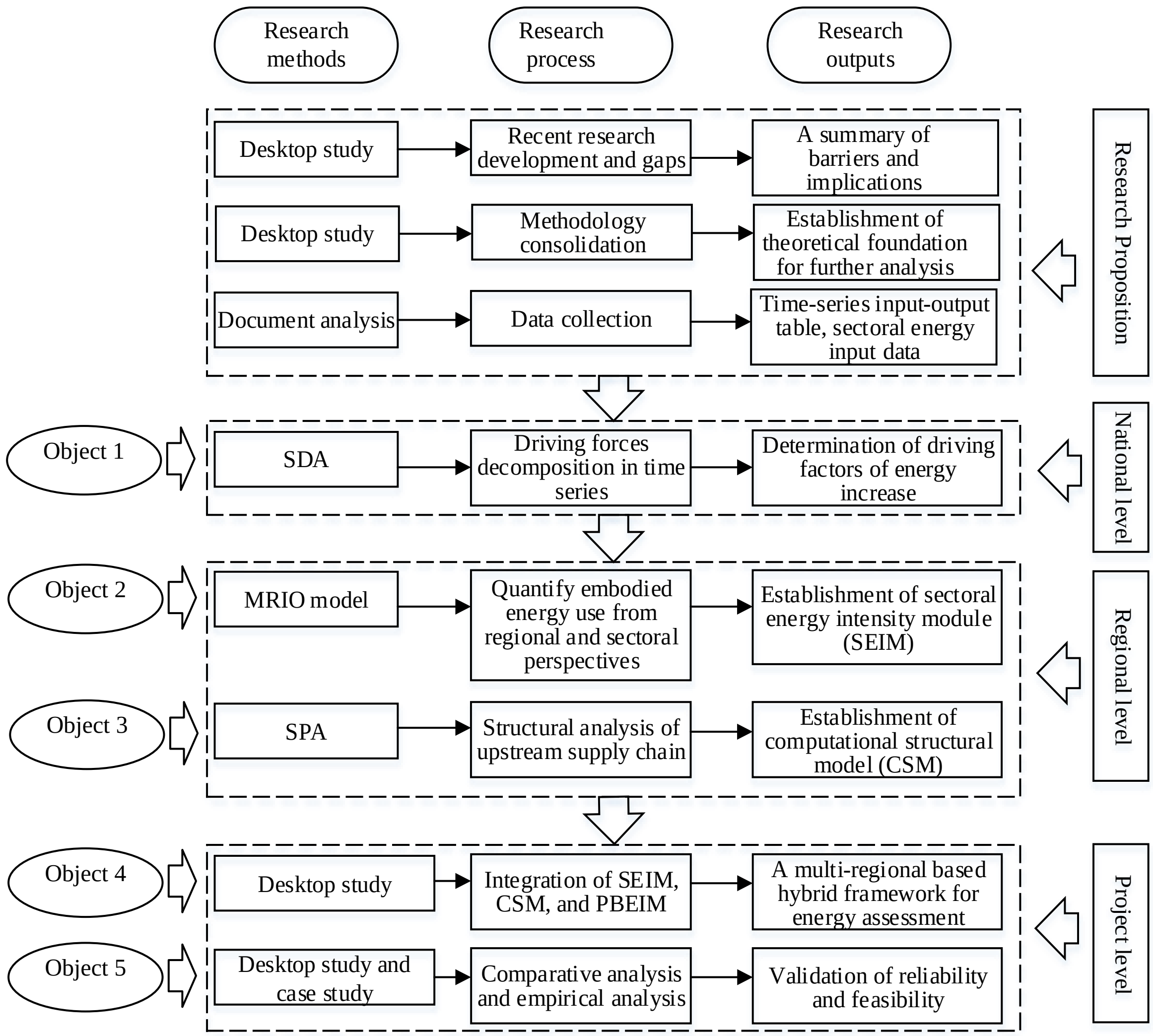


Figure 1.1 Overall framework of the thesis

1.7 Value and Significance of the Research

The study will quantify embodied energy use at three levels of investigation: national level, regional level, and project level. At the national level, the research will explore the driving forces and trajectory of the embodied energy consumption of the construction sector, which will reveal the potential areas for improvements in sustainable construction. At the regional level, the inter-regional energy transfers and the indirect energy input in the upstream supply chain of the construction sector will be systematically analyzed and decomposed, which will not only enhance our understanding of overall energy flows among regional construction sectors but also reinforces the importance of specific energy-intensive paths. At the project level, the embodied energy assessment system will provide valuable information in terms of embodied energy use at the early stage of a construction project, which will enable its stakeholders to take appropriate actions and formulate appropriate strategies to reduce energy use embodied in the project.

From an academic point of view, this research contributes to the knowledge of sustainable construction and fills the knowledge gap by providing a systematic understanding of the current energy consumption status of the construction industry. To achieve this, the driving forces, energy flows, and the supply chain of the construction sector have been analyzed at the regional and sectoral level, which contributes to knowledge regarding the structural analysis methods in the construction sector. In addition, recognizing the hidden linkage in the interregional trade of China's construction sector is of great importance to holistically understand the current energy consumption status of regions and effectively helping policy makers to achieve a fair and equitable energy reduction policy. From the viewpoint of practice, the multi-regional embodied energy assessment framework is an effective tool to pre-estimate the embodied energy use at the initial stage of a project, which could provide an incentive to industry practitioners for their sustainability consideration. It also facilitates the implementation of green building standards and the development of cleaner production in China's construction industry.

1.8 Structure of the Thesis

This thesis comprises nine chapters.

Chapter 1 is an overall introduction highlighting the essential information of the whole research, including the background, research questions and objectives, the scope and design of the research, research methods, and the structure of the whole thesis.

Chapter 2 presents a comprehensive review of the literature regarding the embodied energy analysis of construction projects at the industrial and project levels. Three categories of literature were reviewed: the development and barriers of recent embodied energy research; the study of embodied energy use at the industrial level; and the study of embodied energy use at the project level. Moreover, the knowledge gaps and barriers were also identified to improve the significance of the study.

Chapter 3 describes the methodologies adopted throughout the research. This chapter firstly discusses the research framework, followed by the illustration of detailed methods employed such as literature review, content analysis, data analysis methods, and case study. In addition, three major data analysis methods, namely structural decomposition analysis (SDA), multi-regional input-output (MRIO) analysis, and structural path analysis (SPA) were described in detail.

Chapter 4 presents the driving forces behind energy demand in China's construction sector from 1990 to 2010 by conducting structural decomposition analysis (SDA). Five driving factors were identified, namely change in total energy intensity, change of energy structure, change of production structure, change in final demand volume, and structure change of final demand. Moreover, this chapter also projected the future trajectory of embodied energy consumption for the construction sector during China's 13th (2015-2020) Five-Year Plan.

Chapter 5 provides an account of the embodiment analysis from the sectoral and regional perspective based on multi-regional input-output (MRIO) analysis. This chapter diagrammatically mapped energy flows derived from interregional trade of the regional construction sectors, and established the region-based sectoral energy intensity module that served as one of databases for the hybrid framework.

Chapter 6 investigates and quantifies the indirect energy input throughout the upstream supply chain by employing structural path analysis (SPA). The critical energy paths and nodes with the largest energy improvement potential were identified in terms of regional and sectoral perspective, which served as a theoretical foundation and computational module for development of the hybrid framework.

Chapter 7 proposes a multi-regional hybrid framework for embodied energy assessment of construction projects in China. Case-specific construction information was provided in the input layer, while the integration layer was built by integrating the region-based sectoral energy intensity module (RBSEIM), the process-based energy intensity module (PBEIM), and the computational structure module (CSM).

Chapter 8 validates the multi-regional embodied energy assessment framework with real construction cases. First, comparative analysis with conventional assessment methods was conducted to test the reliability of the developed framework. Second, empirical analysis validated its feasibility in real construction projects and highlighted the effectiveness and advantages in reducing and optimizing energy consumption at the project level.

Chapter 9 summarizes the primary research findings and examines the achievement of the research objectives proposed at the beginning of the study. The theoretical and practical contributions to the national level, regional level, and project level were highlighted. Finally, the limitations of this research and direction for future related studies were discussed.

1.9 Summary of the Chapter

This chapter outlines the overall research proposition, including background information, research questions, research aim and objectives, scope of the study, research design, and value and significance of the research.

Chapter 2 Literature Review

2.1 Introduction

Because of the intensive construction involved in the urbanization process, construction-related energy issues are a worldwide concern. Consequently, there is a growing interest in sustainable development in the construction sector due to its huge environmental burden and ecological damage to the whole society. In fact, the construction sector has a huge impact on resources and the environment, which globally accounts for 1/6 of water consumption, 1/4 of timber consumption, and 2/5 of commodity energy consumption (Augenbroe et al., 1998). The production of building materials also depletes fossil fuels and discharges large volumes of harmful gases. Emissions from vehicles used for material transportation is also a major factor contributing to the global greenhouse effect and ozone layer damage.

This chapter critically reviews the research associated with embodied energy analysis and its application in the construction sector. Three categories of literature are reviewed: the development and barriers of recent embodied energy analysis; the study of embodied energy at the industrial level; and the study of embodied energy at the project level. Moreover, the knowledge gaps and barriers have been also identified to improve the significance of the present study.

2.2 Embodied Energy Analysis

2.2.1 Scope of Embodied Energy

In general, energy consumption of construction projects can be divided into seven phases according to different life cycles, namely energy use in extraction of raw material, manufacturing, transportation, construction (assembly and installation), operation, demolition, and recycle and reuse (See Figure 2.1). To distinguish from operation energy which is associated with the energy required for building operation, the sum of the direct energy use from the onsite construction and the indirect energy use from material production, renovation, and demolition has been identified as the embodied energy for construction projects.

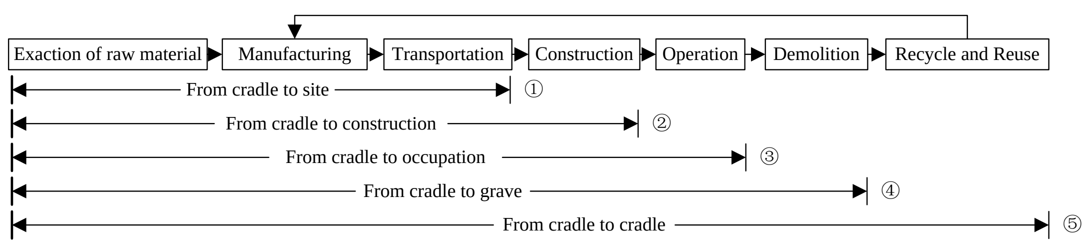


Figure 2.1 The process of whole life cycle of the construction project

More specifically, the total embodied energy consumption can be further decomposed into two components: the direct and indirect embodied energy use. The direct energy use on the construction site includes the energy consumption from construction equipment, onsite transportation, construction electricity supply, assembly and miscellaneous works, and other construction related workers activities (e.g. cooking, water production, and fugitive discharge from septic). The indirect energy use can be further decomposed into three categories: initial, recurrent, and demolition embodied energy consumption. Initial embodied energy use is the sum of energy consumed in the upstream process of the construction, including the production and transportation of materials. Recurrent embodied energy is involved in the energy consumed in the renovation and maintenance during the operation phase. Demolition embodied energy is the sum of energy use in building deconstruction, transportation, recycle and reuse of materials, and landfill disposal.

2.2.2 Recent Development

The original concept of embodied energy arose in the 1980s, and was developed in 1990s. Before the 1990s, due to the large amount of energy consumption and environmental burden, most researchers concentrated their attention on the usage phase of a building's whole life cycle. However, the significant role of the embodied energy use in the whole life cycle of construction projects has been gradually recognized with development of the assessment tools and expansion of the system boundary. More processes upstream through the supply chain of building construction were taken into considerations, such as the extraction of raw material, processing, and transportation, increasing the importance of the embodied phase in the entire life cycle of a building. This change attracted the interests of many researchers: Tucker et al. (1993) found that embodied energy from the construction industry accounted for 20% of the national total energy usage in Australia; Emmanuel (2004) contended that in a cold country the ratio between construction and annual operational energy is 3-6, in a temperate country the ratio goes up to around 3-9, and in a tropical developing country the operational energy is so small that it has little influence on the environment; Huberman and Pearlmutter (2008) suggested that embodied energy accounts for around 60% of the overall life-cycle energy consumption; and Jeong et al. (2012) asserted that steel and concrete used in the embodied phase are responsible for more than 82% of the total CO2 emissions from buildings.

The recent development of the understanding of embodied energy is listed in Table 2.1, from which can be seen that the definition of embodied energy has developed over the past two decades. The major difference lies in the scope of the system boundary. In fact, the understanding of embodied energy has been expanded from its original definition such that the energy consumed in the upstream process into the energy embodied in the phase of materials production, transportation, renovation, maintenance, and demolition. The embodied and operational energy together present the total energy consumption of a specific construction project from cradle to grave. Therefore, it can be concluded that the scope of the construction sector in I-O table is consistent with the recent development of the understanding of embodied energy, which covers the construction activities involved in the whole embodied phase of a specific project. Consequently, the term “embodied energy” in this study is defined as the energy consumed by all of the processes associated with the construction of a project, from the mining and processing of natural resources to manufacturing, transport, project delivery, and demolition process. The value derived from the I-O analysis for the construction sector represent the sum of energy consumed in the whole embodied phase of construction projects.

Table 2.1 Definition and research boundary of embodied energy

Source	Definition	Boundary
Wilson and Young (1996)	Primary energy consumed in extraction, manufacture and delivery to site	From cradle to site
Treloar (1997)	Direct energy used on site and indirect energy embodied in inputs and its upstream process	From cradle to production
Crowther (1999)	Direct energy used in construction and installation process, and indirect energy consumed in building	From cradle to production

	materials manufacturing	
Treloar et al. (2001b)	Energy used in the construction and all upstream process	From cradle to production
Sartori and Hestnes (2007)	The total embodied energy is the sum of the energy needed in the building plus energy used in rehabilitation and maintenance.	From cradle to grave
Dixit et al. (2012)	Energy consumed in building materials during the production, construction, usage and demolition phrase	From cradle to grave

2.2.3 Overview of Methods

Various assessment methods have been employed for embodied energy quantification. Four primary methods are commonly used, namely statistical analysis, process-based analysis, input-output analysis, and hybrid analysis. Statistical analysis is an effective method to reflect the energy productivity and construction efficiency for a certain region or country based on historical data. It is conducted under precise, consistent, and sufficient database which may increase the difficulties during the data collection process. König and De Cristofaro (2012) conducted a benchmark study on environmental assessment of residential buildings by using statistical interpretations.

The last three methods are the major models for life cycle assessment (LCA). In fact, life cycle approaches are the primary methodologies used in calculating the embodied energy of construction projects (Dixit et al., 2012). Process-based analysis quantifies the detailed resource and energy consumption from direct input of the manufacturing process to the indirect input with significant environmental contributions in the upstream and downstream process of the supply chain. Although the case-specific process data to some extent improve the accuracy of the calculation result, this model is time and cost-intensive. In addition, the intuitive determination of system boundary is subject to truncation errors and thereby results in variations (Rowley et al., 2009).

I-O analysis measures the resource consumption and environmental impact with the aid of sectoral monetary transactions in the national or regional based input-output table, which takes all infinite sectoral interdependencies in the modern economy into consideration. It minimizes the time and cost intensity for data collection by using public available data. However, this model calculates the result based on a higher level of aggregation which may be invalid for a particular product due to lack of specificity. Moreover, it also suffers from the inherent computational problems including proportionality, homogeneity, and the outdated input-output data (Treloar et al., 2004).

To eliminate the truncation errors and guarantee the specificity in environmental assessment process, hybrid analysis has been developed to provide more accurate assessment of environmental loadings. In general, three models have been commonly used in previous literature: tiered hybrid, input-output (I-O) based hybrid, and integrated hybrid model. Tiered hybrid model was firstly proposed by (Bullard et al., 1978). The scientific basis of this model is to employ process-based data at important lower order upstream processes, usage phase, and downstream processes whilst supplement I-O data for indirect impacts with negligible contributions from higher order upstream process. Such manipulation to large extent maximizes the accuracy and reliability of calculated results. However, the direct integration of process and I-O model may probably result in double counting. It is therefore important to subtract the process-based flows from the I-O model to represent only the cut-off inventory. Although the application of I-O derived data improve the completeness of the system boundary in the upstream process, truncation errors may still arise in use and downstream phases due to the limitations in data availability for details processes. More importantly, the interface of system boundaries between process-based and I-O based model is flexible, which depends on the research purpose, accuracy requirement, and time restrictions.

I-O based hybrid model is a top-down method which aims to further modify or disaggregate the direct supply chain of the sector in the I-O table that the product being investigated belongs. It allows the incorporation of the case-specific process data into I-O direct coefficient matrix, which provides the analyst with access to detailed process information within complete system boundary. However, according to Joshi (1999) and Suh et al. (2004), as the basic produce for I-O based hybrid analysis, the disaggregation is restrained due to the overdependence of the detailed data of input and sale information for the new hypothetical sector. Treloar (1997) proposed I-O based hybrid approach in a different way by substituting the most energy intensive paths with the process-based inventory data. A number of studies have been conducted under this hybrid framework (Crawford, 2008; Crawford and Pullen, 2011; Lenzen and Treloar, 2002; Treloar et al., 2000b; Treloar et al., 2004).

Integrated hybrid model integrates the I-O model with matrix representation of the physical process flows of a particular product, which makes the computational framework consistent (Bilec, 2007). It incorporates the physical quantities of process-based data into the I-O model directly. However, because of its higher requirement in detailed data, it is time and cost intensive and more complicated to practical application.

In summary, tiered and I-O based hybrid model are more dependent on budget information because only monetary value can be modeled in the I-O analysis for further environmental effect assessment. The results obtained from these two approaches are in the higher level of aggregation because the computational process is based on the sectoral framework derived from I-O model. In contrast, integrated model is prioritized to incorporate physical unit and monetary transactions. According to Suh et al. (2004), it is difficult to determine the most suitable hybrid model intuitively in a certain application, which is to large extent based on the actual data availability and accuracy requirement.

2.2.4 Motives and Obstacles

Apart from the large share and important role in life cycle energy consumption of construction projects, motivations underlying the analysis of embodied energy include the following aspects. First, China still constructs a large number of buildings each year because of its rapid urbanization process, which is bound to produce a large amount of embodied energy from materials production and construction processes. On one hand, the alleviation of this high level of demand is to a large extent dependent on the macro-level control from central government, but the effect of such policy orientation is not obvious in a short period of time. On the other hand, the research community therefor has to seek the process-based optimization of energy consumption and provide energy saving strategies at the project level. More importantly, compared with operational phase which is relatively easy to be controlled or reduced by using energy efficient appliances or adopting advanced insulating materials, there is limited potential for improvement in the embodied phase. In fact, the consumption of embodied energy is mostly determined by the design or pre-construction phase, which is difficult to improve after completion.

However, a number of barriers still exist in embodied energy analysis which may lead to variations in the energy assessment results. First, results from the conventional embodied energy analysis are uncertain and irreproducible because of uncertainties in data collection, system boundary, and data quality. Detailed process data are almost unavailable in the construction sector due to the confidential requirement of clients and contractors. Given that each construction project is basically unique according to the specificity of its design, structure, and quantity of material use, collecting sufficient data to describe an investigated project is extremely difficult. Consequently, related studies have to search for balance between data completeness and loss of accuracy. Such subjective manipulation has highlighted the important role of uncertainty in embodied energy analysis in recent years (Ciroth et al., 2002; Geisler et al., 2005; Sonnemann et al., 2003; Sugiyama et al., 2005). Second, results of embodied energy analysis may be inconsistent for a certain building according to different research scopes and computational structures (Crawford, 2008; Rowley et al., 2009; Sharrard et al., 2008; Suh and Huppes, 2005). Dixit et al. (2012) undertook a comprehensive review of the factors affecting the variation of embodied energy results. They summarized ten critical factors that were identified important by previous research. In addition, the data used for embodied energy analysis in the construction sector mainly comes from publicly available data, client and stakeholders documents, and previous research findings. The transparency and reliability of these data sources need to be further confirmed and clearly clarified in order to guarantee the accuracy of final results. Moreover, public available data used in the embodied energy analysis are normally compiled based on outdated technology and manufacturing levels, leading to underestimate or overestimate the energy inputs of the investigated process. In addition, different geographic locations and construction technologies also contribute to the inconsistency in the calculation results, since the quality of raw materials, construction methods, type of vehicles, and transportation distances are various in different regions and countries.

2.3 Development of Embodied Energy Analysis at the Industrial Level

2.3.1 Overview of the Construction Sector

The construction sector has grown to be the primary industry supporting the development of China's economy in the past thirty years. Figure 2.2 shows the annual gross output value and value added of the construction sector from 2006 to 2013. Its total economic output has grown sharply with an annual average increase rate of 21.1%, which is much higher than the growth rate of China's gross domestic product (GDP). The total gross output of the construction sector accounts for almost 6% of national GDP. After rapid development of the construction sector during the period 2006 to 2010 due to the booming property market, the annually growth rate has been gradually reduced because of macro-controls on quashing speculation and restraining the final demand of housing market from the central government.

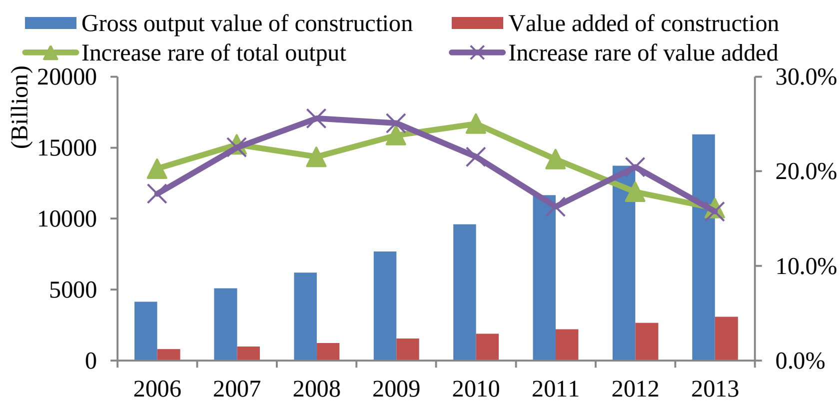


Figure 2.2 Annual gross output value and value added of the construction sector

Source: China statistical yearbook 2014

(2006 to 2013)

Table 2.2 summarizes the number of construction enterprises and the number of employees from 2006 to 2013. It can be seen that China's construction sector is a typical production-extensive and labor-intensive industry, in which the efficiency of the productivity and management is comparatively low. Moreover, the floor area of buildings under construction and completed have increased stably with annual average growth rates of 15.7% and 11.8% from 2006 to 2013 (see Figure 2.3). This highlights the fact that despite the suppression of the property market by the central government, the demand of buildings still keeps growing and is bound to produce significant environmental problems.

Table 2.2 The number of construction enterprises and number of employed persons from 2006 to 2013

	Unit	2006	2007	2008	2009	2010	2011	2012	2013
Number of construction enterprises	Thousand	60.2	62.1	71.1	70.8	71.9	72.3	75.3	79.5
Number of employed persons	Million	28.8	31.3	33.2	36.7	41.6	38.5	42.7	45.0

Source: China statistical yearbook 2014

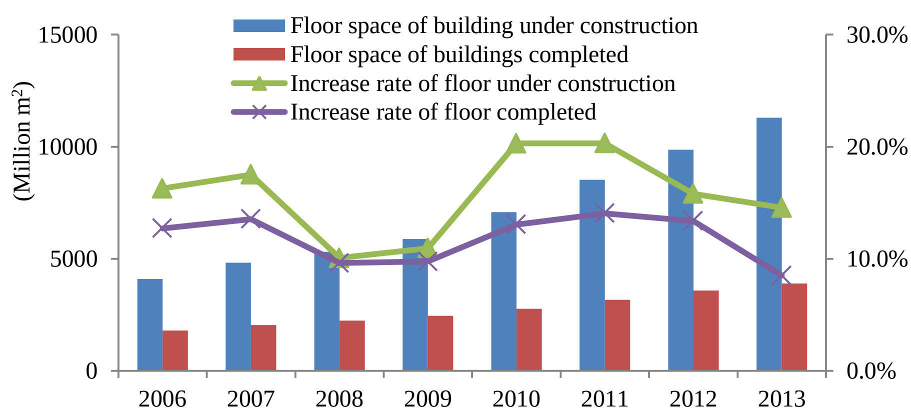


Figure 2.3 Floor area of buildings under construction and completed and their increase rate

Source: China statistical yearbook 2014

In fact, as the result of such intensive construction over the past decade, the construction sector has grown to be one of the largest contributors to national energy consumption and greenhouse gas (GHG) emissions. The direct energy input to the construction sector and the proportion of total national energy consumption is shown in Figure 2.4. Although the direct energy input is only associated with the energy use embodied in the onsite construction, it still accounts for almost 2% in total. However, compared with direct energy input, the indirect energy use embodied in the upstream process of building construction is more significant, accounting for approximately 20%-60% of life cycle energy consumption (Huberman and Pearlmutter, 2008; Tucker et al., 1993). According to the IPCC report, the building sector is responsible for 40% of the primary energy use in industrialized countries (Metz, 2001). Moreover, global CO_2 emissions generated from buildings increased at an average of 2.7% per year from 1999 to 2004 (Metz et al., 2007). Especially in China, the growth rate of energy consumption in buildings was more than 10% over the last few decades (Chang et al., 2014). Being the primary energy consumer, the construction industry accounted for 16% of China's total energy consumption in 2007 (Chang et al., 2010) and was projected to be 20% by 2015 (Chang and Wang, 2011).

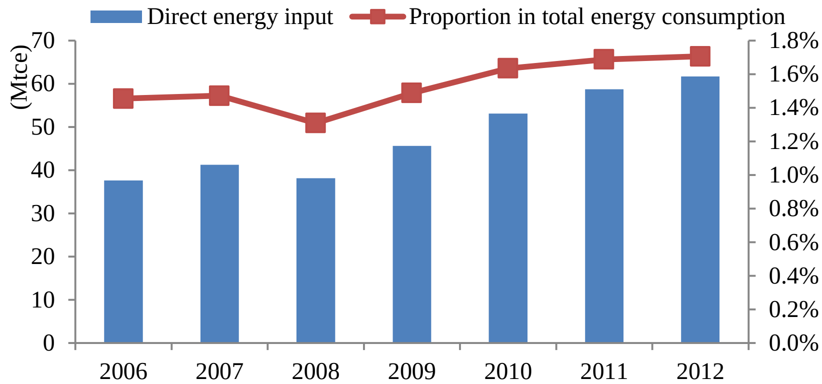


Figure 2.4 Direct energy input to the construction sector and their proportion in total national energy consumption

Source: China statistical yearbook 2014

To alleviate such negative environmental impact from rapid constructions over the country, China's central government took a series of measures and policies to promote energy performance and achieve energy reduction at the national and industrial levels. Figure 2.5 summarized a set of important national energy reduction polices from 2000 to 2015. The central government has enacted a wide range of policies for promoting cleaner production in China. The 11th Five-Year Plan initiated the targets on energy and emission reduction. These targets have been further highlighted and enhanced during the 12th Five-Year Plan period. The measures for Clean Development Mechanism (CDM), which is regarded as a solid foundation for environmental protection, have been also continuously improved from 2005 to 2011. This mechanism is mainly designed for energy and industrial production sectors but rarely implemented on the construction industry (Mok et al. 2014). However, it can be observed that heavy industries attract more focuses and efforts in current Chinese polices for energy conservation. In contrast, the concern on "energy-intensive" sectors from the supply chain perspective (e.g. construction industry) is still weak. Such ignorance may cause the unfair implementation of energy reduction policy. More specifically, national authorities have also promulgated a number of policy instruments for the construction industry in terms of energy conservation. According to Figure 2.6 and Table 2.3, in the 11th Five-Year Plan a plan was put forward to optimize the energy consumption structure in China's economy and make a mandatory 20% reduction in total domestic energy use (CPC, 2012). In the National Plan on New Urbanization 2014-2020 (GOSC, 2014), the central government requires improving the application of renewable energy, accelerating green retrofit, developing environmental friendly materials production, and promoting building industrialization. In the Plan on Green Building (MOHURD, 2013), the total floor area of green buildings under completed, green retrofit of existing residential buildings, and green retrofit of existing public buildings should achieve 1 billion, 50 million, and 60 million square meters respectively at the end of 12th Five-Year Plan. It can be observed that the major concern of current energy regulations for buildings is still on the operational phase rather than the upstream supply chain. Priorities have been given to the reduction of operational energy intensity by enhancing green building construction and green retrofit in existing buildings whereas less emphasis has been placed in upstream processes such as materials production and transportation. Although the policy has been gradually biased toward the upstream supply chain such as the implementation of green building materials evaluation label, it still could make further steps regarding the upstream supply chain.

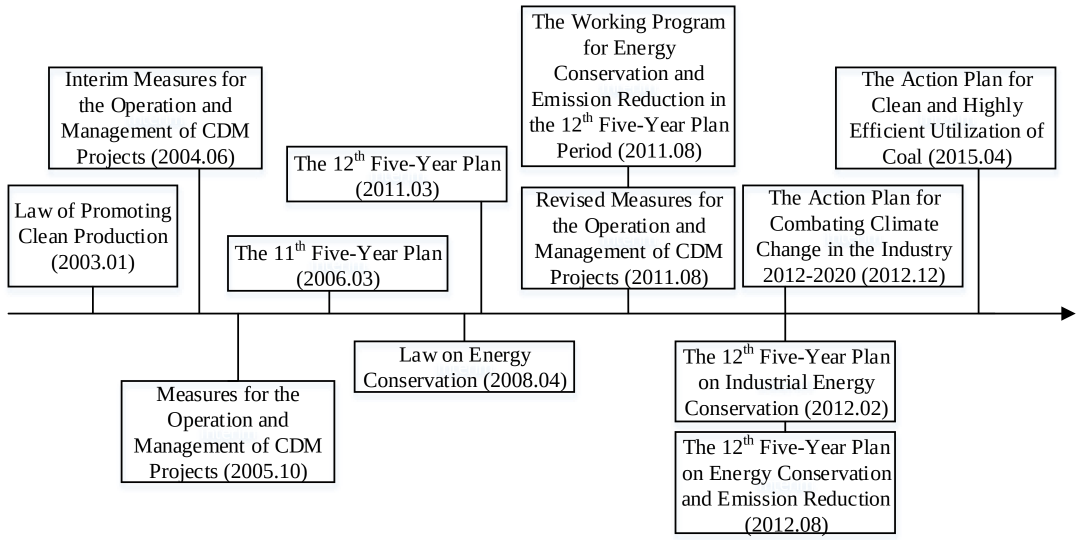


Figure 2.5 National energy reduction polices from 2000 to 2015

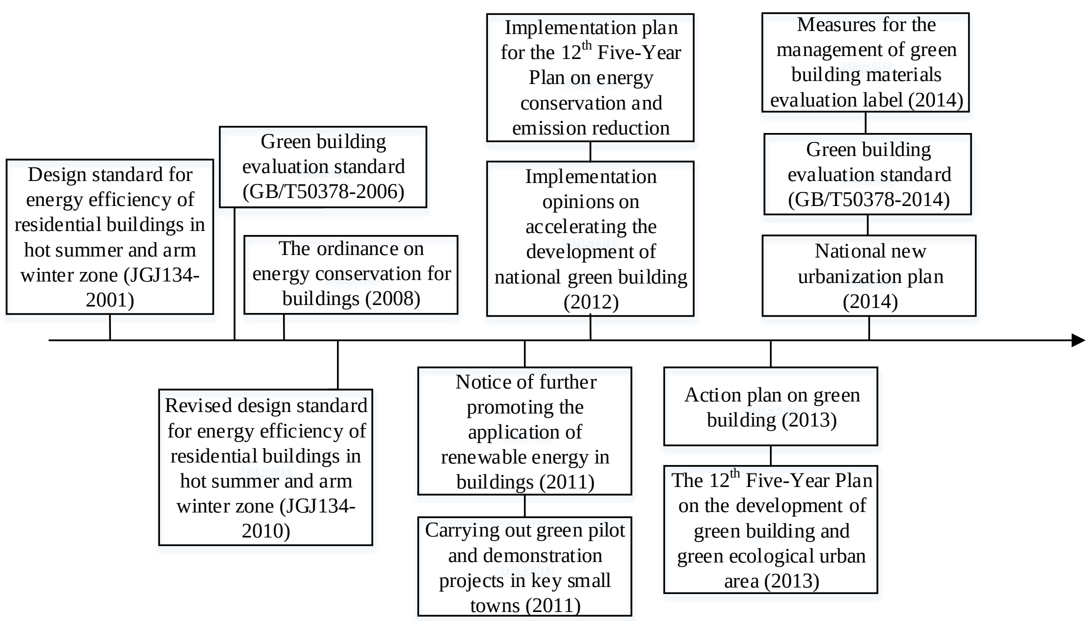


Figure 2.6 Policy instruments for the construction industry in terms of energy conservation from 2000 to 2015

Table 2.3 Profile of different energy reduction policies for the construction industry

	Building type	Scope	Targets
Green Building Evaluation	New and existing	Building's entire life	Land saving, energy saving, water

Standard (GB/T 50378-2014)	buildings	cycle	saving, materials saving, outdoor and indoor environment, construction and operation management
The ordinance on energy conservation for buildings	New and existing buildings	Operation	Energy saving in building operational phase
Design standard for energy efficiency of residential buildings in hot summer and arm winter zone JGJ134-2001	New buildings	Operation	Energy saving in building operational phase
Notice of further promoting the application of renewable energy in buildings	New and existing buildings	Mainly in operation	• The proportion of renewable energy exceeds over 15% in 2020; • The renewable energy is applied in more than 2.5 billion m^2 in buildings;
Implementation opinions on accelerating the development of national green building	New buildings	Building's entire life cycle	• The percentage of green building area exceeds more than 30% in 2020; • The area of green building increases more than 1 billion m^2;
Implementation plan for The 12th Five-Year Plan on Energy Conservation and Emission Reduction	New and existing buildings	Mainly in operation	• New building construction saves more than 45 Mtce[a]; • Green retrofit in existing buildings reduces more than 15% of heating energy consumption; • Energy intensity of public buildings reduces more than 10%;
Measures for the management of green building materials evaluation label	New buildings	Materials production	Energy saving in materials production

Note: a. Mtce is the abbreviation of million tonnes of coal equivalent

2.3.2 Embodied Energy Analysis in the Construction Sector

The embodied energy analysis at the industry level is a systematic energy assessment process, where the data source mainly comes from national average and public statistical data. This sectoral-level investigation is beneficial for framing the overall skeleton of sectoral energy performance and identifying promising areas with the largest energy saving potential.

The construction sectors of five countries have been extensively studied in the past decade. The objective countries, major research focuses, and typical literature are summarized in Table 2.3.

Table 2.4 Summary of studies on the construction sector

Country	Description	Source
Unite states	· Input-output table (1992); · Commodity and service inputs, resource requirements, and environmental emissions; · Four subsectors (civil engineering, public buildings, residential buildings, other construction);	Hendrickson and Horvath (2000)
Norway	· Input-output table (2003-2007); · Nine types of air pollutants; · Time series analysis;	Huang and Bohne (2012)
Ireland	· Input-output table (2005); · Energy and greenhouse gas (GHG) emissions; · Five sub-sectors (Ground work, structural work, services, finishes, plant operation);	Acquaye and Duffy (2010)
Sweden	· Input-output table (2000); · Primary energy use and CO2 emissions; · Six subsectors (residential, dwelling, service, industrial, reconstruction, infrastructure);	Nässén et al. (2007)
China	· Input-output table (2002); · Embodied energy use and environmental emissions; · The projection of energy intensity of the construction sector in 2015;	Chang et al. (2010)

It can be seen that the main focus of these macro-level investigations is to identify the role of the construction sector in the national economy in terms of its environmental impact. The environmental analysis conducted either takes the construction sector as a whole or focuses on its subsectors with a more specific level. However, the classification of subsectors in the construction industry is not consistent across different countries. Acquaye and Duffy (2010) divided the whole construction sector into five subsectors based on the basic procedures of the construction process, namely ground work, structural work, services, finishes, and operation. In contrast, Hendrickson and Horvath (2000) and Nässén et al. (2007) classified the entire sector according to the type of construction, which categorized the entire sector into residential, dwelling, service, industrial, reconstruction, and infrastructure. In fact, the economic sector division is significantly dependent on data availability and the national statistical classification system. In addition, it is obvious that the public data and input-output table employed in each study did not contain up-to-date information as it lagged behind the time period investigated. This might be caused by the fact that the compilation cycle of input-output tables is up to five or seven years. Even the latest available table is still lagging behind the current sectoral linkages and production technology.

In addition to the embodied energy analysis in the whole sector, a number of other studies also focused on a certain type of building or infrastructure based on macro simulation models used in the aforementioned studies. Table 2.4 summarizes the basic research focuses of these studies.

Table 2.5 Summary of studies on a group of buildings

Country	Research focus	Source
United States	· Residential buildings; · Input-output table (1997); · Construction, usage, and demolition;	Ochoa et al. (2002)
UK	· Process-based model; · Detached, semi-detached, and terraced houses; · Construction, use, and demolition;	Cuéllar-Franca and Azapagic (2012)
Sweden	· Detached and dwelling buildings · 2000 input-output table; · Production and processing of materials, transport, construction, and service sectors; · Comparison with process model	Nässén et al. (2007)
Germany	· Deck-access building, high-rise building, and apartment buildings; · Process-based model; · Construction, use, and demolition;	König and De Cristofaro (2012)

It can be seen from the table that in addition to the input-output analysis, process-based analysis has been also employed for macro-level environmental impact assessment based on appropriate assumption with statistical data. Residential buildings have been investigated most in previous research because of their large demand for domestic dwellings in the property market.

In summary, single-region input–output (SRIO) analysis is commonly used for macro-level environmental impact assessment in the construction sector but it fails to capture the hidden linkage and economic network among interregional trade flows. Especially given the fact that the infinite interrelationships in the supply chain mix production technology from both domestic and foreign sources whereas the SRIO model is applied on the assumption that the manufacturing technology in the domestic production process is the same as the technology used in foreign regions, it is crucial to take such difference in production and economic structure into consideration.

In the context of China, very few studies have been undertaken for the construction sector. Wang et al. (2010a, 2010b) conducted a number of studies regarding the sustainability of the construction industry in China, including a comparison of energy conservation regulations and analysis of sustainable design options. By using input–output analysis, Chang et al. (2010, 2011, 2013) conducted a series of studies to measure the sustainability performance of construction projects in China. In addition to the quantification of embodied energy consumption, they also considered the environmental and society indicators by using a SRIO model. Chang and his colleagues also simulated the life cycle energy performance of certain types of building by combining process-based LCA

2.4 Development of Embodied Energy Analysis at the Project Level

To summarize the recent development of embodied energy analysis for construction projects, this section classifies related studies into two major research topics to provide a more comprehensive view of their individual academic standing at the project level. The two topics are: building construction and civil engineering construction.

2.4.1 Building Construction

In general, the types of buildings discussed in previous studies include: residential building, office building, commercial building, hotel, and heritage building. Despite residential buildings attracting most interests from the research community, public buildings (e. g. office buildings, commercial buildings, and hotels) are also the focus of concern for a number of researchers because of their rapidly increasing numbers and comparatively higher operational energy use. For instance, the public building area in China increased dramatically from 3.25 billion square meters in 2000 to 9.31 billion square meters in 2009 (NBSC, 2008). This increase brought about a high-level of energy consumption. By 2006 the energy consumption of public buildings accounted for 28% of the total building energy consumption in China (Jiang and Wu, 2010).

In addition, recent studies also made a great effort to identify the role of different phases regarding their energy consumption (Ding, 2007; Huberman and Pearlmutter, 2008; Kyrö et al., 2011; Scheuer et al., 2003; Treloar et al., 2000a; Verbeeck and Hens, 2010). Scheuer et al. (2003) evaluated the life cycle environmental performance of a university and found that operational energy consumption was dominant (97.7%) when compared to the sum of the energy required for materials production, transportation, construction and demolition. Ding (2007) suggested that the possible ratio between operational energy and embodied energy is 1.6:1 after having calculated the energy consumption of 20 secondary schools in Australia with different operation periods and geographic locations. Xing et al. (2008) asserted that selecting a steel-frame office building could save nearly 25% in energy and more than 50% in air emissions when compared with a concrete-frame. For commercial buildings, Rosselló-Batle et al. (2010) argued that reducing the use of materials with high embodied energy intensity, such as aluminum and steel, in the construction phase and adopting energy efficiency measures and renewable energy in the operation phase, could effectively decrease the environmental impact from a building. By studying five retail buildings with different material types, Van Ooteghem and Xu (2012) concluded that retail buildings with a steel building system were more environmentally friendly. They emphasized that although the most effective approach to improving a building's environmental performance is to save energy in the operational phase as it accounts for 40%-80% of total energy consumption, it is still important to reduce the energy use embodied in the materials production. Kua and Wong (2012) analyzed the construction inventory for a multi-storey commercial building and found that as part of waste management the incineration dominated life cycle greenhouse gas emissions.

More specifically, other studies related to the embodied energy analysis of the building construction mainly involve the following two directions:

(1) Identifying energy-intensive materials and components (e. g. concrete, steel, and cement) by calculating its ratio in total energy use (Asif et al., 2007; Jeong et al., 2012; Utama and Gheewala, 2008; Van Ooteghem and Xu, 2012).

(2) Investigating the effect of the adoption of innovative construction technologies on total embodied energy use

2.4.1.1 Materials and Components

Previous studies discussing building materials mainly focused on either the sustainable properties of a single material or the life cycle environmental performance of a group of materials. The first research direction is focusing on the identification of energy-intensive or energy-efficient materials based on the case-specific process data (Abeysundara et al., 2009; Crawford et al., 2011; Thormark, 2006). According to the literature, some materials were identified as environmental friendly products because of their physical properties (Pearlmutter et al., 2007; Venkatarama Reddy and Jagadish, 2003; Zabalza Bribián et al., 2011), and some might be preferred for a certain project due to external factors such as the convenience regarding geographic location and transportation distance (Morel et al., 2001). The other research direction in recent studies is to identify green materials not only from the perspective of the environment, but also combined economic and social impacts (Abeysundara et al., 2009). Wu et al. (2005) introduced the concept of a green tax to comprehensively evaluate environmentally friendly materials. Most recently, Tatari and Kucukvar (2011) combined life cycle environmental assessment and life cycle cost analysis to calculate the eco-efficiency of materials for further selection.

Table 2.6 Summary of studies on building components

Types of building component	References
Insulation	Dylewski and Adamczyk (2011), Ardente et al. (2008), Anastaselos et al. (2011), Audenaert et al. (2012), Mazor et al. (2011)
Facade	Li (2012), Blom et al. (2010), Kim (2011), Kolokotroni et al. (2004)

Wall	Pearlmutter et al. (2007), Emmanuel (2004), Frenette et al. (2010), Pulselli et al. (2009), Stazi et al. (2012), Azari-N and Kim (2012), Utama and Gheewala (2009), Reddy and Kumar (2010), Monteiro and Freire (2012), Tae et al. (2011)
Roof	Kosareo and Ries (2007), Jo et al. (2010)
Windows	Abeysundra et al. (2007), Citherlet et al. (2000), Su and Zhang (2010)
Floor	Lopez-Mesa et al. (2009), Reza et al. (2011), Abeysundara et al. (2009)
Building modules	Aye et al. (2012), Quale et al. (2012)

As can be seen from Table 2.6 above, the types of building components discussed in previous related studies included: insulation, facade, wall, roof, window, floor, building structure, and building modules. Three types of research methods can be identified in building component related studies, they are: comparative analysis, exploratory analysis, and optimization analysis. Comparative analysis inspects and compares the green property of different building components. Azari-N and Kim (2012) compared the glass curtain wall (CW) with different material combinations, and found that a CW system with glulam timber mullions generated less environmental impacts and human health problems. Kosareo and Ries (2007), by comparing three roof systems, pointed out that the green roof growing medium determined the life cycle environmental performance of green roofs. Lopez-Mesa et al. (2009) conducted a comparison of environmental impacts between situ cast floors and precast concrete floors, discovering that building structures with precast concrete floors have advantages on environmental performance; exploratory analysis was used to explore the life cycle energy consumption and environmental impact of a certain building component. Frenette et al. (2010) made an in-depth analysis of the environmental impact of light-frame wood wall and its role in total embodied impact, and concluded that wood-based products make only a small contribution to total embodied impact. Reddy and Kumar (2010) studied the regularities of embodied energy of cement stabilized rammed earth walls under different cement content, concluding that total embodied energy is positively correlated with cement content in cement stabilized rammed earth walls; optimization analysis optimizes the sustainability performance of buildings in the design stage by selecting environmental friendly components. Stazi et al. (2012) found that the application of solar wall system optimized the sustainability performance of building envelopes both in the production and operation phase. Su and Zhang (2010) optimized building design on the basis of scenario analysis of different window-wall ratios and types of window materials. They found that that the U-value of a window is more important than the window-wall ratios in terms of reducing the life cycle environmental burden in the building design process. Moreover, a complex quantitative relationship exists between the thickness of the external envelope and the total energy consumed during the life cycle of a building. It has therefore consistently received the attention of researchers. Fay et al. (2000) conducted a life cycle energy "cost/benefit" analysis to study the relationship between additional insulation and net savings during the operation phase, revealing that increasing insulation may be less effective compared to other energy efficiency strategies. Pushkar et al. (2005) calculated the full environmental-impact range (FEIR) of various thicknesses of insulation, concrete mass, and block mass during the operation phase in order to construct environmentally optimal buildings. Dombaycı (2007) investigated the environmental performance of optimum insulation thickness in external walls, and concluded that the energy consumption and related emissions can be reduced by almost half if optimum insulation thickness is applied.

2.4.1.2 Construction Technology

Basically, the most effective innovative solution used in contemporary industrial practice is precast construction which has become increasingly important across the entire construction sector. Precast construction refers to the practice of producing construction components in a manufacturing factory, transporting complete or semi-complete components to construction sites, and finally assembling the components to create buildings (Tam et al., 2007a). Other terms and acronyms that are associated with prefabricated construction include off-site construction (Pan et al., 2012), off-site prefabrication (Gibb, 1999), precast concrete building (Kale and Arditi, 2006), modern methods of construction, and industrialized building (Meiling et al., 2013). Compared with the traditional construction technologies, prefabrication construction provides controlled conditions for weather and quality, facilitates the compression of project schedules by changing the sequencing of work flow, and reduces material waste (Li et al., 2014). Thus, prefabrication construction not only reduces construction waste, noise, dust, operation time, operation cost, labour demand, and resource depletion, but also improves quality control, health, and safety (Jaillon and Poon, 2009; Li et al., 2011; Lu et al., 2011; Pan et al., 2007). These advantages have significantly improved the performance of the entire construction industry in both developed and developing countries, such as the US, the UK, Japan, Singapore, and Mainland China.

Given the increasingly important status of prefabrication in the construction field, assessing energy improvements from adopting this innovative construction method has become critical. Despite the contribution of previous studies to the body of knowledge in relation to the prefabrication research domain at the project level, a systematic analysis of the embodied energy consumption of a certain type of prefabrication is rare. Such adoption is a key concern among various stakeholders in the construction process and is expected to influence the delivery of prefabricated buildings significantly. Aye et al. (2012) analysed the embodied energy use of prefabricated building modules using the hybrid LCA analysis method. They found that although prefabricated steel buildings resulted in a significant increase in embodied energy, their reusability of materials represented up to nearly 80% of the savings in embodied energy, which implied high energy-saving potential from this construction method. Monahan and Powell (2011) made an embodied energy analysis for offsite panellised modular house and concluded that this modern construction method resulted in a 34% reduction in embodied energy use when compared with traditional methods. Similarly, Mao et al. (2013) conducted a comparative analysis between prefabrication and conventional construction in terms of embodied energy consumption and greenhouse gas emissions by adopting process-based analysis. They found that semi-prefabrication could produce less embodied energy and greenhouse gas emissions compared with conventional methods.

2.4.2 Civil Engineering Construction

In this research, the definition of civil engineering projects are construction works in railway, roads, tunnels, bridges, dams, ports, and other non-building construction projects. In general, the environmental impact of these infrastructures has been rarely studied in practice. A comprehensive review revealed that most efforts have been put into three categories: pavement construction in the road industry, bridge construction, and tunnel construction. Their major focuses and features have been summarized in below.

In the road industry, the major focus has been on the pavement construction process. Kim et al. (2011, 2012a, 2012b) conducted a series of studies on environmental impacts of road construction projects. They established a framework to estimate greenhouse gas emissions and applied it to eighteen typical highway construction projects in the Republic of Korea. They summarized eight energy-intensive activities during the road construction process on the basis of the emission estimates. In fact, from the view of raw material extraction, manufacturing, transportation, and onsite construction, many researchers have found that material production is the largest contributor through the construction phase while the energy embodied in the equipment use and transportation is relatively small (Cass and Mukherjee, 2011; Inamura et al., 1999; Mroueh et al., 2001). In addition, the comparative analysis has been commonly conducted for road construction to select environmentally friendly alternative materials for pavement construction (Gschösser et al., 2011; Zapata and Gambatese, 2005). Huang et al. (2009) investigated the environmental benefits obtained by using recycled materials for asphalt pavement construction, and concluded that waste glass and recycled asphalt pavements were promising materials for further energy and emissions reduction. It is also worth noting that the road construction is different to building projects since the environmental impact from the road use phase is relatively small. However, a number of studies still investigated the life cycle environmental impact for road construction by taking the pavement rehabilitation and maintenance in the operational phase into consideration (Treloar et al., 2004; Wang et al., 2012).

In terms of bridge construction, there is a contention over the relationship between bridge type and its corresponding environmental load. By comparing the environmental impact of three typical road bridges, namely steel-based, concrete-based, and wooden-based bridges, Hammervold et al. (2011) found that a concrete bridge is more environmentally friendly than the other two types of bridge. Similarly, Collings (2006) investigated three general bridge types - cantilever, cable stayed, and tie-arch bridges, and pointed out that concrete bridges generate a smaller environmental impact than a steel-intensive structure . Itoh and Kitagawa (2003) also found that steel-based bridges have the largest environmental impact. By contrast, although Horvath and Hendrickson (1998) admitted that reinforced concrete bridges perform better in environmental loading during the initial construction phase, steel bridges are still more sustainable over the whole life cycle because of their recyclability. Widman (1998) also emphasized that steel bridges gain more environmental benefits than concrete bridge. In addition, Gervásio and da Silva (2008) revealed that steel-concrete mix bridges are preferred over concrete based in terms of their environmental benefits during the construction process. Such abatement may come from the fact that the bridge construction process is a complicated system with high level of uncertainty in system boundary, models employed, and data sources. Such variations could increase the unreliability of the final outcome (Du and Karoumi, 2014; Du et al., 2014). Because of the important status of structural strength in bridge construction, a number of studies focused on the environmental benefits from reducing the usage of concrete by improving the concrete strength or implementing an innovative bridge structure (Bouhaya et al., 2009; Habert et al., 2012).

Chang and Kendall (2011) systematically analysed greenhouse gas emissions of a comprehensive high-speed rail system. Besides the large contributions from production of materials, results indicated that transportation of construction materials also generated significant emissions. More importantly, tunnels in the rail system were identified as the most sensitive structure which only accounted for 15% of the length but emitted 60% of total emissions. Miliutenko et al. (2012) investigated the life cycle energy use of concrete and rock tunnels, and found the large contributions from production of materials in energy consumption and greenhouse gas (GHG) emissions. Huang et al. (2015) conducted a similar analysis for standard road tunnels in Norway, finding that the construction stage played an important role in a number of environmental impact categories.

2.5 Implications and Research Gaps

A theoretical background at the industrial and project level is essential for a comprehensive understanding of the motivations and barriers identified for embodied energy analysis in the construction sector. A critical review of previous studies revealed a series of limitation in previous relevant research.

There is a lack of a comprehensive understanding of the direct and indirect energy transmissions derived from the construction sector in China. More specifically, previous research rarely took the regional diversity and technology differences into consideration. Therefore, a systematic analysis of the embodied energy consumption of the construction sector at the sectoral and regional level is necessary, which could help decision makers formulate equitable energy reduction policies.

Embodied energy analysis of construction projects in previous literature revealed that the computational structures and system boundary applied to previous studies were not consistent. The truncation error in traditional process-based analysis is estimated to be

50%-70% (Ortiz et al., 2009), which further enhances the importance of the completeness of the system boundary. In contrast, the homogeneity and proportionality of the single input-output analysis should be addressed by integrating project-specific process data. Consequently, it is necessary to establish a comprehensive embodied energy assessment framework with a consistent computational structure and complete system boundary. This could determine the embodied energy consumption with a higher accuracy at the pre-construction stage for a specific project.

The data source for embodied energy analysis in the construction sector mainly comes from publicly available data, client and stakeholders documents, and previous research findings. The availability, transparency, and reliability of these data sources are sometimes uncertain. Moreover, public available data used in the embodied energy analysis are normally compiled based on outdated technology and manufacturing levels, leading to underestimate or overestimate the energy inputs of the investigated process. Therefore, a solid, transparent, and reliable database needs to be established with updated information that can not only alleviate difficulties in data collection but also reflect the level of local production technology and regional characteristics more accurately.

2.6 Summary of the Chapter

This chapter firstly reviewed the definition, development, motives, and obstacles in recent studies in relation to embodied energy consumption. The focus of concern has been put on the embodied energy analysis at the industrial and project level. More specifically, two major directions of research focus on embodied energy analysis of construction projects have been summarized: building construction and civil engineering construction. Finally, future research trends and implications have been identified.

Chapter 3 Methodology

3.1 Introduction

This chapter first presents the proposed research framework in this study. Scientific methodologies are then discussed from both qualitative and quantitative perspective, followed by a detailed description of the research methods which have been adopted to achieve the research objectives in this study.

3.2 Overview of Research Methodologies

Research is a careful investigation towards contributing to the body of knowledge (Chambers English Dictionary). The processes and procedures of such an investigation are understood as the methodology. According to Fellows and Liu (2015), research methodology is the philosophies and procedures of logical understanding implemented to a scientific investigation. In general, there are three types of research design in construction: quantitative research, qualitative research, and combinational/mixed research.

Qualitative research aims to provide insights into people's perception by investigating individual's or group's range of behaviours. Since qualitative data may be unstructured and subjective, more attention needs to be paid to the data consolidation process, such as filtering and manipulation. Two categorizes of data collection are associated with qualitative analysis: interviews and documents. In this study, the major qualitative method is documentation analysis, which provides valuable implications from previous research as well as first hand economic and energy data from public documents.

Quantitative research is an outcome-oriented analysis method in relation to positivism. Compared with qualitative research, quantitative approaches provide confirmatory results without the subjective biases from data collection and consolidation processes. In general, this research is quantitatively dominant, in which quantitative methods have been widely adopted to quantify regional energy consumption with solid numeric data. For instance, the driving forces behind the energy increase of the construction sector and the hidden linkages in the direct and indirect energy interactions of the regional construction sectors have been quantitatively analyzed. On the other hand, qualitative methods are used to extract research questions, identify research gaps, explain the quantitative results, and collect empirical data. More specifically, three types of research methods have been adopted to achieve the research objectives for this study. They are documentation analysis, data analysis, and case studies.

3.3 Research Framework

Detailed analysis techniques and data analytical tools to achieve the research objectives in terms of both qualitative and quantitative research approaches are described in Table 3.1.

Table 3.1 Analysis techniques for research objectives

Research objectives	Research Methodologies	Analysis techniques
1. To explore the driving forces behind energy demand of the construction industry and investigate energy consumption trajectory in past two decades;	1. Desktop study 2. Data analysis	1. Literature review 2. Content analysis 3. Descriptive statistics 4. Structural decomposition analysis (SDA)
(2) To comprehensively quantify the energy uses embodied in China's construction industry and develop the construction energy intensity database of 30 regions;	1. Document analysis 2. Data analysis	1. Literature review 2. Content analysis 3. Multi-regional input-output (MRIO) analysis

(3) To decompose energy transmissions in the upstream process and identify critical energy paths in the entire supply chain from the sectoral and regional perspective;	1. Document analysis 2. Data analysis	1. Literature review 2. Content analysis 3. Depth-first searching based backtracking algorithm 3. Structural path analysis (SPA)
(4) To conceptualize a multi-regional based hybrid framework for assessing embodied energy consumption at the project level by integrating the regional average data and project-specific process data.	1. Document analysis 2. Data analysis	1. Literature review 2. Content analysis
(5) To verify the reliability of the developed framework and validate its effectiveness and advantages in real construction projects.	1. Document analysis 2. Data analysis 3. Case study	1. Literature review 2. Content analysis 3. Comparative analysis 4. Empirical analysis

3.4 Document Analysis

Document analysis is designed to resolve research problems and questions by investigating recorded information and published documents. The major sources of document analysis are various types of documentation. This is the major qualitative method for in-depth content analysis and reviewing existing data. In general, documentation analysis can be categorized into two approaches in detail based on difference on data source, namely content analysis and existing data analysis. Content analysis systematically reviews references from a theoretical perspective (Dane, 1990); in this study, the literature review is the major form of such analysis. Literature review is a method used to systematically understand existing knowledge, findings, theoretical contributions, and practical applications in a certain research field based on secondary sources (Verd, 2004). The target documents for review include academic publications and other paper-based or web-based resources (Rowley and Slack, 2004). In this research, a comprehensive literature review of embodied energy assessment at the industrial and project level for the construction sector has been conducted. Research gaps and limitations were identified and summarized to establish the research objectives, serving as a solid reference foundation for the following analyses. Official publications and regulations issued by central, local, and national departments were reviewed to find existing achievements in the current construction practice. Existing data analysis in this research involved the collection and descriptive analysis of time-series data in public available statistical yearbooks.

3.5 Data Analysis Tools

Data analysis is a process comprising various analytical tools for exploring, transforming, and modeling data, which aims to extract valuable information and form useful conclusions for the specific purpose. The public data collected in this research was further analyzed by a number of analytical techniques, including structural decomposition analysis (SDA), multi-regional input-output analysis (MRIO), and structural path analysis (SPA).

3.5.1 Structural Decomposition Analysis (SDA)

3.5.1.1 Overview of SDA

Decomposition analysis is an effective method to comprehensively understand the relative contribution and mechanism of different driving forces. This method breaks down the total changes into sub-effects induced by a number of factors which quantifies these effects on total energy demand individually at the industrial or national level (Ang, 2004; Ang and Zhang, 2000; Huang and Wu, 2013; Rose and Casler, 1996).

Many different methods based on decomposition theory have been proposed by different researchers (Boyd et al., 1987; Boyd et al., 1988; Howarth et al., 1991; Liu et al., 1992; Reitler et al., 1987). Index decomposition analysis (IDA) and structure decomposition analysis (SDA) are two of the most popular approaches used in previous studies. Of these, IDA is the most time-efficient and has the advantage of lower requirements for specific economic data to explore the driving factors hidden behind the economic system. However, without the use of an input-output table, IDA fails to provide detailed information on the economic structure and supply chain. This implies that only direct effects from the changes of factor can be assessed by index decomposition (Ang and Zhang, 2000; Wang et al., 2013; Weber, 2009).

These theoretical deficiencies have been addressed by employing the SDA model, which is designed to quantify the effects of driving factors based on input–output analysis of the entire economy. SDA enables decomposition analysis to understand the hidden linkage and indirect interactions at the sectorial level and to reflect the structural changes regarding consumption and production (Chang and Lin, 1998; Wier, 1998). The contributions from different factors have been assessed quantitatively and separately with the decomposition of all directly related factors. Although the SDA model has been restricted to the availability of economic data and can only be represented additively due to the use of an input-output table, it has been widely employed to examine the driving forces leading to environmental Chinese loading issues (Guan et al., 2008; Peters et al., 2007; Zeng et al., 2014; Zhang and Liu, 2014; Zhu et al., 2012). SDA has also been applied at the industrial and city level in China with the results playing a significant policy role (Cao et al., 2010; Liang and Zhang, 2011; Wang et al., 2013). Therefore, given the data specificity and information completeness, this research used SDA as the basic model to conduct decomposition analysis.

3.5.1.2 Data Source of SDA

Two categories of data were required in this study: time-series input-output tables and year-based energy consumption data. First, all of the input-output tables are collected from the Chinese National Bureau of Statistics. These tables are all edited into the 28-sector format (see Appendix III) because sector classification was different from 1990 to 2010. Moreover, to keep the price consistent among the different tables, the monetary flows are all concerted into 1990 constant prices via price indexes. Second, all the year-based energy consumption data are obtained from Chinese energy statistical yearbooks. However, the classification of the economic sector in the yearbooks is not consistent with input-output tables. In fact, the I-O table compiled by the National Bureau of Statistics is more specific on the detailed monetary flow data, while the direct energy input data are collected at a more aggregate level. Therefore, it is necessary to disaggregate the sectorial energy consumption data and make them specifically match the sector classification of the input-output tables. Such disaggregation is based on the assumption that the sub-sectorial energy consumption data is proportional to its economic output. Five types of energy have been considered: coal, oil, natural gas, electricity, and other types of primary energy. To avoid the problem of double-counting, national energy balance tables have been used to remove the energy consumed in the energy transformation, intermediate consumption, and losses in coal washing and dressing.

3.5.1.3 SDA Model

Input-output analysis was introduced by Leontief and completed in 1970. It has served as a validation method to analyze "externalities" of products or services by quantifying the inter-industrial interdependence relationship in the entire economic system using publicly available data (Leontief, 1970). Such analytical tools have been used as an efficient method and technique to measure environmental impacts from a top-down perspective for many years (Chang et al., 2011; Joshi, 1999; Wiedmann, 2009; Wiedmann et al., 2007b). In general, input-output analysis can be expressed as:

$$F = C\left(I - U\right)^{-1} V \tag{1}$$

Where F is the target environmental impact, C is a 1*28 vector of the direct energy intensity of all sectors, U is the 28*28 matrix representing the intermediate use coefficient matrix in the input-output table, and V is a 28*1 vector representing the total final demand of each sector.

The form of decomposition is flexible according to various perspectives. In general, the total changes can be decomposed into the effects from three separate factors according to the equation 1: the change of industrial energy intensity (ΔC), the change of production structure ($\Delta\left(I - U\right)^{-1}$), and the change of final demand (ΔV). However, the total change in energy intensity is the sum of energy intensities of various energy types. This overall effect may be caused by the structure change and energy efficiency improvement. Therefore, to measure each individual effect and distinguish the difference between them, an intermediate variable was used in the study by Chang et al. (2008):

$$C^{t(t-1)} = C_{t-1} \frac{\sum_{i=1}^{n} C_{i(t-1)}}{\sum_{i=1}^{n} C_{it}}, \text{ where } i = 5 \text{ types of primary energy sources} \tag{2}$$

Equation 2 indicates that the energy consumption structure is static at the initial year (t-1), and the total amount of energy is equal to the current year (t). Consequently, we have:

$$\Delta C_v = C^t - C^{t(t-1)} \tag{3}$$

$$\Delta C_s = C^{t(t-1)} - C^t \tag{4}$$

Where ΔC_v describes the change in total energy intensity, and ΔC_s describes the change of energy structure. Similarly, another variable for differentiating structure change and growth effect for final demand can be defined:

$$V^{t(t-1)} = V_{t-1} \frac{\sum_{i=1}^{n} V_{i(t-1)}}{\sum_{i=1}^{n} V_{it}}, \ i = \text{categories of final demand} \tag{5}$$

$$\Delta V_v = V^t - V^{t(t-1)} \tag{6}$$

$$\Delta V_s = V^{t(t-1)} - V^t \tag{7}$$

Equation 5 indicates that the final demand structure is maintained in the initial year (t-1) whereas the total volume of final demand is the same as the current year (t). The ΔV_v represents the change of final demand volume, and ΔV_s represents the structure change of final demand. Consequently, the total change in environmental loading F from base year 0 to later year t can be expressed as:

$$\Delta F = \underbrace{E(\Delta C_s)}_{E_1} + \underbrace{E(\Delta C_v)}_{E_2} + \underbrace{E\left[\Delta\left(I-U\right)^{-1}\right]}_{E_3} + \underbrace{E(\Delta V_s)}_{E_4} + \underbrace{E(\Delta V_v)}_{E_5} + \Delta\varepsilon \qquad (8)$$

Here, $E(\Delta)$ is the individual effect on total change ΔF caused by the change in a specific factor. However, the computational process for identifying these individual effects is complicated. The possible solutions have been extensively described in previous reports. In summary, the mathematical model can be divided into two categories by considering whether a residual term is included in the calculation (see Table 3.2). Table 3.2 shows mathematical expressions of different driving factors according to four typical decomposition analysis models.

Table 3.2 Mathematical expressions for four typical structural decomposition models

	Residual term included		Residual term excluded	
Model	D1 (Laspeyres index approach)	D2 (Paasche index approach)	D3 (Polar decomposition)	D4
Features	Estimated based on the initial year (t=0)	Estimated based on the current year (t=1)	Estimated based on the mixture of Laspeyres and Paasche approach	Estimated by calculating the average of all first-order decomposition solutions
E_1	$E_1 = \Delta C_v \left(I-U^0\right)^{-1} V^0 + \Delta\varepsilon$	$E_1 = \Delta C_v \left(I-U^t\right)^{-1} V^t + \Delta\varepsilon$	$E_1 = \frac{1}{2}\Delta C_v \left(I-U^t\right)^{-1} V^t + \frac{1}{2}\Delta C_v \left(I-U^0\right)^{-1} V^0$	$E_1 = \frac{1}{3!}\sum_{i=1}^{3!}\left[\Delta C_v \left(I-U^T\right)^{-1} V^T\right]_i$
E_2	$E_2 = \Delta C_s \left(I-U^0\right)^{-1} V^0 + \Delta\varepsilon$	$E_2 = \Delta C_s \left(I-U^t\right)^{-1} V^t + \Delta\varepsilon$	$E_2 = \frac{1}{2}\Delta C_s \left(I-U^t\right)^{-1} V^t + \frac{1}{2}\Delta C_s \left(I-U^0\right)^{-1} V^0$	$E_2 = \frac{1}{3!}\sum_{i=1}^{3!}\left[\Delta C_s \left(I-U^T\right)^{-1} V^T\right]_i$
E_3	$E_3 = C^0\left[\Delta\left(I-U\right)^{-1}\right]V^0 + \Delta\varepsilon$	$E_3 = C^t\left[\Delta\left(I-U\right)^{-1}\right]V^t + \Delta\varepsilon$	$E_3 = \frac{1}{2}C^0\left[\Delta\left(I-U\right)^{-1}\right]V^t + \frac{1}{2}C^t\left[\Delta\left(I-U\right)^{-1}\right]V^0$	$E_3 = \frac{1}{3!}\sum_{i=1}^{3!}\left[C^T\left[\Delta\left(I-U\right)^{-1}\right]V^T\right]_i$
E_4	$E_4 = C^0\left(I-U^0\right)^{-1}\Delta V_v + \Delta\varepsilon$	$E_4 = C^t\left(I-U^t\right)^{-1}\Delta V_v + \Delta\varepsilon$	$E_4 = \frac{1}{2}C^0\left(I-U^0\right)^{-1}\Delta V_v + \frac{1}{2}C^t\left(I-U^t\right)^{-1}\Delta V_v$	$E_4 = \frac{1}{3!}\sum_{i=1}^{3!}\left[C^T\left(I-U^T\right)^{-1}\Delta V_v\right]_i$
E_5	$E_5 = C^0\left(I-U^0\right)^{-1}\Delta V_s + \Delta\varepsilon$	$E_5 = C^t\left(I-U^t\right)^{-1}\Delta V_s + \Delta\varepsilon$	$E_5 = \frac{1}{2}C^0\left(I-U^0\right)^{-1}\Delta V_s + \frac{1}{2}C^t\left(I-U^t\right)^{-1}\Delta V_s$	$E_5 = \frac{1}{3!}\sum_{i=1}^{3!}\left[C^T\left(I-U^T\right)^{-1}\Delta V_s\right]_i$

The Laspeyres and Paasche index approaches calculate the individual effect of a specific factor by assuming the value of the remaining factors that are held constant at the initial year and current year, respectively. Such assumptions can generate the residual term ($\Delta\varepsilon$) which is a mixed effect because of the simultaneous changes from two or more factors.

Table 1 illustrates that the residual term representing such interaction effects have a direct impact on the total changes. Seibel (2003) argued that the residual term could be neglected when the calculation period is short and the identified factors are not subject to sudden change. In contrast, large residual terms leading to considerable bias in the final result must be considered.

In fact, the decomposition form is not unique because the effects for all the factors can be evaluated either for base time 0 or current time t. Such a technical problem is associated with structural decomposition and is capable of resolving in model D4 by averaging all the first-order decomposition solutions. For a detailed discussion and computing processes related to this method, please see De Haan (2001) and Dietzenbacher and Los (1998). D3 (the polar decomposition) is another effective method addressing the problem of non-uniqueness in decomposing results. It has been commonly used in many studies (Conway, 1990; Wier and Hasler, 1999; Zhu et al., 2012). This method eliminates the residual term by comprehensively considering the effect from the Laspeyres and Paasche indexes.

Finally, totally seven input-output tables (1992, 1995, 1997, 2002, 2005, 2007, and 2010) can be collected from the National Bureau of Statistics, this study divided the investigated time period into six separate intervals (92-95, 95-97, 97-02, 02-05, 05-07, and 07-10).

3.5.2 Multi-Regional Input-Output (MRIO) Analysis

3.5.2.1 Overview of the MRIO analysis

MRIO model allows for a more accurate assessment of the environmental impact and reflects the regional disparity and technology differences in environmental interactions at the interregional trade (Chen and Chen, 2011a; Chen and Chen, 2011c; Friot and Gailllard, 2007; Lenzen et al., 2004a; Mäenpää and Siikavirta, 2007; McGregor et al., 2008b). This model, which presents the environmental interactions by taking account of regional characteristics and sectoral differences, has been extensively studied at the international, national, and regional levels. A clear trend in MRIO analysis is to model energy consumption and carbon emissions embodied in international trade (Ahmad and Wyckoff, 2003; Chen and Chen, 2011b; Chen and Chen, 2011d; Friot and Gailllard, 2007; Hertwich and Peters, 2009; Minx et al., 2008; Nakano et al., 2009). Many studies have also focused on quantifying the embodied energy use and air emissions within the target country because of international trade (Lenzen et al., 2004a; Mäenpää and Siikavirta, 2007; McGregor et al., 2008a; Nijdam et al., 2005; Weber and Matthews, 2007; Weber et al., 2008). However, these studies only considered environmental impacts from the national perspective while ignoring regional disparities within the country. This oversight presents the challenge of investigating strategies from a regional and industrial sector perspective. Only a very few studies have been conducted in the context of China's economy. Liang et al. (2007) employed an MRIO model and scenario analysis to explore regional energy requirements and CO2 emissions in China, which indicated that the population growth has a significant positive relationship with energy use and emissions. Meng et al. (2011) emphasized that emissions transfer embodied in trade flows distorted the actual regional emissions and intensity, which lead to unfair reduction policies from central government. Guo et al. (2012a) provided insight into the characteristic of China's regional CO2 emissions with the application of an MRIO model and concluded that the trend of emissions transfer is from the eastern areas to the central areas. Liu et al. (2012a) employed index decomposition analysis based on time-series inventory data to study China's Greenhouse gas (GHG) emissions from the regional and sectoral perspective; their findings emphasized the importance of reducing the disparity of technology on CO2 emission reduction. Su and Ang (2014) developed a hybrid multi-region model to simulate the CO2 emissions in trade and emphasized that cooperation should be enhanced between developed and developing regions in China to reduce emissions. Zhou et al. (2010) and Guo et al. (2012b) mainly focused on the measurement of GHG emissions by applying input–output analysis at the urban level; the former study was based on statistical data in 2002, whereas the later one used an input–output table from 2007.

3.5.2.2 MRIO model development

The MRIO model has been regarded as an efficient tool and technique to measure environmental impacts from the top-down perspective for many years (Chen and Chen, 2013b; Lenzen et al., 2004b; Peters et al., 2004). This model integrates the regional and sectoral energy input flows into economic monetary flows by using input-output analysis. The format of the revised MRIO table is shown in Table 3.3.

Table 3.3 Revised MRIO table in 2007

<table>
<tr><td rowspan="4">Input</td><td colspan="10">Output</td><td rowspan="4">Total output</td></tr>
<tr><td colspan="7">Intermediate use</td><td colspan="3">Final use</td></tr>
<tr><td colspan="3">R_1</td><td>…</td><td colspan="3">R_m</td><td rowspan="2">R_1</td><td rowspan="2">…</td><td rowspan="2">R_n</td></tr>
<tr><td>S_1</td><td>…</td><td>S_n</td><td>…</td><td>S_1</td><td>…</td><td>S_n</td></tr>
</table>

<table>
<tr><td rowspan="3">R₁</td><td>S₁</td><td rowspan="7">u_{ij}^{rk}</td><td rowspan="7">v_i^{rk}</td><td rowspan="7">O_i^r</td></tr>
<tr><td>…</td></tr>
<tr><td>S_n</td></tr>
<tr><td>…</td><td>…</td></tr>
<tr><td rowspan="3">R_m</td><td>S₁</td></tr>
<tr><td>…</td></tr>
<tr><td>S_n</td></tr>
<tr><td colspan="2">Direct energy input</td><td></td></tr>
</table>

Source: Liu et al. (2012)

According to the above Table 3.3, the basic monetary balance in the input–output table can be expressed as

$$O_i^r = \sum_{k=1}^{m} \sum_{j=1}^{n} u_{ij}^{rk} + \sum_{k=1}^{m} v_i^{rk} \tag{9}$$

Where O_i^r represents the monetary value of the total output of sector i in region r, and it is assumed that there are m regions and each region has n sectors; u_{ij}^{rk} represents the monetary input from sector i in region r as intermediate use to sector j in region k; v_i^{rk} represents the monetary value of the total final use in region k provided by sector i in region r, which normally includes final consumption (e.g. rural and urban household, government consumption, gross fixed capital formation, and stock increase), exports, and other balanced items.

Combined with the energy flows, the energy balance of sector i in region r can be expressed as

$$e_i^r O_i^r = \sum_{k=1}^{m} \sum_{j=1}^{n} e_j^k u_{ji}^{rk} + q_i^r \tag{10}$$

Where e_i^r is the embodied energy intensity of products from sector i in region r, e_j^k is the embodied energy intensity of products from sector j in region k. q_i^r is the direct energy consumption of sector i in region r.

Note that $m \times n$ equations are established under the whole economy, vectors and matrixes that can therefore be introduced to simplify the mathematical expression.

Nominate $E^T = \begin{bmatrix} \begin{pmatrix} e_1^1 \\ \dots \\ e_n^1 \end{pmatrix} \\ \dots \\ \begin{pmatrix} e_1^m \\ \dots \\ e_n^m \end{pmatrix} \end{bmatrix}$ $\quad Q^T = \begin{bmatrix} \begin{pmatrix} q_1^1 \\ \dots \\ q_n^1 \end{pmatrix} \\ \dots \\ \begin{pmatrix} q_1^m \\ \dots \\ q_n^m \end{pmatrix} \end{bmatrix}$ $\quad O = \begin{bmatrix} o_1^1 & 0 & \dots & 0 \\ 0 & o_2^1 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & o_n^m \end{bmatrix}$

$$U = \begin{bmatrix} \begin{pmatrix} u_{11}^{11} & \dots & u_{1n}^{11} \\ \dots & \dots & \dots \\ u_{n1}^{11} & \dots & u_{nn}^{11} \end{pmatrix} & \dots & \begin{pmatrix} u_{11}^{1m} & \dots & u_{1n}^{1m} \\ \dots & \dots & \dots \\ u_{n1}^{1m} & \dots & u_{nn}^{1m} \end{pmatrix} \\ \dots & \dots & \dots \\ \begin{pmatrix} u_{11}^{m1} & \dots & u_{1n}^{m1} \\ \dots & \dots & \dots \\ u_{n1}^{m1} & \dots & u_{nn}^{m1} \end{pmatrix} & \dots & \begin{pmatrix} u_{11}^{mm} & \dots & u_{1n}^{mm} \\ \dots & \dots & \dots \\ u_{n1}^{mm} & \dots & u_{nn}^{mm} \end{pmatrix} \end{bmatrix}$$

Where E and Q are the embodied energy intensity vector and direct energy input vector with $m \times n$ dimension, E^T and Q^T are the transpose of E and Q, respectively; O is the diagonal matrix with $m \times n$ entries, and the coefficients in matrix O are equal to the total economic output. U is the intermediate input matrix in the input–output table with $m \times n$ entries. For the whole economic system, the above group of equations can be expressed in the form of a matrix

$$EO = EU + Q \tag{11}$$

which can be further transformed into

$$E = Q(O - U)^{-1} \tag{12}$$

Based on the embodied energy intensity calculated in Equation (12), the energy use embodied in the final demand can be simply deduced for a general situation. However, as only the construction industry is the focus of this study, further clarification is needed to help understand the embodied energy intensity and interregional energy transfer of the regional construction industry.

(1) *Embodied energy intensity*. Embodied energy intensity measures the direct and indirect energy input within the entire supply chain of the construction sector, which represents the total energy consumption per unit monetary value in the construction sector. The energy intensity vector for the regional construction sector $E_c = [e_c^1, e_c^2, ..., e_c^m]$ can be extracted from vector E.

(2) *Sectoral embodied energy input*. Investigating sectoral embodied energy input provides insight to understand the environmental connections among different sectors. The embodied energy input from sector i to the construction sector can be given as

$$EES_i = \sum_{r=1}^{m} \sum_{k=1}^{m} e_i^k u_{ic}^{kr} \tag{13}$$

(3) *Energy embodied in interregional imports and exports*. Analyzing energy use embodied in interregional trade facilitates an exploration of the hidden linkages from

regions that produce energy to regions that consume energy. The computational process can be given by

$$IM_c^r = \sum_{k \neq r}^{m} \sum_{i=1}^{n} e_i^k u_{ic}^{kr} \tag{14}$$

$$EX_c^r = e_c^r (\sum_{k \neq r}^{m} \sum_{j=1}^{n} u_{cj}^{rk} + \sum_{k \neq r}^{m} v_c^{rk}) \tag{15}$$

Where IM_c^r represents the energy use embodied in interregional imports to the construction sector in region r, EX_c^r represents total energy use due to exports from the construction sector in region r, v_c^{rk} represents the final use of region k provided by the construction sector in region r.

3.5.2.3 Data source of MRIO analysis

The latest available MRIO table was compiled by the Chinese Academy of Science in 2007, which provided the economic interaction data on China's 30 regions (including 4 municipalities, 4 autonomous regions, and 22 provinces) for 30 sectors (See Appendix I and II). Tibet is excluded in this table because of the unavailability of data. Therefore, considering the aforementioned theory, the value of m and n are both 30 in this study. The MRIO table 2007 is compiled under the noncompetitive import assumption, which can effectively avoid the distortion of energy use embodied in interregional trade (Su and Ang, 2013; Zhang et al., 2013). The import item from international trade has been removed to concentrate on the interregional trade flow in China.

Sectoral direct energy input data among different regions were obtained and derived from two sources: the regional statistical yearbooks and the regional energy balance tables in the Chinese energy statistical yearbooks. In addition to the total energy use, the other nine major energy sources were also studied, namely, coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas, and electricity.

Although the MRIO table provides detailed economic and trade data, the availability of direct energy use data that specifically match the sector classification is a constraint. This constraint is exacerbated by the demand of detailed energy types in this study. More importantly, the format of the regional statistical yearbook is also inconsistent across different regions. Therefore, the data processing method used in the study by Guo et al. (2012a) has been adopted in case of a lack of statistics on sectoral energy consumption.

3.5.3 Structural Path Analysis (SPA)

3.5.3.1 Overview of the SPA

The input-output analysis has been commonly used in past years for structural analysis of economic interactions in terms of environmental impacts (Chang et al., 2011; Joshi, 1999; Wiedmann, 2009; Wiedmann et al., 2007b). Single-region input-output (SRIO) analysis has been applied to analyze environmental burden with an input-output table; however, this fails to capture the hidden linkages in the economic network and regional differences among the interregional trade flows (Peters and Hertwich, 2006a, b; Wiedmann, 2009; Wiedmann et al., 2007a). The specific regional characteristics such as the variations in the climate, geographical location, natural resources, and level of the economy directly determine the interregional import and export among different regions. This results in cross-regional environmental shifting.

On the other hand, a systematic structural analysis for such an infinite interrelationship is needed to study the adverse environment impacts linked with interregional production chains. This is especially important for extracting paths with significant environmental impact in the upstream process. Structural path analysis (SPA) is a methodology that quantifies the environmental transmissions in the upstream process and identifies important paths with the largest environmental improvement potential by tracing the intricate production chain. In fact, many studies have focused on environmental implications using SPA techniques. On the global level, SPA was adopted to provide insight into the structural linkages between the Norwegian economy and international trade (Peters and Hertwich, 2006c). Wood (2008) analyzed the greenhouse gas (GHG) emission from international trade by combining SPA and decomposition analysis. Minx et al. (2008) employed an SPA method to identify environmentally important supply paths in the global supply chain of food products. On the national level, Lenzen (2002, 2003) conducted a number of studies focusing on the supply paths with significant environmental impact in context of the Australian economy. Lenzen (2007) also presented a detailed discussion of SPA to extract a manageable number of paths in ecosystem networks via 16 case studies. However, very few studies have been undertaken at the industrial level, especially in the construction industry. Trelor et al. extracted the embodied energy path for the building sector by adopting an SPA method. They established a hybrid LCA model by substituting case-specific data for energy intensive paths (1997; 2001a; 2001b). Chang et al. made a series of input-output analyses to simulate embodied energy use and environmental impact for the construction sector in China. Unfortunately, most of these studies considered environmental impacts of a certain sector from the national perspective while disregarding regional disparities (Chang and Wang, 2011; Chang et al., 2011; Chang et al., 2013).

3.5.3.2 SPA Model Development

Structure path analysis (SPA) explored environmental transmission within the entire economic system by decomposing the direct and indirect effects from interconnections in the upstream process. This method provides an opportunity to inspect the inside of the calculation process of I-O analysis. It helps to identify the key paths and sectors in the production chain where the economic interactions with other sectors lead to significant influences on the final output (Acquaye et al., 2011; Defourny and Thorbecke, 1984; Roberts, 2005). It reveals linkages and indirect transactions between the exogenous final demand and total output by tracing the transmissions among different upstream processes.

Generally, the basic monetary balance for sector i in region r in the input-output table can be expressed as:

$$O_i^r = \sum_{k=1}^{m}\sum_{j=1}^{n} u_{ij}^{rk} O_i^r + \sum_{k=1}^{m} v_i^{rk} \tag{16}$$

Where O_i^r represents the total output of sector i in region r. It is assumed that there are m regions and each region has n sectors; u_{ij}^{rk} represents the inter-industry coefficient of sector i in region r for sector j in region k; v_i^{rk} represents the total final demand of region k provided by sector i in region r that normally includes the final use (e.g. rural and urban household, government consumption, gross fixed capital formation, and stock increase), exports, and the other balance items.

Note that the $m \times n$ equations can be established under the whole economy; therefore, the following is nominated:

$$O = \begin{bmatrix} \begin{pmatrix} o_1^1 \\ \dots \\ o_n^1 \end{pmatrix} \\ \dots \\ \begin{pmatrix} o_1^m \\ \dots \\ o_n^m \end{pmatrix} \end{bmatrix} \qquad U = \begin{bmatrix} \begin{pmatrix} u_{11}^{11} & \dots & u_{1n}^{11} \\ \dots & \dots & \dots \\ u_{n1}^{11} & \dots & u_{nn}^{11} \end{pmatrix} & \dots & \begin{pmatrix} u_{11}^{1m} & \dots & u_{1n}^{1m} \\ \dots & \dots & \dots \\ u_{n1}^{1m} & \dots & u_{nn}^{1m} \end{pmatrix} \\ \dots & \dots & \dots \\ \begin{pmatrix} u_{11}^{m1} & \dots & u_{1n}^{m1} \\ \dots & \dots & \dots \\ u_{n1}^{m1} & \dots & u_{nn}^{m1} \end{pmatrix} & \dots & \begin{pmatrix} u_{11}^{mm} & \dots & u_{1n}^{mm} \\ \dots & \dots & \dots \\ u_{n1}^{mm} & \dots & u_{nn}^{mm} \end{pmatrix} \end{bmatrix} \qquad V = \begin{bmatrix} \begin{pmatrix} \sum_{k=1}^{m} v_1^{1k} \\ \dots \\ \sum_{k=1}^{m} v_n^{1k} \end{pmatrix} \\ \dots \\ \begin{pmatrix} \sum_{k=1}^{m} v_1^{mk} \\ \dots \\ \sum_{k=1}^{m} v_n^{mk} \end{pmatrix} \end{bmatrix}$$

Then all equations can be expressed in the form of matrix:

$$O = (I - U)^{-1} V \tag{17}$$

If the environmental intensity is considered, the total environmental impact can be expressed as:

$$F = C(I - U)^{-1} V \tag{18}$$

Where $C = \left[c_i^r \right]_{1 \times mn}$ is the environmental impact per unit of products from sector i in region r.

The equation can be further expanded based on a power series approximation theory, which is the theoretical foundation for SPA analysis, shown as:

$$F = C(I - U)^{-1}V = CIV + CUV + CU^2V + CU^3V + CU^4V + ... \tag{19}$$

CU^tV represents the environmental impact from the production process in the t^th stage. Given this equation, this study establishes an infinite tree that is based on the computational algorithm implied in the SPA. The tree paths explore the inter-sectoral and interregional connections of different tiers in the upstream production process. Each node in a connected graph is a certain sector in a specific region within the economic system. It represents individual environmental contributions induced from the corresponding final demand. According to Equation 19, it is understandable that the number of nodes is exponential via the growth of tiers.

The paths tree is based on the entire supply chain and can be further inspected from the horizontal and vertical perspective. Horizontally, the paths diagramed between two stages in the supply chain represent the direct environmental input of a certain tier. Consequently, the sum of the total environmental impact of sector i in all tiers can be expressed as:

$$\begin{aligned} & t = 0 : c_i \sum_{k=1}^{m} v_i^k \\ & t = 1 : \sum_{j=1}^{m \times n} c_j u_{ji} \sum_{k=1}^{m} v_i^k \\ & t = 2 : \sum_{l=1}^{m \times n} \sum_{j=1}^{m \times n} c_l u_{lj} u_{ji} \sum_{k=1}^{m} v_i^k \\ & ...... \end{aligned} \tag{20}$$

From the vertical perspective, environmental paths connecting different stages represent the environmental linkage between the producers in the higher order stages of the upstream process to the final consumer. The energy use embodied in a certain path of sector i induced by the final demand in region k can be described as:

$$\overset{Stage0}{c_i u_i^k} + \overbrace{c_j u_{ji} v_i^k}^{Stage1} + \overbrace{c_k u_{kj} u_{ji} v_i^k}^{Stage2} + ... \tag{21}$$

The adoption of equations 20 and 21 enables us to trace the supply chain intuitively. This allows investigation of the energy transmission from the production view. For each energy path that is extracted in this study, the starting point is the final demand v_i^k (consumption) of sector i in region k. The end point represents the energy input for a given production. This energy transfer process established a linkage between the final demand purchased and its corresponding production (Peters and Hertwich, 2006a). Therefore, examining the total energy use from both a consumption and production perspective can effectively establish a holistic map of energy interactions in the construction industry. This may help policy makers to achieve a fair and equitable energy reduction policy.

It is effective to focus on a specific degree of order within a sound number of paths because the number of nodes increases exponentially whereas the value of the node deceases sharply with the growth of the path length. Therefore, an optimized algorithm is commonly used in previous research to cut the redundant paths with negligible value. This optimization not only makes the computational process time-efficient but also helps decision makers extract and identify important paths with large environmental improvements. However, this study used SPA to consider region-specific characteristics which leads to algorithmic differences with the conventional method.

In general, the iterative recalculation of the 900*900 matrices results in an exponential increase of nodes. It is therefore impossible to manually examine the energy path tree when higher order upstream processes are considered (e.g. maximum stage = 10). In addition, the exploration of the energy paths from such computational processes also makes the mathematical operation more challenging. Consequently, a backtracking algorithm based on a depth-first searching strategy was implemented to carry out tests and extract the energy paths of this research. The algorithm enumerates all the possible paths by setting sectors in paths in a trial-and-error way for certain regional construction industries. During enumeration, a vector of thresholds that is 0.005% of the energy consumption of the regional construction industry was set to prune the branches with negligible embodied energy. Figure 3.1 shows the basic iterative computational processes for the construction industry in a certain region r.

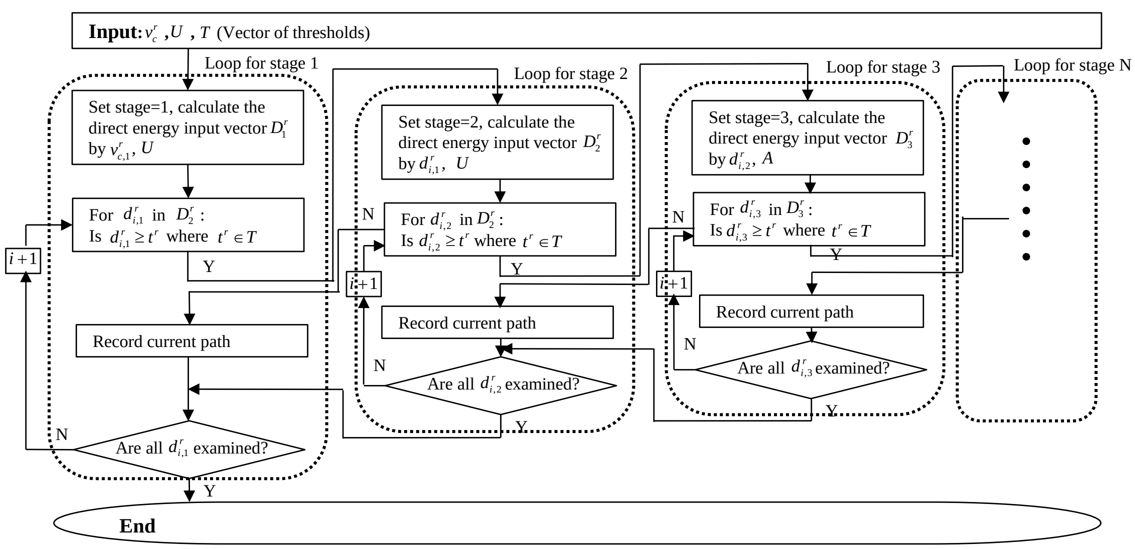


Figure 3.1 Basic computational process for the construction industry in region r

3.6 Case Study

Case study is a research method designed for detailed examination of typical cases, representing the basic features and situations of the subject studied in the context of practice. It may involve other research methods such as document analysis, observation, and field survey. One major limitation of case study is the implementation of this scientific method to large extent depends on the availability of specific data. This research employed case studies to validate the reliability of the developed conceptual framework in nine real construction projects. First, case-specific process data were collected for six typical building projects from previous research. A comparative analysis was then conducted to examine whether the developed framework would yield a robust result based on the same project profile. Second, bill of quantities and material inventory data were collected for three building projects in China. This group of buildings was used to verify the feasibility and advantages of the hybrid framework in real construction projects from a regional and sectoral perspective.

3.7 Summary of the Chapter

This chapter firstly discussed research methodologies and illustrated the overall research framework. Detailed research methods, namely document analysis, data analysis, and case study, were discussed separately. The document analysis was used to systematically investigate recorded information and published documents from a theoretical perspective and collect sufficient statistical data from official documents issued by regional and national departments. The analytical tools used for data analysis included SDA, MRIO model, and SPA, which together serve as a theoretical foundation for comprehensively understanding how direct and indirect energy interactions from the construction sector affect China’s regional sustainability development. Finally, case studies were applied to validate the reliability and feasibility of the developed hybrid framework.

Chapter 4 The Driving Forces behind Energy Demand

4.1 Introduction

China is on a path to rapid urbanization and industrialization. As society's primary energy consumer, it is imperative to understand the driving forces behind the energy increase in the construction sector in order to promote cleaner energy production in China. This could not only facilitate specific policy decisions on energy and environmental issues related to the construction sector but also steer the urbanization process towards more sustainable development. More importantly, the findings of this chapter could serve as the theoretical foundation for comprehensively understanding the current energy consumption status of regional construction sectors. In general, five driving factors have been identified and further investigated, namely the change in total energy intensity, the change of energy structure, the change of production structure, the change of final demand volume, and the change of final demand structure.

4.2 Decomposition of Driving Forces

It is important to begin with a brief discussion of annually embodied energy use before analyzing the driving forces related to energy increases in the construction industry in the past two decades. Figure 4.1 shows that at the beginning of the 1990s, the energy consumption from the construction industry increased stably from 1990-2002 but has grown sharply from 2005 to 2010. Such large increases in energy consumption further emphasize the importance of investigating the hidden driving factors for the construction industry.

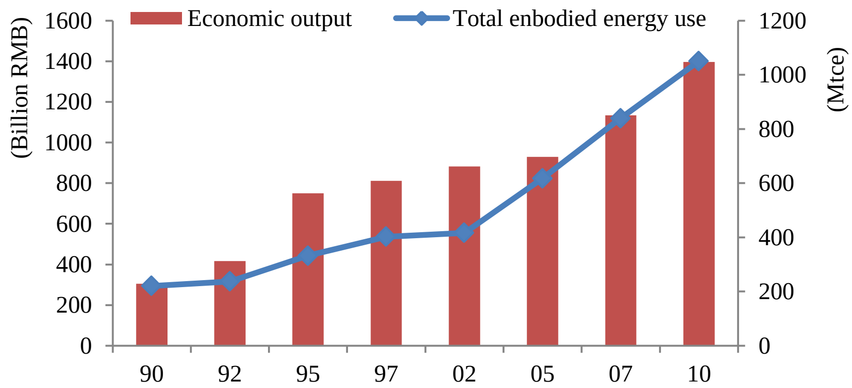


Figure 4.1 Annual economic output and energy use of the construction industry

Source: China Statistical Yearbook on Construction 2013

As mentioned in the methodology section, a structural decomposition analysis of the construction industry from 1990 to 2010 has been conducted through four major methods. The results of the comparative analysis are shown in Table 4.1. The first two approaches estimate the target individual driving factor by assuming that the others remain constant at either base year values or current year values. Such subjective manipulation could generate incalculable residual terms that are bound to add uncertainty. On the other hand, the results of the last two approaches were almost the same. The third method simplified the computational process by considering mixture effects and assigning equal weight on the initial year and the current year in the decomposition formula. More importantly, this method considers mixture effects of driving factors and eliminates the residual terms during calculation. The last method averages all first-order decomposition forms and thereby resolves the problem of non-uniqueness. However, this approach has drawbacks on the complicated calculation process that are applied. Therefore, this study employed the third method to further analyze the hidden driving forces during different time periods.

The total energy increments calculated by four methods are consistent with each other. It was calculated to be almost 900 million tonnes of coal equivalent (Mtce). The result implied that there was a competition between the effects of energy input efficiency improvements and the increasing final demand. Furthermore, the structural change in energy and production also has positive impacts on the embodied energy consumption whereas the reduction effect of structural change in final demand was relatively small.

From the production perspective, efficiency gains in energy intensity were the only factor balancing the energy increment in the construction industry. In fact, the efficiency improvement in energy intensity reduced by 673.5 Mtce (-305%) in total consumption of 1990 level. In contrast, the structural change in energy and production leads to an increase in embodied energy use of the construction industry by 775.2 Mtce (351%). From a consumption-based perspective, the energy use driven by the final demand can be investigated separately based on different demand categories provided by the input-output table. According to the result, the construction industry of China is a typical demand-driven industry—energy consumption has increased by 983.2 Mtce (445%) due to the increased volume of final demand from 1990 to 2010. Further decomposing the final demand by different categories highlighted that the gross fixed capital formation contributed 934 Mtce (423%). In China, investments in fixed capital formation are closely related to infrastructure construction, retrofit, refurbishment, and real estate activities, which are certain to create large energy demands. In contrast, the consistent efforts to optimize the final demand structure have reduced energy consumption by 176 Mtce (80%) from 1990 to 2010. In summary, the change in the volume of final demand and energy intensity were the major factors contributing to the growth or decline in embodied energy consumption of the construction industry. The effects of structural optimization on energy, production, and final demand were relatively minor.

Table 4.1 Results of decomposition analysis by different models (Mtce)

	Laspeyres index approach	Paasche index approach	Polar decomposition	The fourth model
Change of direct energy input	-168.6	-1178.4	-673.5	-621.5
Change of energy structure	107.3	754.8	431.1	397.4
Change of production structure	131.1	396.0	344.1	290.4
Change of final demand	965.3	1001.1	983.2	1015.9
Change of final demand structure	-172.7	-179.1	-175.9	-181.8
Total	862.5	794.4	908.9	900.4

Figures 4.2 and 4.3 present a detailed analysis in seven separate time intervals. In the 1990s, the central government was committed to economy development and infrastructure construction, which aimed to transform the construction industry into the main power for China's economy growth. This policy orientation led to rapid growth in final demand and energy use in construction.

More specifically, from 1990-1992 the change in the volume of final demand and energy structure resulted in a 57.0% and 25.3% increase in total embodied energy use whereas energy intensity reduction, structural optimization in production, and change in final demand structure together offset the total embodied energy consumption by 73.7% of the 1990 level. In total, the energy consumption increased 8.7% from 1990-1992.

From 1992 to 2002, all the five affecting factors were consistent with the former 2-year interval. The volume growth of the final demand is the largest driving force. It resulted in an increase of embodied energy consumption by 161.7% (384 Mtce) followed by effects from structural changes in energy consumption (105.1%) and production (28.0%). In contrast, the major reduction factor is the efficiency improvements in energy intensity.

This achieved a 144.7% (343 Mtce) reduction in total. Subsequently, the structural change in final demand was a minor effecting factor contributing 64.0% (205.5 Mtce) of the reduction in energy consumption of the construction industry.

Starting in 2000, the total embodied energy consumption has grown sharply due to the booming property market. From 2002 to 2005, energy use embodied in the construction industry was driven mostly by changes in production structure (40.6%) with smaller effects due to the increasing volume of final demand (12.4%) and energy intensity (0.1%). The overall energy increment was 213 Mtce (51.2%), which represented the largest percentage change during the period from 1990 to 2010.

To alleviate this negative environmental impact from the intensive urbanization all over the country, the central government took a series of measures to achieve energy reduction and conservation during the 10th (2001-2005) and 11th (2006-2010) Five-Year Social and Economic Development Plans. For instance, the 11th Five-Year Plan put forward a plan to optimize the energy consumption structure in China's economy and made a 20% reduction in total domestic energy use mandatory. This aimed to restructure the economic growth pattern from resource-intensive to resource-efficient. More specifically, China adjusted the production structure by shifting from an energy-intensive industry towards more energy-efficient industry to achieve a structural energy saving. The Ministry of Housing and Urban-Rural Development improved the energy efficiency of the construction industry through two major strategies—one is the adoption of innovative techniques in building material production, and the other is promoting more applications of low energy-intensive materials during the construction process.

Consequently, such a policy orientation is effective for the following two periods. From 2005-2007, the change in volume of the final demand and production structure were two primary factors leading to 43.9% and 19.2% energy increases versus 2005 levels, respectively. In comparison, changes in energy intensity and final demand structure were the major drivers of reduction—this cut 36.4% of the embodied energy consumption in total. Unfortunately, such energy saving measures could not outweigh the effects of energy-driven factors. The consistent efforts on structural optimization by the central government paid off from 2007 to 2010. The structural adjustment in energy, production, and final demand has a significant positive impact in energy reduction. It balanced the total energy increase by reducing energy demand by 26.8%. The growth in the final demand volume was the most dominant factor (43.4%) for energy increase during this period.

In sum, by comprehensively reviewing the driving forces behind seven time periods from 1990 to 2010, the embodied energy consumption of the construction industry was investigated in accordance with several dominant trends. First, the total energy demand is driven by consistently increasing volume of final demand. Based on an average annual increasing rate of 0.8%, the urbanization rate in China is estimated to reach a historic high of 51.5% at the end of “The Twelfth Five-Year Plan”. Such rapid urbanization brings a long-standing and considerable energy demand to China. Relatively speaking, the effort of improving energy intensity is also significant in energy reduction in the construction industry. This has offset a large amount of energy consumption driven by the high levels of final demand growth. Second, according to Figure 4.4, the trend of percentage change in the incremental energy consumption in different investigated periods revealed that although the energy consumption surged from 2002, the annual growth rate continued to reduce from 2005 due to the implementation of energy conservation regulations and policies.

Figure 4.5 examines the energy increase in the construction industry according to different fuel types. It is clear from this figure that the coal consumption is dominant in all energy sources followed by oil and other primary energy—this highlights that the construction industry is a typical fossil fuel energy-oriented sector. The downward trend of the coal consumption during 1992-2002 has been reversed due to the surging economic output from the construction industry in 2002. Further examination of the driving forces indicated that such a surge in the energy consumption is the result of increased energy intensity and final demand volume. However, this substantial consumption of coal was consistently reduced afterwards due to the great efforts in structural optimization by the central government.

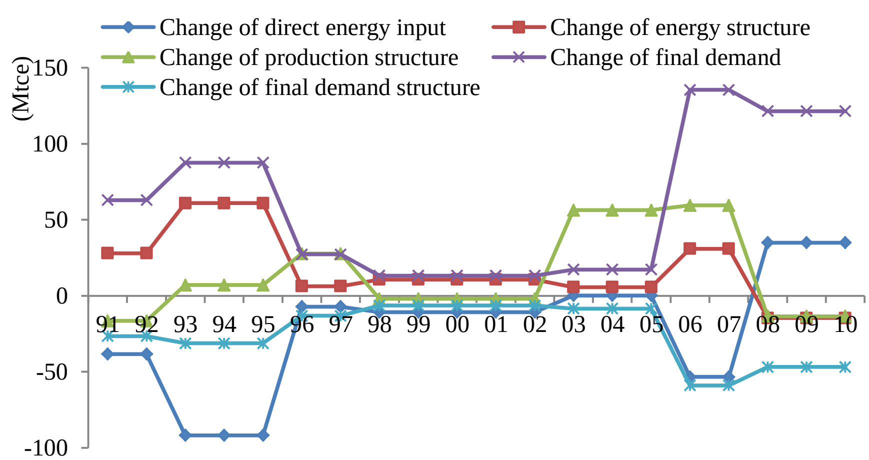


Figure 4.2 Trends of five driving factors from 1990 to 2010

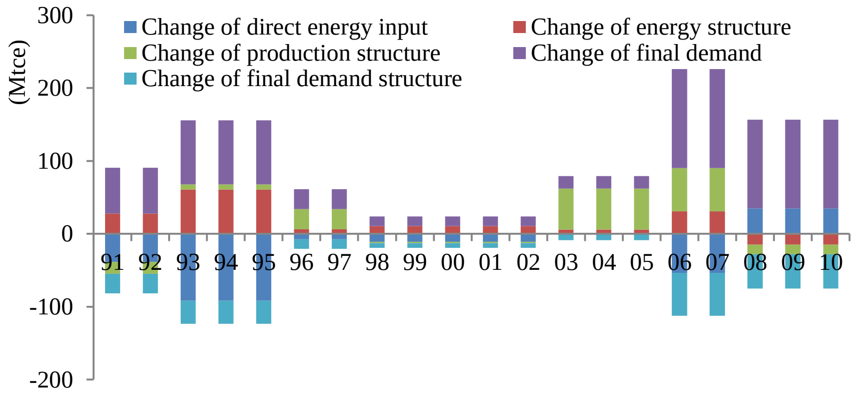


Figure 4.3 Contribution of five driving factors in the total energy consumption change

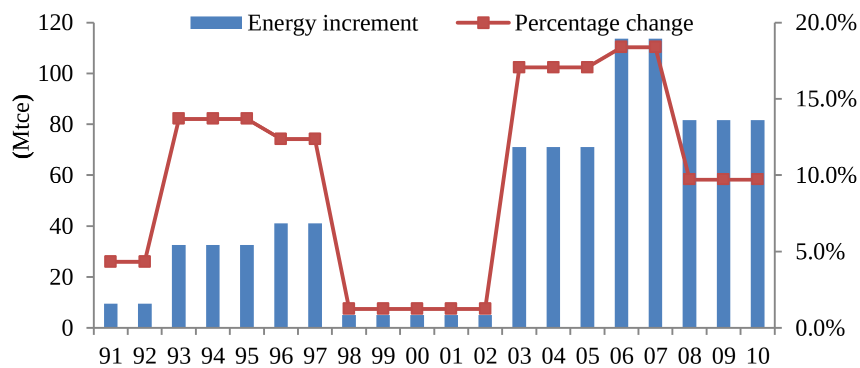


Figure 4.4 Summary of energy increment and its percentage change for different periods

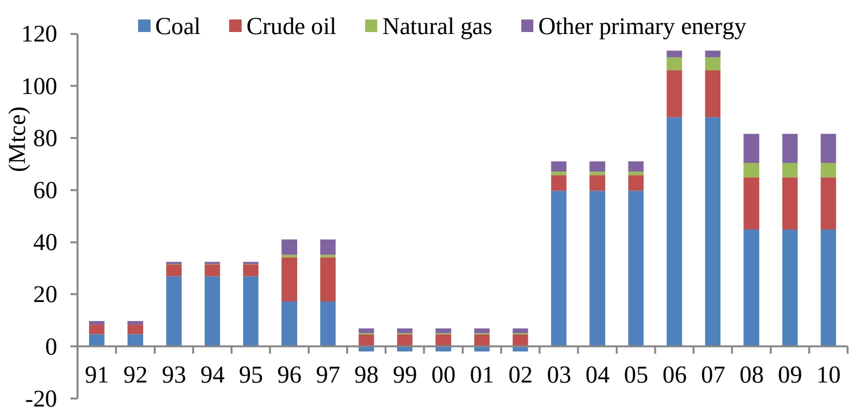


Figure 4.5 Change in total energy consumption from 1990 to 2010 by different fuel types

4.3 The projection of the 13th (2016-2020) Five-Year Plan

Measuring the potential driving forces in the projected scenario helps the central government achieve equitable energy reduction policies in consumption. Therefore, this study made a projection scenario for the future energy consumption in China's construction industry. The latest available input-output table from 2010 has been adopted as the initial year to predict the economic data. Similarly, the energy consumption data obtained from the 2011 Chinese Energy Statistical Yearbook are used as the baseline to predict energy consumption patterns and volume in 2020.

To project the energy consumption trajectory, a number of assumptions adopted by the World Energy Outlook 2007 have been used in this study to estimate the volume and pattern of energy consumption. Table 4.2 and Table 4.3 summarized four categories of data required for projection. First, the annual growth rate for major energy-intensive sectors has been assumed (e.g. iron and steel, non-metallic minerals, chemicals, and transportation). Second, the basic economic structure involved in agriculture, industry, and service was also determined. The proportion of service increased to 47% whereas the percentage of agriculture and industry reduced to 3% and 50%, respectively. This adjustment adopted by the World Energy Outlook 2007 highlights the switch in China's economic structure from manufacturing-based to service-based. Third, the annual growth rate of different primary energy sources has been assumed. The primary energy consumption including coal and oil is projected to grow by 3.0% and 4.0% per year from 2010-2020, respectively. Clean energy sources such as natural gas and renewable energy in other primary energy will grow faster (5.7% and 3.4%, respectively) according to the structural optimization in future energy consumption. The annual growth rate of total energy consumption is assumed to be 3.2%. Fourth, the GDP growth rates in the past two decades have been reviewed to predict the volume of economic output in 2020 (Table 3). Given the difference between the scheduled and actual rate over the past two decades as well as the economic downturns since 2006, the average annual growth rate is assumed to be 6.5% for the 13th Five-Year Plan period. To predict future production structure, the RAS method has been proved to be an effective technique to reconstruct the input-output table. It has been used to estimate the inter-industrial coefficient in 2020. The data required by RAS method are calculated based on the assumption that the sectoral data of total intermediate sales and total interindustry purchases are proportional with their total gross outputs.

Table 4.2 Date required for projection

Sector	Energy consumption growth rate	Proportion in GDP	Energy source	Growth rate
Agriculture	1.3%	3%	Coal	3.0%
Industry	3.2%	50%	Oil	4.0%
Iron and steel	2.9%		Natural gas	5.7%
Non-metallic minerals	1.1%		Others	3.4%
Chemicals	2.2%			
Transportation	5.4%			
Service	3.3%	47%	Total	3.2%

Note: all the data listed in this table are obtained and estimated based on the World Energy Outlook 2007-China and India Insights, Chapter 9.

Table 4.3 Scheduled and actual annual growth rate of economy in China from 1991 to 2015

	8th Five-year	9th Five-year	10th Five-year	11th Five-year	12th Five-year
	1991-1995	1996-2000	2001-2005	2006-2010	2011-2015
Schedule	6.0%	8.0%	7.0%	7.5%	7.0%
Actual	12.30%	8.60%	9.70%	11.20%	8.20%

The percentage changes in the total energy consumption according to different driving factors are shown in Figure 4.6. The total embodied energy consumption in the construction industry would reach 1408 Mtce by 2020 with a 34.0% increase of 2010 level. The energy reduction from structural optimization is significant—the structural change in energy, production and final demand are three major factors causing energy reduction. These three factors together reduce 24.7% (260 Mtce) of 2010 level. It is also worth noting that although the volume of final demand is the largest driver for energy increments, it experiences a slowdown in this scenario, especially versus the trend from 2002-2010. Figure 4.7 shows the change of energy increments for different fuel types. Based on the assumed growth rate in the economy and energy use, the consumption of carbon-intensive energy sources (e.g. coal and oil) has been significantly reduced.

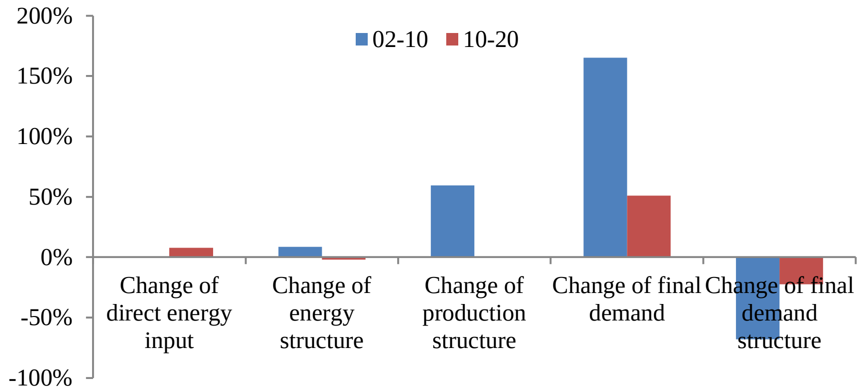


Figure 4.6 Percent change in the total embodied energy consumption for five driving factors

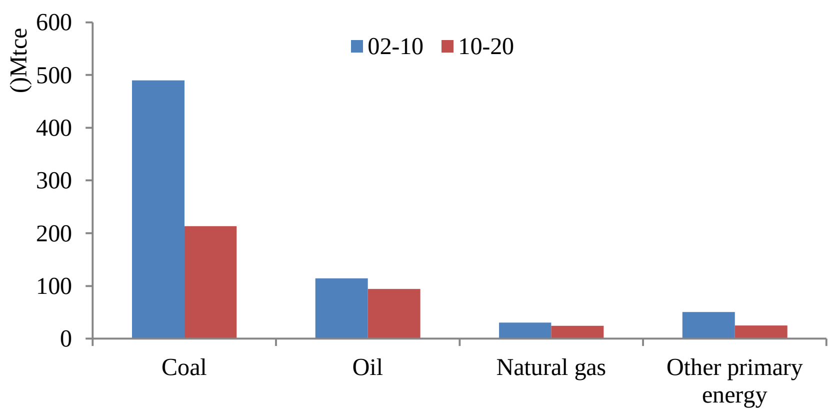


Figure 4.7 Change of the energy increments by different fuel types

4.4 Scenario analysis

4.4.1 Scenario analysis for the projection

Given that the assumptions used in the projection are crucial for robust model results, this study therefore conducted scenario analysis based on the bottom-level assumptions and variables. Moreover, energy consumption from the construction industry is inevitable in China due to the rapid urbanization process and requirement for improving people's living standard. According to the projection in the section 4.3, the structural optimization has been demonstrated as the major reduction drivers for the energy consumption of the construction industry. Therefore, the focus of concern in this scenario analysis is to explore how the structural optimization suppresses the energy increment from a production-based perspective based on the same projected GDP growth rate. Table 4.4 shows the changes of basic data under different scenarios. Reference scenario is consistent with the assumptions in original projection. Optimistic scenario is adopted to enhance the positive effect from the structural optimization on energy reduction. Therefore, the proportion of economic output in service is assumed to increase by 10% while the share of industry reduces by 10%. Simultaneously, a 10% increase is assumed for the annual growth rate of clean energy and renewable energy, and the growth rate for energy-intensive sectors (e.g. Iron and steel, non-metallic minerals, and chemicals) is assumed to reduce by 10%. By contrast, pessimistic scenario puts emphases on the negative effect from structural changes on energy consumption. Accordingly, the sharing of economic output in industry is adjusted to 55%, the growth rate of clean energy and renewable energy declines by 10%, and the growth rate for energy-intensive sectors increases by 10%.

Table 4.4 Basic profile of different scenarios

	Reference scenario	Optimistic scenario	Pessimistic scenario
Agriculture	(3%)	(3%)	(3%)
Industry	(50%)	(45%)	(55%)
Iron and steel	2.9%	2.6%	3.2%
Non-metallic minerals	1.1%	1.0%	1.2%
Chemicals	2.2%	2.0%	2.4%
Service	(47%)	(52%)	(42%)
Natural gas	5.7%	6.3%	5.1%
Other primary energy	3.4%	3.7%	3.1%

Note: the number of percentage presented in the bracket is the sharing of economic output in the national GDP.

According to Figure 4.8, the energy increment calculated under the pessimistic scenario was 460.5 Mtce with a 43.8% increase of 2010 level, which was 29.2% higher than the result obtained in the reference scenario. In contrast, the result calculated in optimistic scenario was 240.7 Mtce with a 22.9% increase of 2010 level, which was 32.5% lower than the original projection. This finding provides an insight into how the structural optimizations in production and energy consumption affect the total energy use of the construction industry. It can be seen that the energy increase driven by the volume of final demand has been restrained significantly due to the structural optimization of production and energy in the optimistic scenario. Figure 4.9 shows the energy increment according to different primary energy sources. Similarly, optimistic scenario performed best regarding the suppression of energy increments in different primary energy sources. On one hand, as a typical carbon-intensive source causing global warming, coal was consumed the least in the optimistic scenario. On the other hand, the proportion of clean energy (natural gas) and renewable energy in total energy consumption has been improved from 6.8% and 6.9% to 8.9% and 7.1%, respectively. In summary, the results of scenario analysis indicate that the steering of production structure from heavy manufacturing to service-based economy as well as the adjustment of energy consumption structure by improving the proportion of clean and renewable energy have significant positive effect on energy reduction of the construction industry.

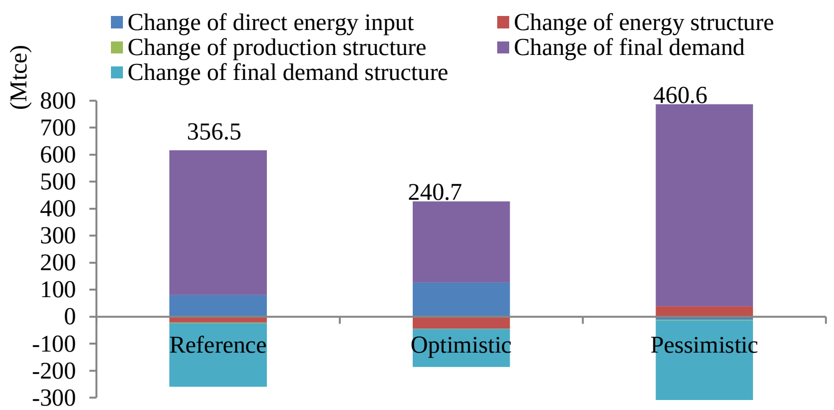


Figure 4.8 Energy increments of different driving factors in three scenarios

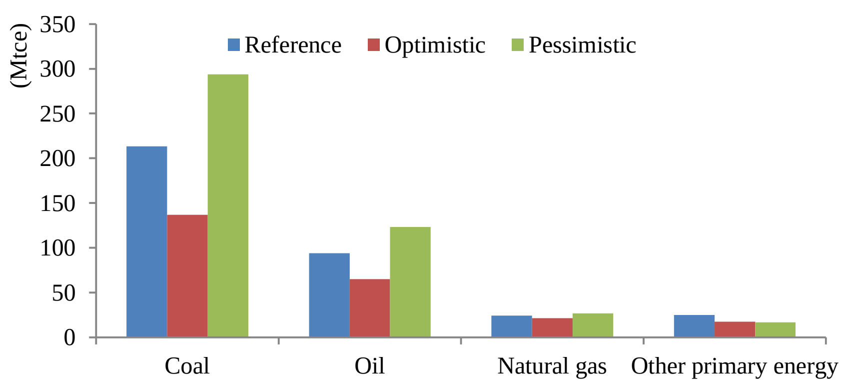


Figure 4.9 Energy increments of different primary energy sources in three scenarios

4.4.2 Scenario analysis in sector aggregation

The uncertainties in the input-output analysis come from two major sources. One is the theoretical assumptions before analysis including the assumption of proportionality, homogeneity, and identity of production technology. The other is due to transformation and reconstruction in the compilation of input-output tables. In general, the methodological uncertainties are mostly unavoidable and hard to estimate in the computational process. In contrast, uncertainties from subjective compilation can be quantified and improved based on uncertainty analysis. Moreover, Weber (2009) also emphasized that the level of sector aggregation has a direct impact on results accuracy—this is the most critical factor influencing the uncertainty in structural decomposition. Unfortunately, very few studies have discussed this problem systematically due to a lack of public data. Therefore, this study focused on sector aggregation.

Broadly speaking, sector aggregation is the result of the tradeoff between the level of detail in analysis and the availability of environmental data from the statistical yearbook. Generally, the I-O table compiled by the National Bureau of Statistics is more specific on the detailed monetary flow data. However, direct energy input data are recorded at a more aggregate level, where the sector classification standard is not consistent with the I-O table. Moreover, due to the improvement of sector classification standards in the past two decades, the compilation of input-output table has been changed across different years. Sector aggregation has to be performed to keep the consistency in table format across the time series.

The level of sector aggregation thus directly affects the final results of the I-O analysis because the number of sectors has been predetermined in structural decomposition analysis. As a result, the sector aggregation strategy needs to be implemented to match these two systems (Su et al., 2010). One strategy is to aggregate the I-O sectors to match the energy sector data. This strategy not only guarantees the accuracy of sector aggregation but also avoids extra assumptions. The other approach disaggregates energy consumption data to match the I-O table that retains all economic information while bearing the drawbacks on the subjective estimation of energy use among the sub-sectors.

Thus, this study employed multi-scale I-O tables to conduct uncertainty analysis. Generally, the I-O table with 28 sectors (presented in this study) has been recombined into tables with 18 sectors, 8 sectors, and 4 sectors to verify the impact of changes in the level of sector aggregation (Appendix 1). Figure 4.10 shows that all scenarios agree on the dominant driving forces for energy increment in the construction industry. Besides, the sequence of importance for driving factors underlying each scenario is consistent with original findings except the result calculated by a 4-sector format table. In this scenario, the effect of structure change in production is stronger than the effect of change in the energy structure. This is inconsistent with other scenarios. Such inaccuracy may lead to a misunderstanding of the importance of the factor under study. Moreover, the results of the I-O analysis with 8 and 4 sectors have been changed considerably due to the loss of detailed information on economic data. Therefore, it is advisable and necessary to perform decomposition analysis based on sufficient economic information.

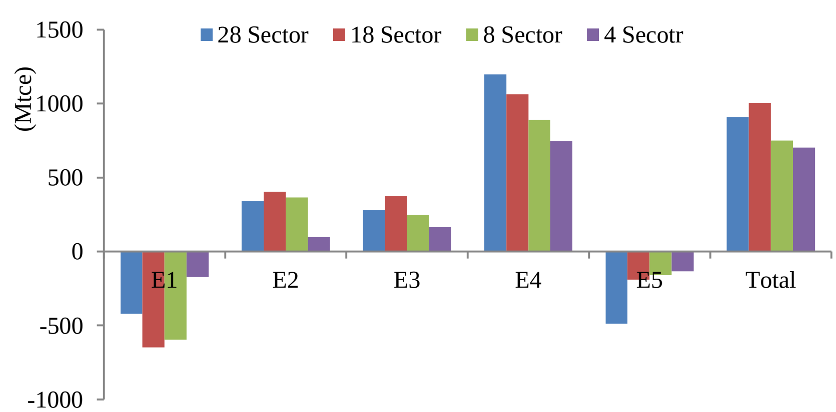


Figure 4.10 Changes of driving factors by different scenarios

4.5 Summary of the Chapter

This Chapter employed structural decomposition analysis to achieve objective 1. The driving forces behind energy use in China's construction industry from 1990 to 2010 have been explored and a systematical review of the major trends and improvements in energy consumption has been presented. The driving forces have been divided into 5 factors, namely change in total energy intensity, change of energy structure, change of production structure, change of final demand volume, and the structure change of final demand. Seven time intervals have been analyzed separately to investigate the driving forces at different periods. Then this chapter conducted predictive analysis for the energy consumption trajectory of the 13th Five Year Plan based on a series of assumptions on energy increase rate. Uncertainty analysis has also been undertaken to examine the effect of sector aggregation and disaggregation on the identification of driving factors. At last, critical factors have been identified for further policy consideration.

Chapter 5 Embodiment Analysis of the Regional Energy Use

5.1 Introduction

Chapter 4 identified the driving forces behind the changes of total embodied energy consumption of the construction sector in time series. However, it is also imperative to have a holistic investigation of the energy requirement involving the direct energy input from the onsite production process and the indirect energy consumption from the upstream process. Moreover, the ignorance of the indirect environmental pollution along with the insufficient understanding of current energy consumption status at the regional and sectoral levels could result in unfair or irrational policies for the construction industry. Given the lack of consideration of regional disparity in traditional perspectives, it is also critical to take account of region-specific characteristics. However, traditional single-region input–output (SRIO) analysis fails to capture the hidden linkage and economic network among interregional trade flows. In general, the infinite interrelationship in the supply chain mixes production technology from both domestic and foreign sources. Unfortunately, the SRIO model is applied on the assumption that the manufacturing technology in the domestic production process is the same as the technology used in foreign regions. Therefore, this model is unable to describe these differences in production and economic structure. Recent improvements in environmental impact accounting allow for a more accurate assessment of embodied energy consumption. Multi-regional input–output (MRIO) model, which presents the environmental interactions by taking account of regional characteristics and sectoral differences, has been extensively studied at the international, national, and regional levels in previous research. Unfortunately, it has been rarely studied at the industrial level, especially on the construction sector. This chapter aims to evaluate the energy use embodied in the construction sector of China by considering regional diversity and technological differences with the aid of a multi-regional input–output model, which could help decision makers achieve equitable energy reduction policies at the national or regional level.

5.2 Spatial Analysis of Embodied Energy Use

The total energy use embodied in the construction sector of 30 regions in 2007 is shown in Figure 5.1. Clearly, the construction sector in China is a typical demand-driven industry where gross fixed capital formation represents the highest relative contribution in all final demand categories. The total embodied energy use from the construction sector in China is 793.74 Mtec, which accounts for approximately 29.6% of the total national energy consumption. This result is also consistent with the study by Chang et al. (Chang et al., 2010). In addition, the construction sector of Zhejiang (R11) consumed the most embodied energy of 57.91 Mtec, followed by Jiangsu (R10) with 55.13 Mtec, and Henan (R16) with 49.62 Mtec. However, the underlying fundamentals that drive the energy consumption are different. The energy requirement in Zhejiang (R11) and Jiangsu (R10) is driven by the large amount of local construction activities, whereas the effects of energy intensity involved in the construction process within these two places are negligibly small. Instead, the driving factor for Henan (R16) is the high energy intensity. By contrast, despite the lower amount of energy consumption in Ningxia (R29) and Shanxi (R4), these regions still have drawbacks on high energy intensity because of their inefficient manufacturing and production process.

Region division in China is normally based on geographic relationship (Liang et al., 2007; Meng et al., 2011). However, this study categorizes China based on the value of energy intensity, which aims to provide a holistic map to represent their level in production technology of the construction sector.

Table 5.1 Description of area categories

Area	Province/municipality	Energy intensity (Tonnes per 10^4 RMB)	Geographic location
1	Hainan (R21), Fujian (R13), Guangdong (R19)	=<1.0E–04	Southern Coastal
2	Jiangxi (R14), Shandong (R15), Anhui (R12), Beijing (R1), Jiangsu (R10), Zhejiang (R11), Shanghai (R9)	1.0E–04~1.2E–04	Central–Eastern Coastal
3	Tianjin (R2), Hebei (R3), Guangxi (R20)	1.2E–04~1.4E–04	-
4	Xinjiang (R30), Yunnan (R25), Liaoning (R6), Hubei (R17)	1.4E–04~1.6E–04	-
5	Gansu (R27), Hunan (R18), Qinghai (R28), Shanxi (R26), Inner Mongolia (R5), Sichuan (R23), Chongqing (R22), Guizhou (R24)	1.6E–04~1.8E–04	West
6	Jilin (R7), Heilongjiang (R8)	1.8E–04~2.0E–04	Northeast
7	Henan (R16), Shanxi (R4), Ningxia (R29)	>=2.0E–04	Central

Table 5.1 shows that a geographical relationship still exists although all regions are divided according to the value of energy intensity. The southern coastal area, eastern coastal, and some parts of the central area have shared similar low energy intensity in the construction sector which is mainly due to their developed economy and advanced production technology. For regions in the northeast, west, and several places in the central area, the construction sectors are representing energy intensive because of their underdeveloped economy and inefficient production process.

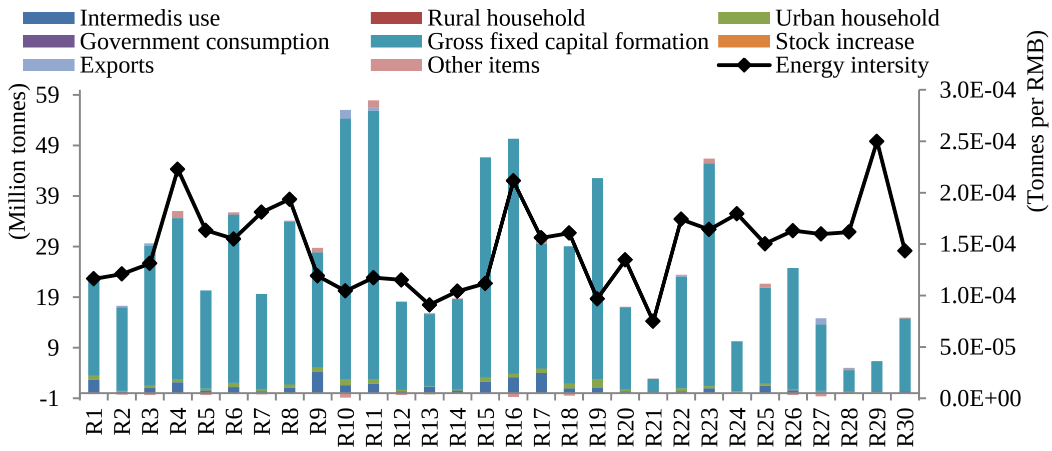


Figure 5.1 Total energy use embodied in the construction industry by region

To reflect the current energy consumption status and importance of the construction sector in each region, all 30 regions were further divided into four groups according to their energy intensity and total amount of energy use (see Figure 5.2). It's worth noting that Shanxi (R4), Liaoning (R6), Heilongjiang (R8), Henan (R16), and Sichuan (R23) in the upper right quadrant not only carried out extensive construction activities but also exhibited higher energy intensity. The energy consumption of the construction sector in Jiangsu (R10), Zhejiang (R11), Shandong (R15), and Guangdong (R19) in the upper left quadrant was mainly driven by their large scale of construction activities. The construction sector in Inner Mongolia (R5), Jilin (R7), Hunan (18), Chongqing (R22), Guizhou (R24), Shaanxi (R26), Gansu (R27), Qinghai (R28), and Ningxia (R29) in the lower right part was driven by high energy intensity.

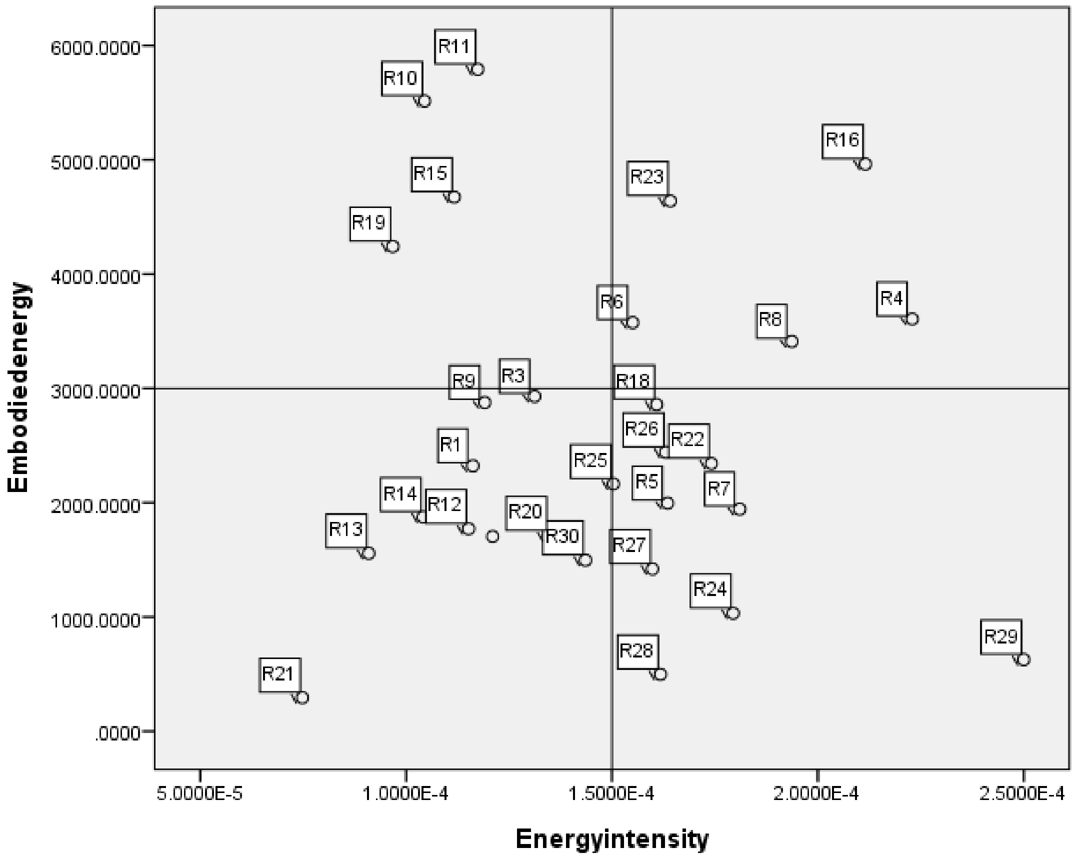


Figure 5.2 Distribution of thirty regions in categorization coordinates

Ten types of energy sources have been investigated for the regional construction sectors. However, to avoid double-counting problems that arise from calculating the relative percentage of different energy types, all energy sources have been combined into four types of primary energy, which have been analyzed and presented in Figure 5.3. With regard to the proportion of primary energy use for each region, coal dominates in all energy types with the percentage ranging from 29.69% in Hainan to 72.03% in Shanxi. This situation could be better understood by especially considering the fact that the consumption of cement and steel in the construction sector was 934.51 and 224.79 Mt in 2007, which accounted for 73.76% and 19.87% of primary material use in China (NBSC, 2012). Coal and crude oil, as the fundamental energy sources for cement and steel production, were consequentially consumed most in the total embodied energy use. In summary, the construction sector in China is typical fossil fuel energy oriented, which leads to a large amount of ecological damage.

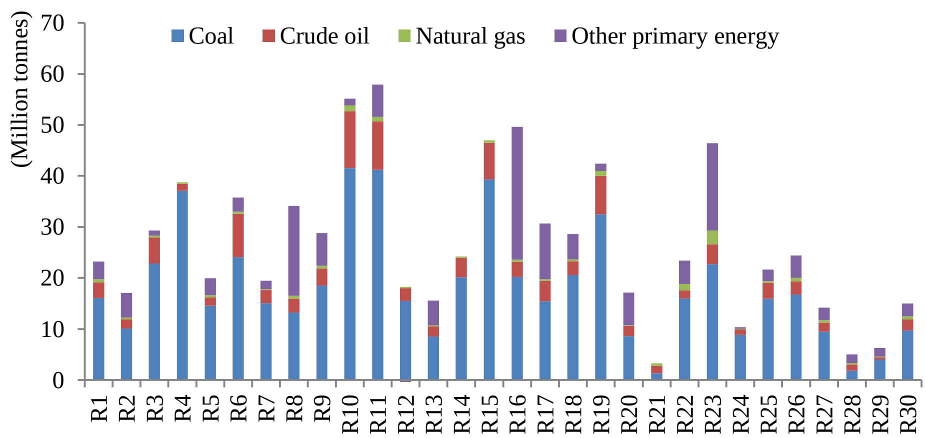


Figure 5.3 Percentage of different primary energy categories among different regions

5.3 Sectoral Analysis of Embodied Energy Use

In addition to provide regional environmental connections, MRIO model also explores the hidden linkage among different economic sectors. Figure 5.4 summarized embodied energy use of different economic sectors. It can be found that Smelting and Pressing of Metals (S14) was the largest contributor to the national energy consumption, followed by the chemical industry (S12) and the construction sector (S24). More importantly, given the very small contribution of the direct energy input to the construction site, the indirect energy consumption plays a dominant role in the construction sector.

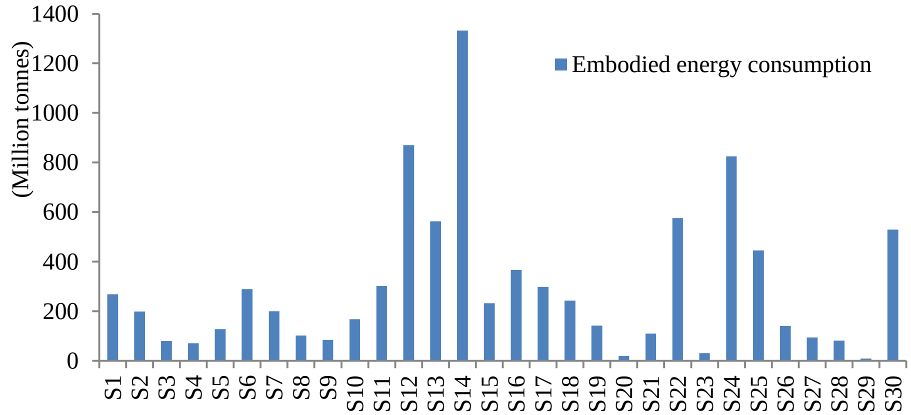


Figure 5.4 Embodied energy consumption by sectors

Table 5.2 shows the rankings of all energy suppliers for the construction sector across China's entire economy. The following can be identified as the top ten correlated sectors in the construction sector of China: manufacturing of non-metallic mineral products (S13), smelting and pressing of metals (S14), transportation, storage, post, and telecommunications (S25), chemical industry (S12), manufacturing of metal products (S15), manufacturing of electrical machinery and equipment (S18), manufacturing of general and special purpose machinery (S16), processing of petroleum, coking, processing of nuclear fuel (S11), other services (S30), and production and distribution of electric power and heat power (S22). Among them, manufacturing of non-metallic mineral products (S13) and smelting and pressing of metals (S14) represent the highest relative contribution to the embodied energy use from the construction sector in terms of coal, coke, crude oil, fuel oil, natural gas, and electricity. Simultaneously, transportation, storage, post, and telecommunications (S25) is the dominant energy suppliers for gasoline, kerosene, and diesel oil consumption. Besides, the service sector also plays an important role in upstream process of building construction, with energy consumption being mainly a result of labor, financial, and real estate related activities.

Table 5.2 Rankings of energy suppliers by sector in terms of different energy types

	Total energy	Coal	Coke	Crude oil	Gasoline	Kerosene	Diesel oil	Fuel oil	Natural gas	Electricity
S1	21	22	20	19	19	19	16	21	18	20
S2	16	13	17	23	21	21	18	24	22	19
S3	29	29	29	29	29	29	29	29	29	29
S4	30	30	30	30	30	30	30	30	30	30
S5	4	11	12	11	11	12	9	12	13	10
S6	27	26	28	25	25	27	25	28	26	26
S7	25	25	27	26	28	28	27	26	25	25
S8	23	24	25	22	22	23	22	19	24	23
S9	12	12	11	12	12	11	12	11	12	11
S10	19	20	19	24	24	22	24	20	23	21
S11	11	7	14	3	13	10	13	8	5	12
S12	3	4	6	5	6	8	6	4	3	3
S13	1	1	2	1	2	2	2	1	1	2
S14	2	2	1	2	3	3	3	2	2	1
S15	6	5	3	7	9	9	7	7	9	4
S16	8	8	5	9	8	7	8	9	10	7
S17	18	17	10	16	16	15	17	16	16	16
S18	7	6	4	6	5	5	5	6	8	5
S19	26	27	26	27	27	25	26	25	27	27
S20	28	28	24	28	26	26	28	27	28	28
S21	13	18	15	17	20	18	19	17	21	17
S22	9	3	13	10	15	14	11	5	6	6
S23	20	19	23	18	23	24	23	18	14	18
S24	15	15	9	15	14	16	14	14	19	14
S25	5	9	7	4	1	1	1	3	4	9
S26	14	14	16	13	7	4	10	13	11	13
S27	22	21	22	20	18	17	20	22	17	22
S28	17	16	18	14	10	13	15	15	15	15
S29	24	23	21	21	17	20	21	23	20	24
S30	10	10	8	8	4	6	4	10	7	8

5.4 Energy Use Embodied in the Interregional Trade

The energy use embodied in interregional imports and exports is shown in Figure 5.4. Zhejiang (R11) is the leading region with importing embodied energy flow of 24.38 Mtce, followed by Jiangsu (R10, 16.39 Mtce), Beijing (R1, 15.24 Mtce), and Shaanxi (R26, 13.31 Mtce). Shaanxi is also the largest exporter with 9.45 Mtce of embodied energy outflow, followed by Henan (R16, 6.44 Mtce), Hunan (R18, 6.40 Mtce), and Sichuan

(R23, 4.90 Mtce). Except for Henan (R16) and Hunan (R18), the remaining 28 regions have positive net embodied energy use, which implies that their construction sector receives energy input from other regions' economy. A close examination of the imports indicates that the energy flow due to interregional trade of construction activities represents a highly region-concentrated distribution. Hebei (R3), Henan (R16), Shaanxi (R26), and Liaoning (R6) have been identified as the major energy suppliers for the construction sector of three economic areas in China. The energy outflow from Henan is dominant in energy imports of Yangtze River Delta area [Shanghai (R9), Jiangsu (R10), and Zhejiang (R11)], accounting for 10.02%, 14.74%, and 16.25% of their total energy imports. Hebei is the primary energy supplier of the Circum–Bohai Sea economic area [Beijing (R1) and Tianjin (R2)], and is responsible for 64.50% and 43.26% of their total imported energy use. Liaoning (R6), Jilin (R7), and Heilongjiang (R8) constitute the northeast area of China where the energy flows represent multi-direction distribution.

Such spatial distribution may have arisen for two reasons. First, developed regions along the eastern coast are highly dependent on the natural and energy resources from central and western parts of China according to their resource limitations. According to the China Statistic Yearbook 2008 (NBSC, 2008), as the primary mineral resources for iron, steel, cement, and aluminum production, the ensured reserves of major ferrous metals, major non-ferrous metals, and non-metal minerals of these four regions accounted for 20.92%, 55.39%, and 59.54% of total reserves in China in 2007. This fact made a substantial contribution on energy and resource input in the upstream process of building construction in regions around these resource-abundant areas. Second, a close geographic linkage exists between the energy supply regions and energy required areas because of the convenience of material transportation. In summary, energy transportation due to interregional imports for the construction sector in China is from the central parts to the eastern coastal areas with a resource-dependent distribution.

Further analysis of energy embodied in exports found that the amount of energy exported from regional construction sectors is scattered among different regions. Such energy outflows are mainly transferred in the form of labor mobility and service supply. More specifically, as the typical labor intensive sector, the construction sector is highly related to the labor input and consulting services provided by professional institutions and enterprises, which is regarded as the major carrier for energy exports from the construction sector. In fact, a further examination of the top four energy exporters shows that Shaanxi (R26), Henan (R16), and Sichuan (R23) are the three largest labor exporters in China. Moreover, the construction sector of Jiangsu (R10) ranked first not only in the number of local construction enterprises but also in the annual revenue in 2007. Such prosperous development of the local construction industry was bound to produce large demand of consulting services.

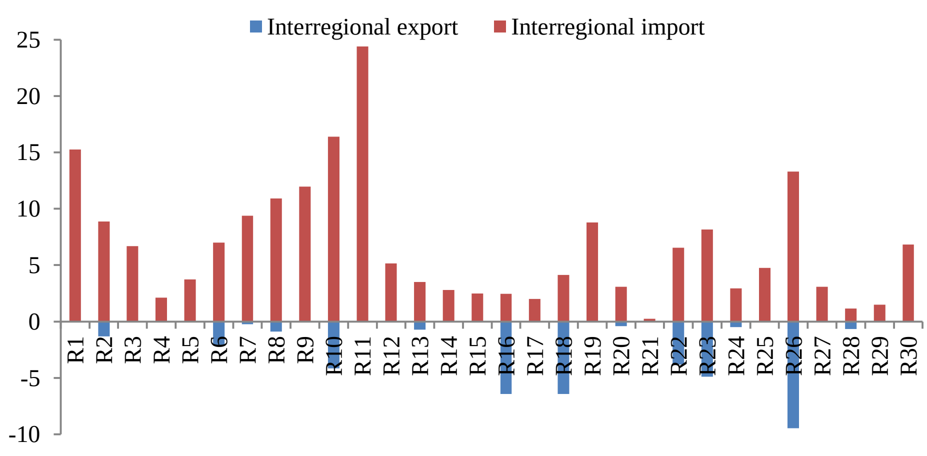


Figure 5.5 Energy use embodied in interregional imports/exports related to the construction industry

5.5 Discussions

Since the aim of this chapter is to analyze the embodied energy use of the construction sector, consideration of the basic features relevant to construction activities is necessary. Therefore, the results obtained in this study have been further validated and compared with previous research. Figure 5.5 shows the percentage between direct energy input and embodied energy use. The share of direct energy use for the construction sector ranges from 0.7% (Hainan) to 12.02% (Hebei). From the perspective of life cycle analysis, direct energy input to construction projects mainly involves onsite electricity use and fuel consumption by construction equipment and vehicles, whereas the indirect energy use is related to building materials production and transportation in the upstream process. The ratio estimated in this chapter is in line with previous research where the ratio estimated by the process-based LCA approach ranged from 1.77% to 11.49% (Chen et al., 2001; Kua and Wong, 2012; Wu et al., 2012). This fact further verifies the possible application of the MRIO model for energy assessment in the embodied phase at the industrial or project level.

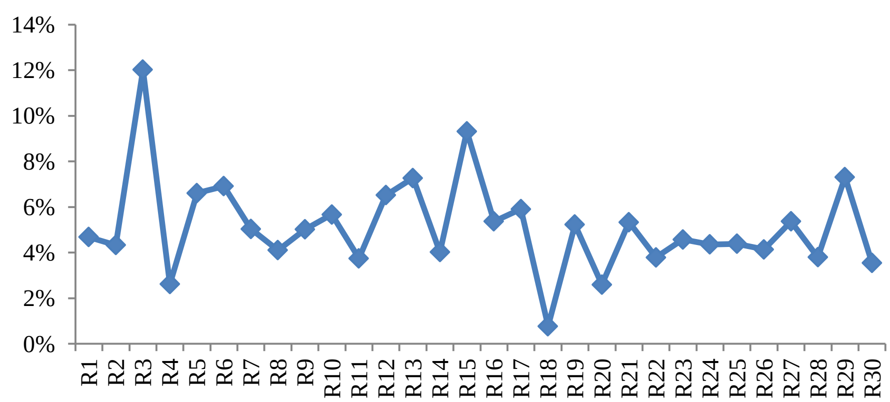


Figure 5.6 Regional percentage of direct energy input and embodied energy

Recognizing the hidden linkage and energy flow embodied in the interregional trade of the construction sector is of great importance to the holistic understanding of current energy consumption status. According to the aforementioned analysis results, the energy resource flows are from the central part to the eastern coast of China. More specifically, Henan and Hebei province have been identified as the major supplier of the Yangtze River Delta area and the Circum-Bohai Sea economic area. From the traditional production perspective, these energy suppliers need to be restricted by imposing tighter energy policies. However, the exploration of such hidden energy mobility can provide consumption-based insight for policymakers, thereby requiring provinces in developed areas to take more responsibility for reducing the volume of their energy use.

In addition, this study analyzed the embodied energy consumption of the construction sector by taking regional diversity and technology difference into consideration. More specifically, at the regional level, a number of regions [e.g., Ningxia (R29), Shanxi (R4), and Henan (R16)] need to change their production process into intensive mode and improve their manufacturing technology, eliminating conventional low production efficiency and high energy consuming behavior. The other regions [e.g., Jiangsu (R10) and Zhejiang (R11)] face challenges because of their highly increased construction volume. Therefore, upgrading energy productivity and optimization of production structure can be regarded as an offset for such driving force. In addition, the current energy consumption model is still fossil fuel oriented, which is the main source of GHG emissions. Therefore, the energy consumption pattern of the construction sector can be adjusted to become more sustainable and clean by enhancing the utilization of renewable power, such as natural gas and electricity.

At the sectoral level, the top three energy suppliers of the construction sector, namely manufacturing of non-metallic mineral products (S13), smelting and pressing of metals (S14), and transportation, storage, post, and telecommunications (S25), are typical energy-intensive sectors. They are highly related to a number of basic construction activities in the upstream process, including iron and steel production, cement production, and material transportation. Therefore, on one hand, the increasing use of environmentally friendly materials with low energy intensity is an effective way to reduce energy consumption in construction activities. On the other hand, the inter-industrial economic relationship needs to be further optimized and upgraded within the entire supply chain.

5.6 Summary of the Chapter

MRIO analysis has been conducted in this chapter to explore the direct and indirect energy use embodied in the interregional trade induced by construction activities from a regional and sectoral perspective. The results can be regarded as a solid reference to re-recognize the spatial and sectoral characteristics of embodied energy requirements of the construction sector. The national and regional embodied energy use has been calculated, and the characteristic of demand-driven and fossil fuel oriented have been explored for the construction sector. A re-classification of 30 regions based on the value of construction energy intensity has been presented, and the overall map of energy flows from the regional construction sectors has been diagramed in which flows are from resource-abundant areas in the central part to resource-deficient areas in the eastern coast.

Chapter 6 Structural Analysis of the Energy Supply Chain

6.1 Introduction

MRIO analysis helps to re-recognize the embodied energy use of the construction sector by considering the effect of specific regional characteristics such as the variations in the climate, geographical location, natural resources, and level of the economy. However, it fills to capture the cross-regional environmental shifting in upstream process of the supply chain. Therefore, a systematic structural analysis for such an infinite interrelationship is needed to study the adverse environment impacts linked with interregional production chains. This is especially important for extracting paths with significant energy consumption in the upstream process. Structural Path Analysis (SPA) is a methodology that quantifies environmental transmission in the upstream process and identifies the critical paths with highest energy reduction potential by tracing the intricate production chain. For the SPA in the construction sector, Trelor et al. extracted the embodied energy path for the building sector by adopting an SPA method. They established a hybrid LCA model by substituting energy intensive paths with case-specific data (1997; 2001a; 2001b). Chang et al. made a series of input-output analyses to simulate embodied energy use and environmental impact for the construction industry in China. Unfortunately, most of these studies considered the environmental impacts of a certain sector from the national perspective while ignoring regional disparities (Chang and Wang, 2011; Chang et al., 2011; Chang et al., 2013).

This Chapter uses SPA based on the multi-regional input-output (MRIO) model for the construction sector. By considering region-specific characteristics, the MRIO-based SPA can provide a sufficient understanding of the hidden linkage and correlations in the environmental interactions from the interregional trade of the construction sector. This can help decision makers achieve equitable energy reduction policies at the national or regional level. On the other hand, it can also explore the link between consumption and production in the interregional supply chain of the construction sector. Thus, individual cross-regional supply paths with significant contributions are able to be identified for further analysis.

6.2 Overview of the Supply Chain

The number of energy paths and their corresponding relative contributions for each stage has been calculated in Table 6.1. It is worth noting that the energy paths in the first stage consumed the most energy in the supply chain and accounted for approximately 40% of the total energy consumption in the construction industry. The second stage is notable because the number of energy paths is almost 4-fold the number of paths in the first stage. This indicates that the sectorial interactions have extended to the breadth of the whole economy in this stage for the construction sector. In this study, a threshold value of 0.005% was used to filter almost 80% of the overall impacts. The number of paths would be infinite and the value of the energy path in the higher stages could be extremely small because the SPA used in this study was based on multi-regional input-output tables with 900 entries. Therefore, the 80% energy path information could be regarded as an acceptable proportion to guarantee both confidence and convenience by cutting unessential paths.

Table 6.1 Summary of energy paths in the first five stages

Stage	Number of energy paths	Sum of embodied energy use	Proportion of total energy	Cumulative percentage
0	30	4149.2	5.23%	5.23%
1	4051	32364.4	40.77%	46.00%
2	15856	18345.6	23.11%	69.11%
3	13568	6829.8	8.60%	77.71%
4	4929	1628.8	2.05%	79.76%
5	1026	300.4	0.38%	80.14%

Table 6.2 describes the top 3 energy paths for 30 regions in the supply chain. These paths in each region cumulatively account for more than 20% of the total energy consumption in the regional construction industry. In general, for paths in zeroth stage, the direct energy consumption on the construction site in some regions has large impacts on the total energy use. This includes Beijing (A1) and Hebei (A3). Energy supply from the manufacturing of non-metallic mineral products (S13) and smelting and pressing of metals (S14) represent the most important paths to the regional construction sectors. Most of these energy paths are in the first stage of the supply chain representing the direct building materials input such as cement and steel. Some are in the second stage by intra-sector purchase.

In addition, transportation, storage, posts and telecommunications (S25) also have significant first-stage energy contributions. Energy originating from S25 is consumed by transporting building materials from the offsite factory to the construction site. Other supply chains of concern for the construction sector are the second-stage contributions from chemical industry (S12), production and distribution of electric power and heat power (S22), and mining industries (e.g. mining and washing of coal (S2), mining and processing of metal ores (S4), mining and processing of nonmetal ores (S5)).

On one hand, products provided by chemical and mining industries are necessities for manufacturing metal and non-metallic mineral products. The energy supply from mining industries is particular significant, especially in resource-abundant regions such as Henan (A16), Qinghai (A28), and Ningxia (A29), On the other hand, S22 is the major power sector—it directly and indirectly influences the energy input of the construction sector. In summary, upon reviewing the whole supply chain—especially the paths in the higher order stages—the critical sectors hidden behind the upstream process can therefore be identified. This includes the direct suppliers (e.g. manufacturing of metal and non-metallic products, electricity production, and transportation) and indirect suppliers (e.g. chemical and mining industries).

Table 6.2 Top 3 energy paths by region

	Value	Path	%		Value	Path	%
R1	324.9	R1S24<-R3S13	15.8%	R16	1336.2	R16S24<-R16S5	28.8%
	108.8	R1S24	5.3%		275.5	R16S24<-R16S21	5.9%
	91.8	R1S24<-R1S13	4.5%		263.7	R16S24<-R16S13<-R16S5	5.7%
R2	115.5	R2S24<-R3S13	6.9%	R17	457.7	R17S24<-R17S14	17.2%
	110.9	R2S24<-R2S14	6.6%		392.4	R17S24<-R17S13<-R17S12	14.7%
	102.1	R2S24<-R2S13<-R2S14	6.1%		181.3	R17S24	6.8%
R3	352.2	R3S24	12.5%	R18	686.1	R18S24<-R18S13	24.8%
	242.3	R3S24<-R3S14	8.6%		162.3	R18S24<-R18S14	5.9%
	179.0	R3S24<-R3S13	6.3%		157.6	R18S24<-R18S13<-R18S22	5.7%
R4	603.1	R4S24<-R4S14	17.8%	R19	776.5	R19S24<-R19S13	18.8%
	300.5	R4S24<-R4S13<-R3S12	8.9%		191.3	R19S24<-R19S13<-R19S13	4.6%
	234.1	R4S24<-R4S14<-R4S14	6.9%		119.7	R19S24<-R19S25	2.9%
R5	398.4	R5S24<-R5S14	20.5%	R20	500.2	R20S24<-R20S13	29.8%
	213.6	R5S24<-R5S13	11.0%		167.6	R20S24<-R20S14	10.0%
	132.0	R5S24	6.8%		65.4	R20S24<-R20S25	3.9%
R6	498.9	R6S24<-R6S13	14.4%	R21	50.3	R21S24<-R21S13	17.7%
	304.4	R6S24<-R6S14	8.8%		38.8	R21S24<-R21S14	13.7%
	247.1	R6S24	7.2%		18.3	R21S24<-R21S22	6.4%
R7	234.6	R7S24<-R7S14	12.3%	R22	359.9	R22S24<-R22S13	15.6%
	174.4	R7S24<-R7S13	9.2%		195.7	R22S24<-R22S14	8.5%
	124.8	R7S24<-R8S14	6.6%		88.8	R22S24	3.9%
R8	538.5	R8S24<-R8S14	16.3%	R23	695.6	R23S24<-R23S14	15.3%
	244.0	R8S24<-R8S13<-R6S14	7.4%		678.3	R23S24<-R23S13	14.9%
	160.6	R8S24<-R7S14	4.9%		212.3	R23S24	4.7%
R9	356.8	R9S24<-R9S13	14.5%	R24	152.8	R24S24<-R24S13	15.0%
	191.0	R9S24<-R9S14	7.8%		120.1	R24S24<-R24S14	11.8%
	144.4	R9S24	5.9%		45.1	R24S24	4.4%

R10	710.8	R10S24<-R10S13	13.3%	R25	449.0	R25S24<-R25S13	22.3%
	296.3	R10S24<-R10S14	5.5%		159.2	R25S24<-R25S14	7.9%
	89.9	R10S24<-R10S13<-R10S22	1.7%		114.0	R25S24<-R25S25	5.7%
R11	553.0	R11S24<-R11S13	9.9%	R26	337.8	R26S24<-R26S13	14.2%
	247.4	R11S24<-R11S14	4.4%		153.9	R26S24<-R26S14	6.5%
	113.7	R11S24<-R3S14<-R11S13	2.0%		101.2	R26S24	4.2%
R12	256.6	R12S24<-R12S14	14.8%	R27	317.8	R27S24<-R27S13	22.7%
	200.6	R12S24<-R12S13	11.5%		151.5	R27S24<-R27S14	10.8%
	115.6	R12S24	6.7%		76.3	R27S24	5.4%
R13	192.9	R13S24<-R13S14	13.5%	R28	119.4	R28S24<-R28S14	24.3%
	103.3	R13S24<-R13S13<-R13S13	7.2%		61.5	R28S24<-R28S13<-R28S13	12.5%
	113.3	R13S24	7.9%		19.0	R28S24<-R28S14<-R28S4	3.9%
R14	344.0	R14S24<-R14S14	18.8%	R29	111.8	R29S24<-R29S14	18.0%
	169.3	R14S24<-R14S13	9.3%		104.6	R29S24<-R29S13	16.8%
	91.9	R14S24<-R14S14<-R14S14	5.0%		31.2	R29S24<-R16S5<-R29S2	5.0%
R15	657.5	R15S24<-R15S13	14.8%	R30	134.1	R30S24<-R30S13	9.1%
	462.6	R15S24<-R15S14	10.4%		80.9	R30S24<-R30S25	5.5%
	435.7	R15S24	9.8%		73.9	R30S24<-R30S14	5.0%

6.3 Regional Analysis

Multi-regional input-output-based SPA can provide insight from the regional perspective, especially the regional interactions in the higher upstream stages of the construction sector. This study aggregates sectorial information at the region unit. In addition, to clearly represent the geographic relationship between energy suppliers and main areas of China, the regions in the zeroth stage have been aggregated into 8 areas (Table 6.3). Consequently, Figure 6.1 can be used to represent interregional energy flow linkages within the whole supply chain of China’s construction sector. The width of the line represents the amount of energy use transferred from one place to another. Self-sufficiency is the major characteristic for the first-stage energy supply in the regional construction sectors with the exception of Beijing. This fact emphasizes the importance of local production and energy efficiency level for improving energy performance of the regional construction sector. Notably, most energy consumed in the construction sector of Beijing is imported from Hebei. As the capital of China and a major world metropolis, Beijing faces many challenges and pressures for local resources due to its rapid urbanization and growth. It is understandable that Beijing has to import resources from an energy-rich adjacent region.

In fact, Hebei and Inner Mongolia comprise the major energy suppliers for the construction sector in northern China. Henan was identified as a hub for energy imports in the construction sector in eastern and western regions since it is rich in energy resource and is also geographically close to these two areas. The eastern coast (A4) has to import energy from a number of resource-abundant regions (e.g. Hebei, Henan, Inner Mongolia, Shaanxi, and Guangdong) because of extensive construction activities performed in this area. Moreover, in higher order of upstream processes the cross-regional energy flows decreased sharply. This further emphasizes the importance of local production technology and economy development.

Table 6.3 Region division

	Area	Region
A1	Beijing-Tianjin	Beijing, Tianjin
A2	Northeast	Liaoning, Jilin, Heilongjiang
A3	Northern coast	Hebei, Shandong
A4	Eastern coast	Jiangsu, Shanghai, Zhejiang
A5	Southern coast	Fujian, Guangdong, Hainan
A6	Central	Shanxi, Henan, Anhui, Hubei, Hunan, Jiangxi
A7	Northwest	Xinjiang, Qinghai, Ningxia, Gansu, Shaanxi, Inner Mongolia
A8	Southwest	Sichuan, Chongqing, Yunnan, Guangxi, Guizhou

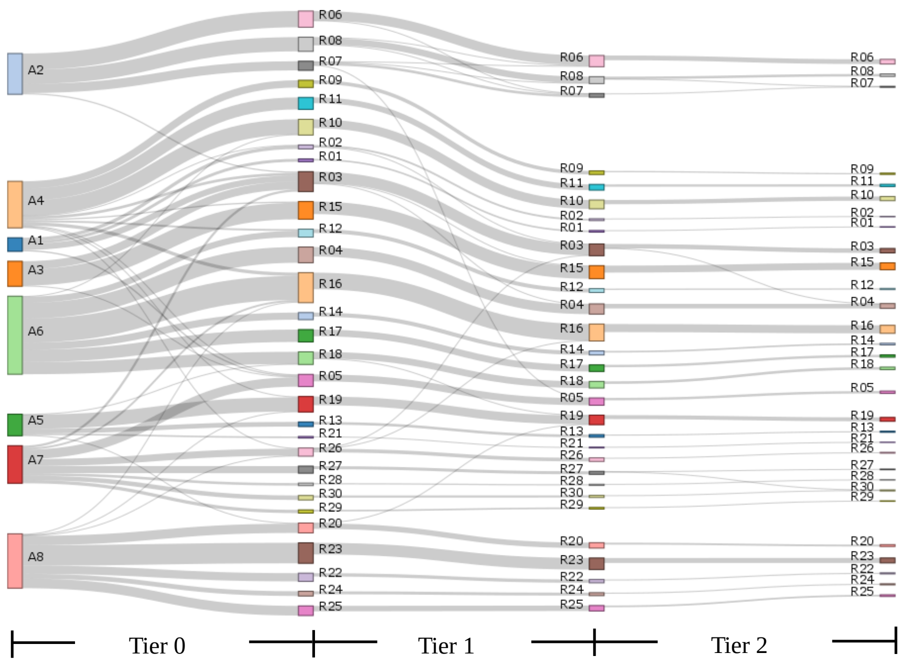


Figure 6.1 SPA of the construction industry by region

6.4 Sectoral Analysis

This section aggregates the regional information from the sector unit. The purpose of sectoral analysis is to diagram energy paths into sector categories of different upstream stages. The inter-sectoral transactions up to stage 3 are shown in Figure 6.2. The results show that the energy inputs from S13, S14, S5, S12, and S25 to the construction sector are significant in the first-stage production process. Such direct energy input has crossed into the breadth of the whole economy in the second stage where the number of paths increased dramatically. In the third stage, a number of hidden sectors that are normally ignored in the traditional analysis have been explored due to their significant contributions. S22—the basic power supply sector—has consistent but indirect impact on the construction sector. Extraction of petroleum and natural gas (S3) is the major raw material supplier for oil derivatives and coke products (S11), whilst these products in S11 are one of the basic energy sources for manufacturing metal and non-metallic products. These are used widely in construction.

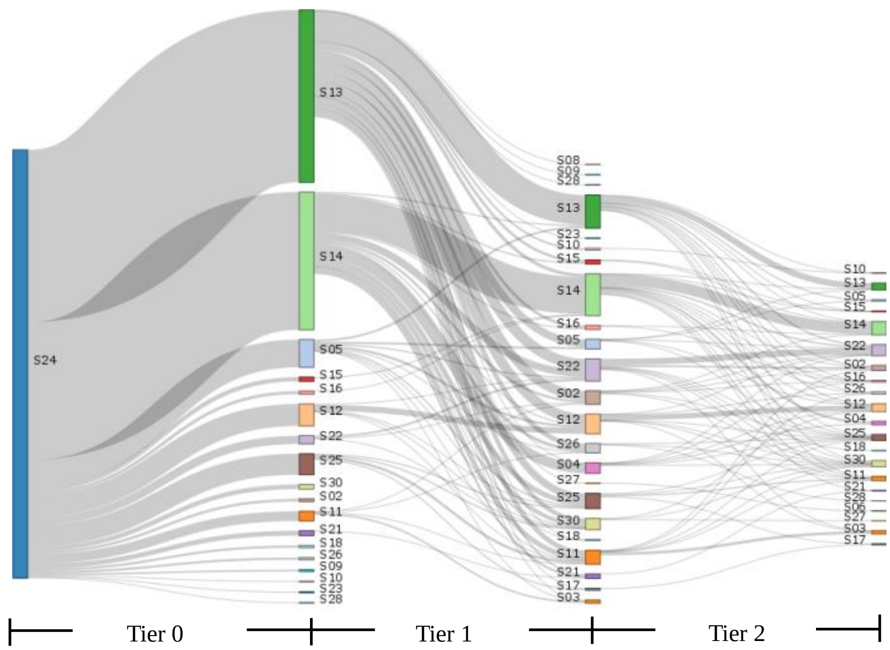


Figure 6.2 SPA of the construction industry by sector

6.5 Sensitivity Analysis

Treloar et al. (2001a) extracted 90% of total energy consumption in the first five upstream stages using a 113-sector format table. Peters and Hertwich (2006c) analyzed upstream structural contributions from the first eight stages of the supply chain by considering 97.8% of total emissions. In the present study, a threshold value of 0.005% of the embodied energy consumption of regional construction industries was used to filter nearly 80% of the overall impacts in the first five stages. Such empirical results provide a cutoff indicator for tracing back valuable information on upstream energy transfers in the context of China. However, the cutoff threshold and the upstream system boundary were subjectively predetermined. Therefore, the SPA result, to a large extent, depends on the nominated arbitrary threshold and the inspected upstream stages. These subjective choices are unavoidable during the computational process; thus, quantifying these uncertainties and their effects on the final results by conducting sensitivity analysis is vital.

6.5.1 Sensitivity of the number of paths

Many studies have summarized the appropriate number of paths to focus on the environmental bottlenecks in the supply chain (Peters and Hertwich, 2006c; Wood and Lenzen, 2009). This study provides a possible solution to the number of paths that can efficiently review upstream interactions. Figure 5 shows the changing trend of energy use embodied in each path according to their rankings. The change rate evidently decreased continuously with the increasing number of paths. On the basis of this trajectory, an optimized number of paths (X_0) can be identified to cut off paths with insignificant impact while retaining the most valuable information for the whole supply chain. The value of X_0 in this study is approximately 4500. Comparing this number with those provided in Table 1 implies that the optimized number suggested in Figure 5 is nearly equal to the number of paths in the first two stages (4081). This number accounts for 10.3% of the total number of paths while consuming nearly half of the total energy.

In addition, a comparative analysis between the present study and related research was also conducted. The results are presented in Table 4. The number of paths in the first two stages is different from those in previous research because the total number of paths in the upstream process has been determined directly by the scale of the I–O table. Moreover, although the computational system boundary and the number of paths in each stage vary among different studies, the percentage in the total number of paths and the relative proportion in total energy use are consistent. This finding implies that the paths in the first two stages or the path percentage of 10% can be regarded as the key cutoff points to simplify the calculation process and identify key paths with the largest potential for energy reduction.

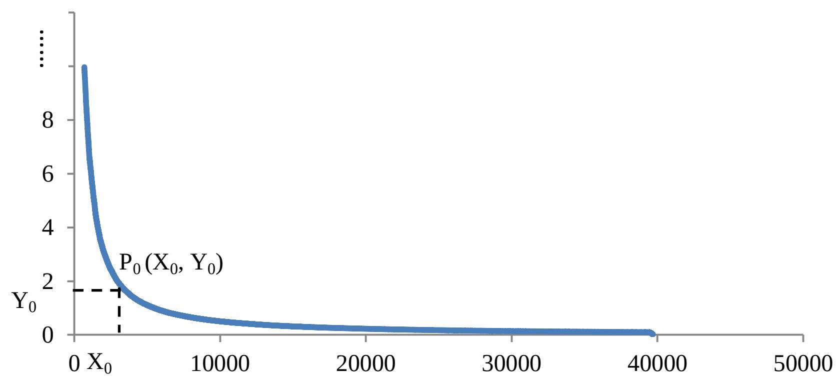


Figure 6.3 Relationship between the value of the paths and their path rankings.

Table 6.4 Results of comparative analysis

Reference	Number of paths in first two tiers	Percentage in total number of paths	Cumulative proportion	Scale of I-O table
Treloar (1997)	74	4.3%	40.9%	109
Treloar et al. (2001b)	65	10.9%	60.7%	113
Treloar et al. (2001a)	70	12.4%	55.4%	113
This study	4351	11.0%	46.0%	900

6.5.2 Sensitivity of threshold

As previously mentioned in the methodology section, the cutoff threshold for mapping upstream interactions in this study is 0.005% of the total energy consumption in the regional construction industry. To examine the sensitivity of the threshold, a series of values from 0.002% to 0.015% has been adopted. The percentage changes in the number of paths and the sum of the embodied energy use for each stage according to the different thresholds is shown in Figures 6.4 and 6.5. Clearly, the first two stages (e.g. stage 0 and stage 1) are unaffected by the change in the threshold. This relates primarily to the fact that paths representing the onsite and direct energy input to the construction sector are considerable. All of these are larger than the max threshold assumed in the sensitivity analysis. More importantly, the change in the threshold is more sensitive to the number of paths—this reduced almost 80% in the 0.015% scenario and increased more than 1.8 times in the 0.002% scenario. In contrast, it has smaller influences on the sum of the embodied energy use for each stage. This only leads to 60% changes in the final results. Close examination of figure 5 further revealed that the number of paths is more sensitive to the threshold reduction rather than increasing. This implies that a lower value of the threshold could lead to an explosion in the energy paths that may causes additional processing problems. In contrast, an appropriate and higher value of the threshold (0.005%-0.01%) could simplify the computational process by cutting insignificant paths and retaining the most valuable energy information.

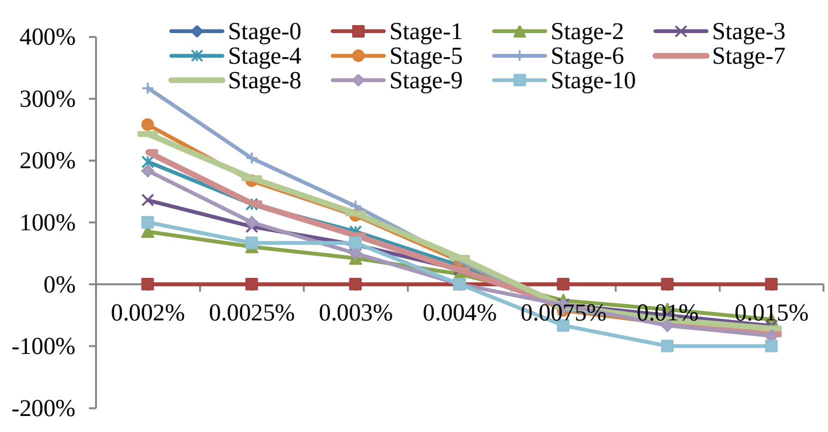


Figure 6.4 Percent changes in the number of paths according to different thresholds

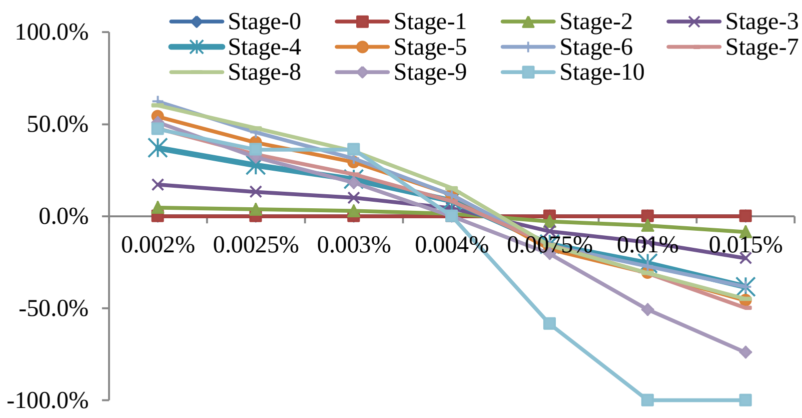


Figure 6.5 Percent changes in energy consumption according to different thresholds

6.5.3 Sensitivity of the number of stages

Figure 6.6 shows the change of cumulative energy consumption according to different thresholds by stages. The change in the cumulative energy consumption is less obvious in the higher order stages. In fact, comprehensively reviewing all the alternative thresholds shows that the cumulative energy consumption has increased dramatically in the first 5 tiers (e.g. stage 0, 1, 2, 3, and 4). However, the impact on total contributions becomes negligibly small in the higher order stages. Consequently, it is also effective to focus on these most sensitive stages rather than investigating all possible stages, which is both time intensive and unnecessary.

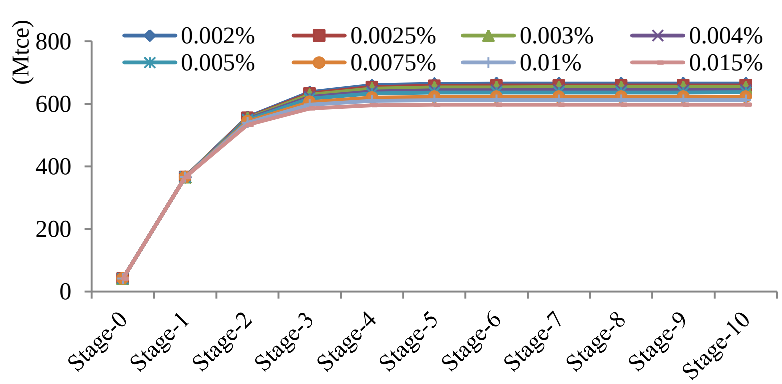


Figure 6.6 Change in the cumulative energy consumption by stage

6.6 Discussions

Energy paths with significant contributions have been identified and mapped in the entire supply chain of the construction sector. This basic attribute of SPA emphasizes the importance of the system boundary in presenting energy paths. Generally, the number of paths is mainly dependent on the actual objectives proposed before analysis. The excessive decomposition of the supply chain can derive infinite energy paths. Such manipulation may distract from the focus of the most important paths and increase the computation difficulties. To address this drawback, an appropriate cut-off rule for accurate estimation in SPA has been reported.

Investigating the energy paths in the first 5 stages or calculating 90% of the total energy consumption has been commonly used as the max value for narrowing the system boundary. In this study, energy paths in the first five stages provide 80% energy consumption information for upstream interconnections. However, such detailed investigations are still labor and time-intensive. In contrast, many other studies only focus on the top ranking paths (e.g. top 9, 10, 20, 25, 30, and 100) for further study (Minx et al., 2008; Peters and Hertwich, 2006c; Wood, 2008). This simplified process is time-saving and work-efficient especially in the small scale input-output analysis. However, it excludes regional specific characteristics during computation.

This study decomposes the supply chain within more specific regional data and extracts energy intensive paths from the regional and sectoral perspective. Thus, such excessively simplified manipulation may ignore a large number of paths that may be not highlighted in the whole economy but are critical for the regional energy reduction. Therefore, selecting an appropriate number of paths and stages for investigation is crucial for SPA at the regional level. Figures 6.3, 6.4, and 6.5 show that energy paths extracted in the first two tiers are important. These energy paths only account for 10% of the total energy paths but consume almost 50% of the total energy consumption. In addition, the paths in the first two tiers can also exclude the uncertainty from the threshold selection because they are basically unaffected by the subjective threshold proposed before analysis.

6.7 Summary of the Chapter

This Chapter conducted MRIO based SPA to map the energy flows in the entire supply chain of the construction industry. By considering both the regional-specific characteristics and technology differences, this study revealed the interconnections in the direct and indirect effects in the upstream process from the regional and sectoral perspective. The most energy-intensive paths in the total energy flow tree and 30 regions have been identified. In fact, the direct input from manufacturing of non-metallic mineral products (S13) and smelting and pressing of metals (S14) are the most important energy sinks in the regional construction industry. In addition, the regional analysis explored the self-sufficiency characteristic for energy resource consumption in the regional construction industry and sectoral analysis identified sectors hidden in the higher order of the supply chain for further investigation. Finally, a systematic analysis of the changes in the threshold and system boundary has been undertaken to balance the difficulty in computational process and loss of valuable information in SPA.

Chapter 7 Hybrid Framework for Assessing Embodied Energy Consumption of Construction Projects

7.1 Introduction

Although the embodied energy use of construction projects has been extensively studied in recent years, it still lacks assessment tools to predetermine the embodied energy consumption at the initial stage of construction projects. Moreover, the regional specificity is also rare considered during assessment process. Therefore, considering the huge quantity of resource and energy consumption as well as the difficulties in data collection during the embodied phase, this study establishes a simplified framework for assessing embodied energy consumption by seeking for the balance between result accuracy and data specificity.

Based on the database derived from MRIO analysis in Chapter 5 and computational structure decomposed in Chapter 6, this chapter aims to integrate the regional average data from macro perspective with the case-specific process data from micro perspective, where both the system completeness and project specificity have been incorporated consistently. This comprehensive framework is expected to not only allow a quick assessment of embodied energy consumption at the early stage of construction projects but also address difficulties in collecting specific process data during evaluation.

7.2 Overview of the Framework

Generally, previous studies in relation to embodied energy assessment of construction projects have focused on four topics: materials and components, building construction, civil engineering construction, and construction technology. According to the scope of the construction sector defined in multi-regional analysis and computational structure established by the proposed framework, this framework is applicable to assess the embodied energy consumption for building and civil engineering projects.

Traditionally, the hybrid technique is a combination of the process-based and input-output methods, which quantifies the energy consumption and environmental effect of a specific product based on process-based and I-O derived data; this model provides improvements in assessment accuracy and boundary completeness (Heijungs and Suh, 2002). However, the conventional hybrid method integrates the I-O derived data at the national level, which ignores regional disparities and technology differences. This may lead to the misinterpretation of energy use especially when the local production technology for the construction process being studied is very different from national average level. For instance, there is an imbalance in the economy and technology development between China's eastern coast and western interior. Consequently, the ignorance of such disparity may execrate the errors between the simulated value and actual consumption. Therefore, it is important to integrate regional characteristics and technology differences into the hybrid method.

This study thereby established a multi-regional hybrid framework to assess the embodied energy use for construction projects (See Figure 7.1). This improved hybrid framework comprises four layers from the view of bottom-up. First, external project information including the basic project profile and material inventory data were collected and provided at the first layer. The data source of this layer is the design drawings, project documents, and bill of quantities. Second, the integration layer is to integrate and apply the methodologies and database that foster the theoretical fundamentals of how the entire framework develops and functions. Three modules have been established and presented at this layer. The region-based sectoral energy intensity module (RBSEIM) has been calculated by MRIO analysis, which presents the level of energy efficiency of 900 sectors in 30 regions based on the regional average economic data. The process-based energy intensity module (PBEIM) is an energy intensity database for primary materials and major construction-related activities. It is derived from process-based calculation but adjusted by the coefficients reflecting the level of local technology development and production. The computational structure module (CSM) directly determines the system boundary and mathematical algorithm for computation. In general, the most energy-intensive paths in 30 regions have been identified by SPA with average regional economic data. These paths are further extracted and substituted by project-specific data derived from PBEIM. The third layer provides the outcome of the investigated project. It includes the results of regional and sectoral analysis for the embodied energy use as well as the recommendations for energy reduction strategies according to the optimization analysis in this layer. The last layer presents key users that can benefit from and apply this assessment framework. Project-related stakeholders (e.g. clients, contractors, project managers, suppliers, etc.) and policy makers could use this framework as a basic assessment and benchmark tool to inspect the embodied energy use of construction projects at the project and regional level.

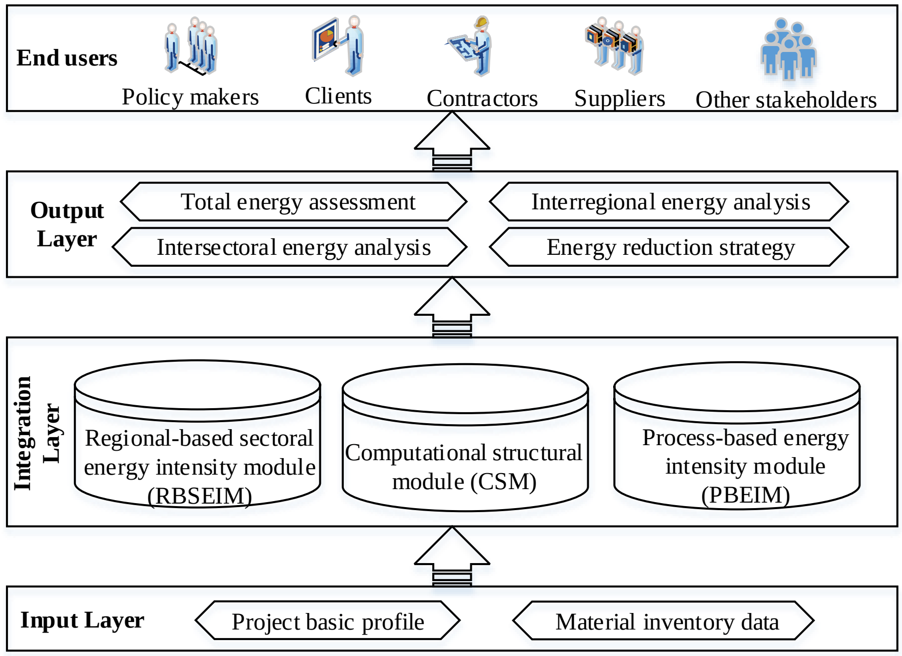


Figure 7.1 Multi-regional hybrid framework for assessing embodied energy of construction project

7.3 Input Layer

The input layer comprises the basic project profile and material inventory data. The function of this layer is to define the quantity of materials used and characteristics of the target construction project (See Table 7.1). The project profile describes the features of the investigated project, including the location, building type, gross floor area, and total cost. The material inventory data are mainly derived from the bill of quantities. As discussed in Chapter 6, there are six energy-intensive sectors identified as the primary energy suppliers for the construction process, namely manufacture of non-metallic mineral products (S13), smelting and pressing of metals (S14), mining and processing of nonmetal ores (S05), chemical industry (S12), transportation, storage, posts and telecommunications (S25), and production and distribution of electric power and heat power (S22). They directly and indirectly influence the energy consumption embodied in the project construction process. In fact, according to findings obtained in Chapter 4, these six sectors together account for approximately 80% of total energy use for the construction sector. Therefore, it is unnecessary to collect process-based data for all construction-related activities, especially at the early stage of the construction. More importantly, such simplification can not only alleviate the time intensity and difficulties in collecting process data but also retaining most of valuable information regarding embodied energy assessment.

The primary building materials and activities involved in these six energy-intensive sectors are listed in Table 7.2. In summary, totally 14 primary materials and 2 major construction-related activities are identified as the main contributors to the total embodied energy use for a certain construction project. Therefore, it is critically important to provide the quantity and cost information for these major contributors in the input layer. In addition, since the developed hybrid framework is constructed based on a multi-regional concern, the origin of primary materials can be utilized to provide valuable information not only on mapping the interregional energy transfers but also changing the view of the investigation from the consumption-based to the production-based. The transportation distance between the suppliers and the construction site can be obtained from Google Maps or the like.

Table 7.1 The basic information collected in the input layer

Part	Content	Information collected
Part I	Basic project profile	Location, construction period, building type, gross floor area, and total cost
Part II	Material inventory data	Bill of quantity, material origin

Table 7.2 Primary materials and consumption sources identified for the six key sectors

Sector	Construction items
Manufacture of non-metallic mineral products (S13)	Concrete, cement, glass, ceramic tiles, plaster, lime, brick
Smelting and pressing of metals (S14)	Steel, aluminum, copper
Mining and processing of nonmetal ores (S05)	Sand, gravel
Chemical industry (S12)	Insulation, paint
Transportation, storage, posts and telecommunications (S25)	Material transportation
Production and distribution of electric power and heat power (S22)	Onsite electricity use

7.4 Integration Layer

7.4.1 Region-Based Sectoral Energy Intensity Module (RBSEIM)

This module provides two categories of energy intensities for further calculation. The first database is the embodied energy intensity of 30 regional construction sectors. By multiplying the total cost of a specific construction project, it provides a possible solution for directly and roughly estimating the total embodied energy consumption for a certain project. However, it is expected to improve the accuracy of this sketchy estimation by integrating case-specific process data in other modules. The second database is the embodied energy intensity of 900 sectors calculated by MRIO analysis based on the regional average economic data. This group of energy intensity multipliers is used as the computational foundation for the multi-regional embodied energy assessment since it provides the sectoral energy information by holistically considering the regional specific characteristic and technology difference. These sectoral embodied energy intensities are then used as the multipliers to calculate the sectoral energy input to the target construction project when monetary flow data are available from the input-output table and project profile.

Because of the important role that these databases play in the proposed framework, this section examines the reliability of data obtained from MRIO analysis. Displayed in Figure 7.2 is the percentage between direct energy input collected from the statistical yearbooks and total embodied energy calculated by MRIO analysis for the construction sector in 30 regions. The share of the direct energy use in the 30 regional construction sectors ranges from 0.7% (Hainan) to 12.02% (Hebei). From the perspective of life cycle analysis, direct energy input for the project construction mainly involves onsite electricity use and fuel consumption by construction equipment, while indirect energy use is related to building materials production and transportation through the upstream process. The ratio estimated in this study by the MRIO model is in-line with the results estimated by the process-based approach in previous studies, where the ratio ranged from 1.77% to 11.49% (Chen et al., 2001; Kua and Wong, 2012; Scheuer et al., 2003; Wu et al., 2012). This further enhances the possible application of the MRIO model for energy assessment in the embodied phase of construction projects.

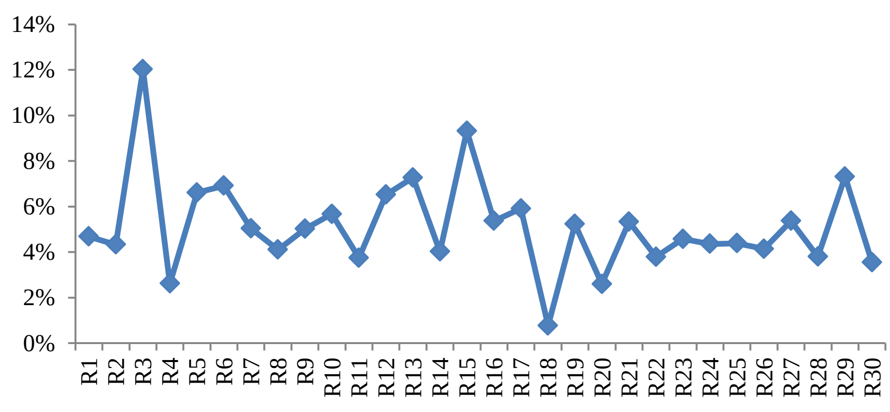


Figure 7.2 Regional percentage of direct energy input and embodied energy

7.4.2 Process-Based Energy Intensity Module (PBEIM)

7.4.2.1 Process-based energy intensity for construction materials

Given that the process-based embodied energy intensities are critically important for the next analysis and accuracy improvements in the proposed hybrid assessment framework, they have been extensively studied from different sources. Table 7.3 and 7.4 summarize the embodied energy intensity collected in context of China and other countries. It is worth noting that the embodied energy intensity for a certain type of material is basically consistent among different studies in China. In contrast, intensities found from studies conducted in Thailand, Australia, United States, and Europe fluctuate due to the changes of geographical location. The process-based data obtained in China are slightly higher than the data collected in other countries. This may have arisen from the fact that the manufacturing process of these materials in China is more energy-intensive. In summary, given the findings from previous research in and out of China, it is undeniable that intensities derived from different studies remain similar. The China Building Material Academy compiled the energy intensities for several typical building materials based on the statistical data collected from the building material management department and the National Bureau of Statistics of China. Sichuan University has also established the Chinese Life Cycle Database (CLCD) and developed eBalance LCA software in context of China. Thus, these two data sources can be regarded as the major reference in investigating building-material energy intensity in China. In addition, a detailed analysis further reveals that local production technology, particularly the specific production technique selected for the manufacturing process, also has a direct effect on the value of energy intensity. Therefore, given that the energy intensity of concrete increases with its strength, this study used 1.6 GJ/m^3 as the energy intensity of C30 concrete, which is the major type of concrete used in China (Shuai et al., 2009). The selected production technique and the type of cement produced influence the energy intensity of cement. A major type of cement, that is, ordinary Portland cement 42.5, which is produced through the pre-calcining process (PCP) with an energy intensity of 5.5 MJ/kg, was selected for this study (Gong, 2004). Similarly, rolled primary steel (the main type of steel used in the construction process), float glass that was 2 mm thick, and general purpose polystyrene (insulation) were identified as the primary materials used in the construction process with corresponding energy intensities of 29, 0.08, and 117 MJ/kg, respectively. The energy intensities for other materials were also determined using similar process as shown in Table 7.5.

Table 7.3 Process-based energy intensities collected from China

	Unit	Li et al. (2013)	Zhang et al. (2009)	Gu et al. (2006)	Gong (2004)	Zhao et al. (2004)	Zhong (2005)	Yang (2009)
Concrete	GJ/m^3	1.6				1.6	1.6	2.5
Cement	GJ/t	5.5	6.8	5.5	2.3–3.6	5.5	5.3	7.8
Steel	GJ/t	29-32.8	34.5	29	24.7–32.8	29	26.5	56.6
Glass	GJ/t	16	19.9	16	24	16	17.6	14.1
Aluminum	GJ/t	180		180		180	421.7	
Insulation	GJ/t			117		117		90.3
Ceramic tiles	GJ/t	15.4		15.4		15.4	29.4	
Brick	GJ/t	2	2.1			1.2–2.0	2	2
Plaster	GJ/t	3.8	2.6			6	3.8	2.9
Lime	GJ/t	5.3	5.7	7.8		0.1	5.3	6.2
Copper	GJ/t	71.6		70		71.6	71.6	
Paint	GJ/t			61.5		60.2	77.6	
Sand	GJ/t	0.6				0.6	0.6	
Gravel	GJ/t	0.2		0.2		0.2	0.9	

Table 7.4 Process-based energy intensities collected from other countries

	Unit	Huberman and Pearlmutter (2008)	González and Navarro (2006)	Scheuer et al. (2003)	Kofoworola and Gheewala (2009)		Asif et al. (2007)	Bribián et al. (2011)	Thormark (2001)
Concrete	GJ/m^3	1.15	1.2		1.3	1.0–1.6	1	1.1	1.6
Cement	GJ/t			3.7	3.6	5.8		4.2	

Steel	GJ/t	35	32	28	22.1	35		24.3	23
Glass	GJ/t	18	16	8	18	16	13	15.5	18.6
Aluminum	GJ/t	211	191	207	216.5	191–227	232	136.8	180
Insulation	GJ/t	116	117	94.4				103.8	120
Ceramic tiles	GJ/t		2.5	5.5	2.2		8.0	15.6	
Brick	GJ/t	1.08		2.7	1.9	1.0		2. 2–6.3	3.1
Plaster	GJ/t		6.1				5.0		6
Lime	GJ/t			0.1					
Copper	GJ/t			71.6				35.6	71.5
Paint	GJ/t			60.2	81.5				29.5
Sand	GJ/t			0.6	0.2				0.005
Gravel	GJ/t	0.79	2.5	0.2	0.1				0.005

Table 7.5 Process-based energy intensities used in this study

	Unit	Embodied energy intensity
Concrete	GJ/m^3	1.6
Cement	GJ/t	5.5
Steel	GJ/t	29
Glass	GJ/t	16
Aluminum	GJ/t	180
Insulation	GJ/t	117
Ceramic titles	GJ/t	15.4
Brick	GJ/t	2.0
Plaster	GJ/t	3.8
Lime	GJ/t	5.3
Copper	GJ/t	71.6
Paint	GJ/t	60.2
Sand	GJ/t	0.6
Gravel	GJ/t	0.2

7.4.2.2 Process-based energy intensity for electricity supply

For purchased electricity, studies on embodied energy analysis of its production process have been extensively undertaken in the past few years. In fact, the types of energy sources used to produce electricity as well as the system boundary have a direct impact on the value of embodied energy intensity. Table 7.6 summarizes the embodied energy intensity for electricity generation resulting from previous research. It can be found that the value of energy intensity is similar for a certain type of energy source in different geographic locations and system boundaries. A complete life cycle analysis of electricity production should include fuel extraction, facility construction and demolition, facility operation and maintenance, residual products from fuel, network construction, operation, demolition, and transmission losses. This study employed EU energy intensity data to calculate the embodied energy use from electricity production. Moreover, given the fact that the electricity supply is the result of mixed sources of power (coal, oil, gas, hydro, and nuclear) in China, the percentage distribution of energy sources for electricity generation in China shown in Table 7.7 is used as the weighting factor to calculate the weighted average energy intensity (Equation 1).

$$EE_{grid} = W_i \times EE_i \tag{1}$$

Where EE_{grid} is the weighted average energy intensity of electricity production from cradle to grave, W_i represents the proportion of energy source i used for electricity production, EE_i is the EU embodied energy intensity of electricity production by fossil fuel type i.

Therefore, the weighted embodied energy intensity for electricity production is 8.9025 MJ/KWh.

Table 7.6 Distribution of the amount of electricity among different generation method

Ref.	Region	Year	Scope	Sources	MJ/KWh
1	Hong Kong	2007	-	Average [a]	6.425
2	Australia	2003	Cradle to grave (Include facilities construction and demolition)	Coal	12.704
				Natural gas	5.771
3	Sweden	2005	Cradle to grave (Include facilities construction and demolition, network construction, operation, demolition, and transmission losses)	Average	0.068
				Coal	7.778
				Oil	6.200
				Hydro	0.056
				Nuclear	0.034
				Natural gas	4.622
				Wind	0.135
4	Thailand	2009	Cradle to grid	Thermal power	7.778
				Combined cycle power	6.087

5	Korea	1998	IPCC method (Include distribution loss)	Average	5.185
	Japan	1997	Japan method (Include distribution loss)	Average	4.283
	Europe	1994	CORINAIR method (Include distribution loss)	Average	4.960
6	Canada	2001	Cradle to grid (Include facilities construction)	Coal	11.836
				Oil	8.770
				Hydro	0.023
				Nuclear	0.169
				Natural gas	4.994
7	Europe		Cradle to grave	Coal	11.283
				Oil	9.469
				Hydro	0.045
				Nuclear	0.180
				Natural gas	5.287
				Wind	0.135

Reference: 1.EPD (2008); 2. May and Brennan (2003); 3. Vattenfall (2005); 4. Phumpradab et al. (2009); 5. Lee et al. (2004); 6. Gagnon et al. (2002); 7. EURELECTRIC (2011).

Table 7.7 Percentage distribution of energy sources for electricity generation in China

Country	Total Production of Electricity (Million KWh)	Electricity Generation from Coal (%)	Electricity Generation from Oil (%)	Electricity Generation from Gas (%)	Electricity Generation from Hydro (%)	Electricity Generation from Nuclear (%)
China	4208261	77.80	0.30	1.60	17.20	1.80

Source: China Energy Statistical Yearbook 2012

7.4.2.3 Process-based energy intensity for transportation

With regarding to the embodied energy intensity of transportation, the process data for different transportation tools found in previous research are listed in Table 7.8. The embodied energy intensities (ton-km) for different types of lorries were obtained from the Ecoinvent v2.0 software, while the intensity data for road and rail transportation were sourced from Zhong (2005) and Yang (2009). Although the type of transportation tool employed and the loading weight can be used to easily determine energy intensity, the identification of suppliers is to large extent dependent on the procurement system. Consequently, the pre-estimation of transportation methods before construction is difficult. Therefore, this study used the average value as being representative of the embodied energy intensity for transportation.

Table 7.8 Transportation energy intensity for different types of lorries

Source	Load	Energy intensity (MJ/tkm)
Ecoinvent v2.0	Lorry 3.5-7.5t	7.44
	Lorry 7.5-16t	3.29
	Lorry 16-32t	1.89
	Lorry >32t	1.32
Zhong (2005)	Road transportation (gasoline)	3.04
	Road transportation (Diesel oil)	2.06
	Rail transportation	3.05
Yang (2009)	Road transportation	5.45
	Rail transportation	2.09

7.4.3 Computational Structure Module (CSM)

The computational structure module aims to build the mathematical foundation by integrating the case-specific process data into the multi-regional analysis framework. Given the fact that the I-O derived value of primary materials are mutually exclusive in the I-O model, it is therefore possible to substitute the process-based inventory data for I-O derived value because the substitution at the path level may not result in the unwanted iterated effect on the rest of the I-O model by running I-O analysis (Treloar et al., 2001). The basic purpose of the algorithm used in the framework is to subtract the I-O derived value by the case-specific process data from the initial total energy consumption. Consequently, to avoid double counting, the I-O derived value aiming to be recalculated by the process analysis should be subtracted from the initial total energy consumption. Then the reminder of I-O model represents only the part being insignificant in the complete LCA analysis and is thereby appropriate to add to the case-specific process data. This manipulation could improve the accuracy of the whole assessment system. The integration process is shown in Figure 7.3.

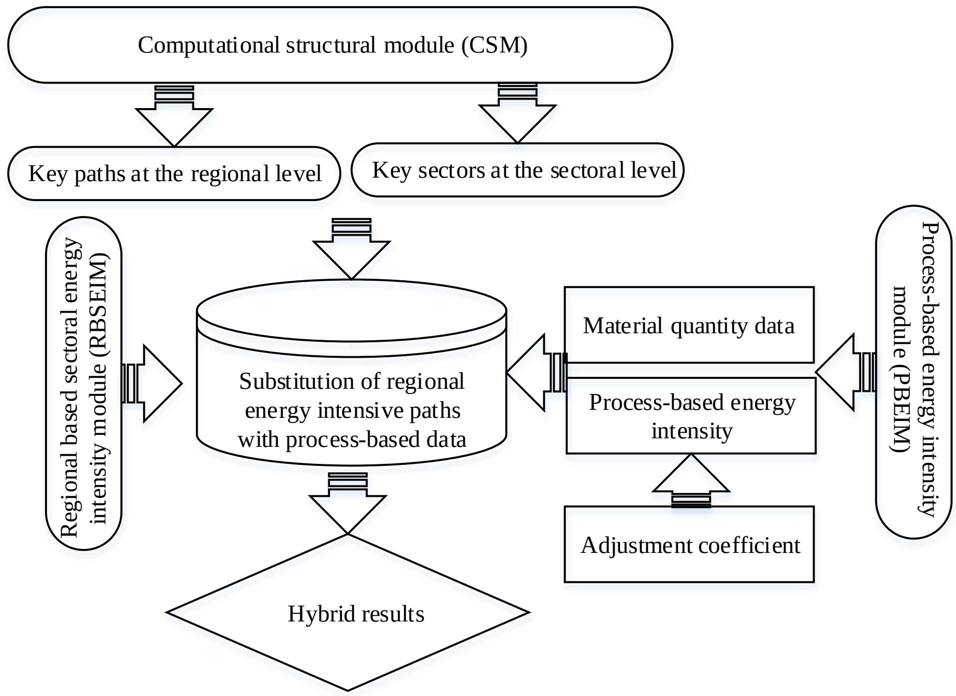


Figure 7.3 Integration process among CSM, RBSEIM, and PBEIM

It can be observed that the accuracy of final result is capable to be improved by two categories of process data. One is the process-based embodied energy intensity for critical materials identified in Table 7.2. The other one is the process-based quantity data for a certain project. The final result calculated by integrating these case-specific characteristics may be more accurate than the result obtained based on regional average data. Table 7.9 shows the types of data used for critical construction activities in the multi-regional based hybrid framework.

Table 7.9 Types of data used for critical construction items

Construction items	Energy intensity	Quantity
Primary materials production	Process data	Bill of quantity
Material transportation	Process data	Regional average data
Onsite electricity use	Process data	Regional average data

Although both the process-based energy intensity and quantity data for primary building materials are available from relevant literature and the bill of quantities for the target project, it is difficult to know the transportation distance from offsite factory to the construction site since the procurement may not be carried out at the early stage of construction. Similarly, the onsite electricity use is also unpredictable because the amount of consumptions to a large extent depends on the occupants (e.g. clients and contractors) behaviors on the construction site. Therefore, for these construction activities that could not be measured before project construction, regional average data provided by MRIO analysis were used as the alternatives for quantity estimation.

7.4.4 Data Consolidation

7.4.4.1 Adjustment of process-based energy intensity data

Although process-based embodied energy intensity is obtained from the step-by-step energy aggregation and detailed analysis of resource input during manufacturing process, it still lacks consideration of regional energy efficiency and productivity. This origin difference for a certain type of material may vary the embodied energy consumption. Therefore, this study transforms the process-based data from national average level into regional level by multiplying adjustment coefficients. The adjustment coefficient is designed to reflect the level of local economy development and energy productivity, which can provide a solution to adjust energy data by considering regional characteristics and technology differences.

Therefore, the adjustment coefficient can be defined as:

$$\lambda_i^r e_i^p = e_i^r$$

Where e_i^p is the process-based embodied energy intensity of material i, λ_i^r is the adjustment coefficient for material i in region r, e_i^r is the adjusted embodied energy intensity for material i in region r.

On the other hand, it is assumed that the average of adjusted embodied energy intensities of material i in 30 regions is equal to process-based data e_i^p:

$$\frac{\sum_{r=1}^{30} e_i^r}{30} = e_i^p$$

Given that the sectoral energy intensities calculated by MRIO analysis reflect the regional disparities and technology differences, they could be regarded as the representative to reflect the level of local production and technology. Therefore, we can establish the relationship between MRIO derived energy intensity and the adjustment coefficient:

$$\frac{\lambda_i^{r+1}}{\lambda_i^r} = \frac{e_{i,i-o}^{r+1}}{e_{i,i-O}^r} \quad (r = 1, 2, 3, ..., 29)$$

Consequently, the adjustment coefficients for six energy-intensive sectors in 30 regions can be calculated as shown in Table 7.10

Table 7.10 Adjustment coefficients for 6 key sectors in 30 regions

	S5	S12	S13	S14	S22	S25
R1	1.33	0.38	0.61	0.69	0.55	0.82
R2	1.14	0.67	1.26	0.50	0.87	0.71
R3	0.50	1.13	0.64	0.63	1.05	0.97
R4	0.75	2.06	0.87	1.07	1.08	0.92
R5	0.41	2.53	0.79	1.04	0.96	1.18
R6	0.63	0.94	0.80	0.76	0.99	1.07
R7	0.70	0.73	1.08	1.68	1.49	1.15

R8	0.73	1.28	1.87	2.87	0.83	1.14
R9	0.59	0.42	0.76	0.50	0.82	0.51
R10	0.59	0.47	0.63	0.45	0.59	0.85
R11	0.31	0.40	0.53	0.73	0.56	0.82
R12	0.43	0.79	0.71	0.65	0.70	0.85
R13	0.28	0.54	0.41	0.95	0.69	0.66
R14	0.39	0.53	0.58	0.53	0.80	0.71
R15	0.26	0.64	0.47	0.59	1.69	0.98
R16	5.93	0.95	0.88	0.42	0.37	1.05
R17	0.52	1.05	0.73	1.17	1.00	1.06
R18	0.75	1.13	1.37	0.62	2.84	0.38
R19	0.32	0.33	0.64	0.52	0.65	0.86
R20	0.22	0.72	1.03	0.71	0.44	1.02
R21	0.61	0.68	0.90	3.05	0.62	0.37
R22	0.88	1.17	0.93	0.98	1.19	1.19
R23	0.58	1.04	0.94	1.00	1.00	1.23
R24	0.67	1.48	1.46	1.44	1.56	1.29
R25	0.95	1.63	1.90	0.75	0.81	1.53
R26	1.25	1.11	1.37	1.01	0.88	0.96
R27	0.55	1.69	1.18	0.59	0.94	1.21
R28	1.57	0.81	1.00	1.61	1.80	1.12
R29	5.54	1.58	2.01	1.55	1.01	2.12
R30	0.63	1.14	1.65	0.94	1.21	1.29

It is worth noting that the adjustment coefficients in the northern and western parts of China are higher than the other areas, which further implies the imbalanced development of economy and productivity in different areas of China.

7.4.4.2 Price consolidation

The process-based embodied energy intensity has been measured in million Joule base on the weight unit whereas the hybrid framework requires presenting the energy intensity in the unit of tonnes of coal equivalent in the monetary flow. Therefore, it is necessary to keep the unit consistent during the integration process.

First, the coefficient 29.3076 MJ/kgce has been used to transfer the tonnes of coal equivalent into million Joule. Second, the construction process involves a wide range of materials where the price may vary even for the same type of material because of the differences in manufacturing technology and origin. Therefore, average prices were implemented for a certain material when there were too many detailed categories under the same type of material.

To further reflect the regional disparities in materials price, the detailed information were collected from the construction cost network of 30 regions and other related websites. Unfortunately, detailed price data were still unavailable for a number of regions. Figure 7.4 shows the construction cost per square meter in different regions of China. It can be found that the unit price of building construction is almost stable with the range from 800 Yuan/m^2 to 1200 Yuan/m^2, which implies that as the largest contributor of building unit price the cost of building materials is similar among different regions. This was further enhanced by the comparisons of materials prices among 10 typical regions in 8 geographical areas in China (see Table 7.11). It can be observed that the prices for primary construction materials such as concrete, cement, and steel are consistent in those regions. Because the classification of 8 areas is based on the geographic linkage, the level of economy development and production technology for the regions located in the same area is similar. Therefore, this study estimated the cost of 14 materials in price-unknown regions based on the assumption that the price of materials in the same area is the same. This assumption could balance the requirement for considering regional differences and the limitation of data availability.

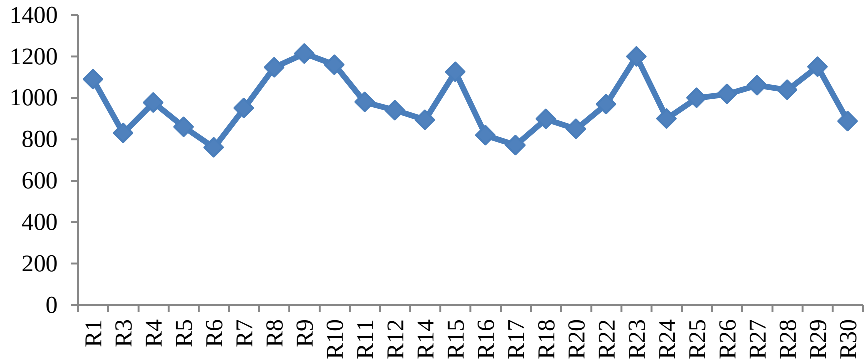


Figure 7.4 Construction cost in different regions of China

Source: the construction cost network of 30 regions

In addition, the price information collected for 30 regions is a comprehensive price which contains the retailer's profit and other additional expenses such as the transportation fee. In contrast, the inter-sectoral purchase of products in the multi-regional input-output table is measured based on basic cost (e.g. the direct purchase price). Therefore, the data assumption used in the study by Chang et al. (2014) that the basic cost of materials was equal to be 90% of the comprehensive prices has been adopted to address such inconsistency. The regional electricity price refers to the two largest electricity supply enterprises in China, namely State Grid Corporation of China and China Southern Power Grid. The information on transportation fee was collected from China price information network. The closest year was collected as the alternative in case the cost information for the year 2007 was unavailable. Finally, to keep the price constant for the year 2007 the price index was introduced to adjust all the basic cost of materials, electricity supply, and transportation fees into 2007 level.

Table 7.11 Materials prices of 10 typical regions in 8 geographical areas

		A1	A4	A2		A4		A6	A5	A8	A7
		R1	R3	R6	R7	R9	R10	R18	R19	R20	R27
Concrete	Yuan/m3	350	360	349	390	385	390	367	417	380	400
Cement	Yuan/t	390	390	351	420	420	365	342	460	375	385

Steel	Yuan/t	3500	3900	2500	2750	3922	3150	2555	2980	3900	3700
Glass	Yuan/m2	27	23	35	28	31	31		27	25	
Aluminum	Yuan/t	24000	24000	19000	18600				24000	25000	24800
Insulation	Yuan/t		26000	17500	18000				18500		
Ceramic tiles	Yuan/m2						27			22	
Brick	Yuan/piece	0.8	0.45	0.4	0.48	0.52	0.58	0.54		0.5	0.54
Plaster	Yuan/m2		11			13	13			26	27
Lime	Yuan/t		280	230	214	351	334	360		420	
Copper	Yuan/t	57150				68500			59000		59000
Paint	Yuan/t	24000		12300		13000	14450			24000	11250
Sand	Yuan/t	51	26	56	64	78	78	68	90	81	55
Gravel	Yuan/t	59	58	53	59	65	87	69	87	59	60

Source: the construction cost network of 30 regions

7.5 Output Layer and Users Layer

The output layer reports the energy assessment results at the project level. It first provides insights into the regional and sectoral analysis of the total embodied energy consumption for the investigated project. Then a breakdown of total energy use in terms of primary building materials is presented. Finally, based on the existing analyses results, this layer provides effective energy reduction strategies by optimizing the origin of materials. The end users including clients, contractors, project managers, and other project-related stakeholders could benefit from the reports provided by the developed hybrid framework. It will help end users comprehensively understand the overall energy use of the target project in advance, which could incentivize industry practitioners to take sustainability issues into consideration, facilitate the implementation of green building standards, and promote the development of cleaner production in China’s construction industry.

7.6 Summary of the Chapter

This chapter proposed the multi-regional hybrid framework for assessing embodied energy consumption of construction projects. The framework comprised four layers. The input layer contained the basic profile and material inventory data of the target project.

The integration layer was constructed based on three modules: RBSEIM, PBEIM, and CSM. The RBSEIM was the database of regional-based sectoral energy intensities derived from MRIO analysis; PBEIM is the database of process-based energy intensities for critical construction activities; and CSM built the computational structure which serve as the theoretical foundation for the framework operation. All the collected process-based data have been further modified to reflect regional disparities and technology differences by multiplying the adjustment coefficients. The energy assessment reports derived from the developed framework could provide an overview of the total energy consumption at the regional and sectoral level as well as effective energy reduction strategies for the target construction project.

Chapter 8 Framework Validation

8.1 Introduction

This chapter applies the proposed multi-regional embodied energy assessment framework to verify its reliability and feasibility in real construction projects. The validation process contains two steps: comparative analyses with previous studies and empirical analyses in real cases. They are separately organized according to different objectives. First, by applying this framework into building cases studied by previous research, a comparative analysis was conducted to verify the reliability of the developed framework. Empirical analyses were also designed to examine the feasibility of developed framework for different types of buildings in different regions. More importantly, the advantages such as providing regional and sectoral insight into embodied energy consumption as well as energy saving strategies of the proposed framework were also presented in this section.

8.2 Comparative Study

8.2.1 Profile of Building Cases

A literature review was first conducted to collect information of typical construction projects in China. According to the availability and completeness of inventory data, a total of six construction projects have been collected as the sample cases for the next comparison. Table 8.1 shows the basic information of the six chosen construction projects, including the location, building type, structure, gross floor area, and original method used to assess the embodied energy consumption in each case. It can be seen that the basic building profile is different for all six cases. These differences could further benefit validation of the developed framework.

Table 8.1 Basic profile of different construction projects

Case	Location	Building type	Structure	Gross floor area (m2)	Method	Source
1	Hebei	Office	Frame-shear wall	49166	Hybrid LCA	Chang et al. (2012)
2	Jiangsu	Office	Brick-concrete	1460	Process-based	Li et al. (2013)
3	Beijing	Office	Reinforce-concrete frame	35685	BEPAS	Zhang et al. (2006)
4	Beijing	Residential	Frame-shear	7000	Process-based	Gu et al. (2006)
5	Beijing	Residential	Brick-concrete	5050	Process-based	Zhong (2005)
6	Beijing	Residential	Reinforce-concrete frame	26717	Process-based	Zhong (2005)

According to Table 8.1, Office buildings and residential buildings were focus of concern in this study. The total floor area of office buildings completed in China increased from 69.3 million m^2 in 2000 to 206.4 million m^2 in 2011, representing an annual increase rate of 10.4% over the past 12 years (NBSC, 2012). The completed gross floor area of residential buildings in 2011 accounted for 63.4% of all completed building floor area, and is responsible for more than 60% of the economic output of the construction industry (NBSC, 2012). Such high growth rates have had a significant effect on the amount of energy use during the building construction process. Therefore, it is critically important to pre-estimate the energy consumption of these two types of buildings and provide specific energy reduction strategies in advance.

However, since most of material suppliers' information was not made available in previous studies, it is difficult to find out the origin of materials. Such ignorance may lead to the invisibility of energy interactions through the supply chain for a certain project. Therefore, this section assumes that all the materials used in each case were supplied through the local procurement system.

8.2.2 Results of Analysis

The total embodied energy consumption of the six chosen projects was recalculated by referring to the specific construction process of each project. This study conducted comparative analysis from the following two aspects:

(1) The comparison between the results obtained from the hybrid framework and pure MRIO analysis;

(2) The comparison between the results obtained from the hybrid framework and original method used in each study;

According to Table 8.2, the value calculated from hybrid framework is much higher than the pure multi-regional input-output mode. The overall relative changes between these two methods range from 50.4% to 60.5%. Chang et al. (2012) and Crawford (2008) conducted similar comparisons, and found that the relative change between hybrid model and I-O model is 5% and 18-56%, respectively. The results from this study are higher than the values in Chang et al. (2012) but in-line with the findings by Crawford (2008). In fact, the scale of the input-output table used in each study is very different. The sectoral classification in the studies by Chang et al. (2012) and Crawford (2008) is 135 and 106 sectors respectively whereas this study investigated the Chinese economy by using 900-sector format input-output table. The variation of sector scale has a direct impact on the final results. Furthermore, the relative changes of energy use embodied in electricity supply and transportation are smaller than the material production due to the fact that the only process-based energy intensity data have been collected and used during the computational process while the quantity estimation is based on regional average data provided by MRIO table.

Table 8.2 Comparison between input-output analysis and hybrid framework

		Multi I-O (GJ/m2)	Multi hybrid(GJ/m2)	Gap (%)
Case 1	Total	5.20	10.50	50.5%
	Material	2.52	7.47	66.3%
	Electricity	0.11	0.33	65.5%
	Transport	0.18	0.32	42.2%
Case 2	Total	1.05	2.23	52.9%
	Material	0.48	1.63	70.5%
	Electricity	0.01	0.04	64.9%
	Transport	0.01	0.01	42.2%
Case 3	Total	1.60	4.05	60.5%
	Material	0.22	2.60	91.6%
	Electricity	0.01	0.02	67.5%
	Transport	0.07	0.12	42.2%
Case 4	Total	1.93	3.88	50.4%
	Material	0.26	2.14	87.7%
	Electricity	0.01	0.02	67.5%
	Transport	0.08	0.14	42.2%
Case 5	Total	1.68	3.60	53.3%
	Material	0.24	2.14	89.0%
	Electricity	0.01	0.02	67.5%
	Transport	0.07	0.12	42.2%
Case 6	Total	2.01	4.80	58.1%
	Material	0.28	3.07	90.8%
	Electricity	0.01	0.02	67.5%
	Transport	0.08	0.14	42.2%

The result of the comparative analysis between previous research and this study for the embodied energy consumption is shown in Figure 8.1. It can be seen that the energy use embodied in materials production is dominant. Although gaps still exist in the values of the energy consumption calculated by the traditional method and improved hybrid model, they are still in the same order of magnitude. In addition, the infinite interrelationship between the construction sector and other sectors in the upstream supply chain leads to inter-sectoral input spreads in the whole economy. An obvious advantage for integrating input-output analysis in the proposed framework is to take such infinite interactions into consideration. It can be seen in Figure 8.1 that the energy use consumed by the category of other sectors accounts for a significant proportion. This category of energy consumption includes the energy use embodied in the materials with lower energy intensity or smaller quantity as well as the energy input from a number of service sectors, such as real estate and financial services that are highly related to the building construction process. In fact, such energy consumption is commonly ignored or excluded by process-based studies because of their relatively insignificant contribution and cut-off rules for simplifying the system boundary.

In addition, the results obtained from the multi-regional hybrid framework reflect the effect of changes in geographical location, building type, and structure on the total embodied energy consumption. As shown in Figure 8.1, with the same building type and structure, the construction energy intensity for the office building in Hebei (Case 1) is higher than the other construction projects located in developed regions such as Beijing (Case 3) and Jiangsu (Case 2). In addition, based on the same geographical location and building type, the frame-shear or concrete frame structure is more energy intensive than the brick-concrete structure. This is understandable since the former two types of structures are more cement and steel-intensive.

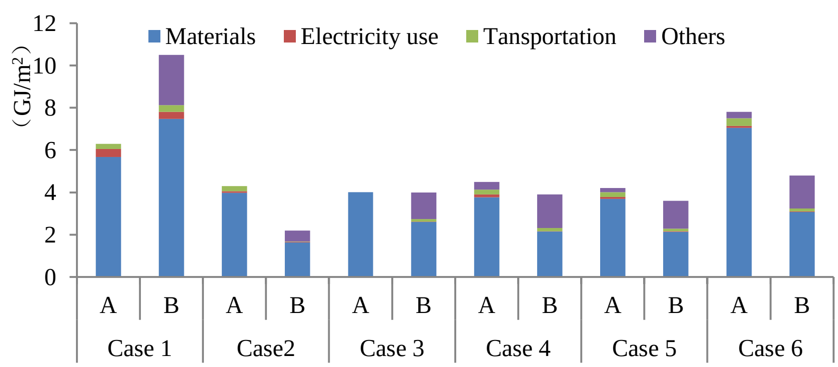


Figure 8.1 Comparison of embodied energy consumption between previous research and this study

Figure 8.2 shows the percentage changes of embodied energy consumption regarding materials production, electricity use, and transportation for the six chosen cases. Since the building projects in cases 4, 5, and 6 are all located in Beijing and analyzed by the same assessment model in their original research (process-based model), they can be investigated together. In summary, the embodied energy consumption calculated by the hybrid framework is smaller than the result calculated by the process-based model in the original study. This might be caused by several reasons: first, because both process-based quantity and energy intensity data are used in the original studies for estimating the energy use embodied in the materials production, transportation, and onsite electricity use, which may enlarge the value of total embodied energy consumption. Second, the embodied impact from original research was represented by the national average level, whereas this study took regional-specific characteristics into consideration. The process-based embodied energy intensity data have been corrected by multiplying adjustment coefficients, which are designed to reflect the level of local economy development and production technology. Beijing is the capital of China and a major world metropolis where the level of manufacturing efficiency and energy productivity should be higher than the national average level. Such regional advantage has also been reflected in the adjustment coefficients of six chosen sectors in Beijing, where most of them are smaller than 1, except sector 5 (Table 7.11). In contrast, if we assume that materials used in these three cases are all imported from the neighboring-Hebei province where the products are more energy-intensive with lower productivity, the results calculated by the hybrid framework are 4.4, 4.5, and 5.1 GJ/m^2, which are highly consistent with results of 4.5, 4.3, and 7.8 GJ/m^2 in the original study. In fact, the resource and energy consumed in the construction projects in Beijing are mainly from Hebei. According to Chapter 6 section 6.3, Beijing faces many challenges and pressures for local resources due to its rapid urbanization and growth. Therefore, Beijing is a typical energy receiver in the interregional energy transactions, which has to import resources from an energy-rich adjacent region (Liu et al., 2012a; Zhang et al., 2013). Similarly, in case 2, Jiangsu is much more energy efficient and technology advanced (see Table 7.11). Consequently, a comparatively large difference exists between the result obtained in the hybrid model and the process-based model. Moreover, it is also worth noting that the energy use embodied in the electricity apply has changed most, followed by transportation and materials production. In contrast, the change in total energy consumption is less obvious. Such trends can be explained by the fact that because the process-based quantity data for transportation and electricity use is difficult to estimate at the early stage of construction, the regional average data from the multi-regional input-output table have been implemented. This manipulation results in the loss of accuracy, which may lead to underestimate the embodied energy consumption when compared with the results calculated by the process-based model.

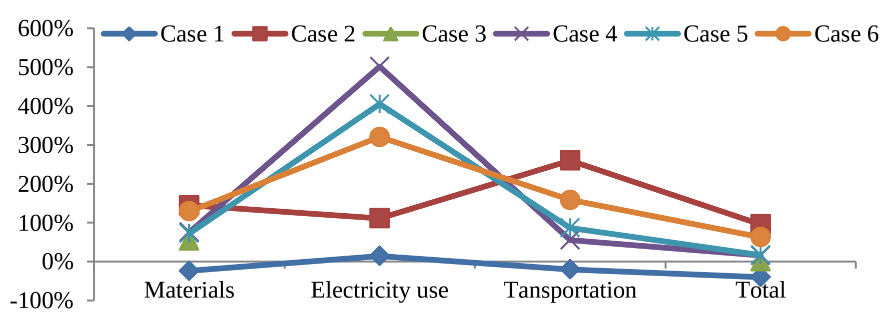


Figure 8.2 Relative changes of embodied energy use for different construction items

8.3 Empirical Study

8.3.1 Profile of Selected Buildings

After validating the improved hybrid framework by conducting comparative analysis with previous research, this section applies the framework to construction practice, with the aim of verifying the effectiveness of default functions in the hybrid framework for the real building projects. The basic building profile and inventory data are listed in Table 8.3. It can be seen that two projects are located in Guangdong province where the economy and production technology are well developed. The other one is in the Southwest of China-Sichuan province, where the economy is comparatively backward. The inventory data for primary construction materials of the target project have been collected by referring to project-related documents including the bill of quantities, accounting receipts, stakeholder's reports, and secondary data from the procurement agency. This study applies the hybrid framework to commercial, residential, and office buildings which covers a broad range of building structure and gross floor area. These differences are expected to reflect the effects of building diversity on the total embodied energy consumption.

Table 8.3 Building basic profile and project inventory data

	Project 1	Project 2	Project 3
Location	Guangdong	Sichuan	Guangdong
Building type	Residential + commercial	Residential	Office
Structure	Reinforced concrete frame	Frame-shear	Reinforced concrete frame
Gross floor area (m2)	11508	6890	20105
Sand (t)	124.86	801.93	216.25
Gravel (t)	4863.76		
Insulation (t)	158.27		
Paint (t)	1.13	24878.88	1.8
Concrete (m3)	4443.45	1739.55	16736.95
Cement (t)	11536.5	612.32	120.13
Glass (t)	86.03	4.29	189.44
Ceramic product (t)	14.65	10.2	

Plaster (t)	0.06		
Lime (t)	6.76		
Brick (t)	14.38	64.11	1730.4
Steel (t)	823.13	331.81	1375
Aluminum (t)	244.22	48.59	86
Copper (t)	0.3	1.2	0.5

8.3.2 Results of Analysis

8.3.2.1 Overview of the total embodied energy consumption

Table 8.4 Comparison of different assessment methods

	Project 1	Project 2	Project 3
I-O based	3.18	3.89	1.96
Process-based	5.13	4.34	2.65
Multi-regional hybrid	6.31	6.18	3.37

Table 8.5 Total embodied energy consumption of three projects (GJ/m^2)

	Project 1	Project 2	Project 3
Material	4.13	4.03	2.03
Electricity	0.75	0.13	0.66
Transport	0.25	0.18	0.16
Hybrid	6.31	6.18	3.57

Table 8.4 shows the results obtained from three embodied energy assessment methods. It is worth noting the results of process-based calculation were higher than that in the I-O analysis due to the advantage on considering process-based specific data. On the other hand, multi-regional hybrid integrates the case-specific inventory data into the complete system boundary, resulting in the increase in the energy intensity.

It can be found in Table 8.5 that despite project 1 and 3 being in the same region, the embodied energy intensity is very different. Upon close examination of these two cases it can be found that project 1 is characterized by its steel-intensive structure due to the area of commercial construction, where the weight of steel accounts for almost 20% of total materials. In contrast, the steel use of the office building in project 3 is only responsible for 6.7% of the total weight. In addition, project 3 has been awarded a three-star green building in China meaning that it has been constructed with a number of environmental friendly features. First, the investigated building in project 3 was encouraged to use materials with low energy intensity wherever possible. For instance, according to the interview, the client selected glass curtain walls instead of aluminum curtain walls to reduce energy use embodied in the building envelop. Second, recycled materials have been also widely used to save energy consumption where the ratio between recycle and total materials is 8.1% in this project. Finally, this project is to a large extent dependent on localized material suppliers. In fact, the weight of materials procured in the scope of 500km accounts for almost 98% of total materials which effectively reduces energy consumption embodied in the transportation process.

The residential building in Sichuan is more energy-intensive, which consumes almost the same energy as the complex building in project 1. This might be caused by the fact that the level of manufacturing productivity and energy efficiency are comparatively low in Sichuan when compared with the national average level. Furthermore, because Sichuan contains plentiful hydroelectric resources, the energy intensity for electricity production is almost carbon-clean and less energy-intensive especially when compared with projects in coal power dominant regions (e.g. project 1 and 3).

8.3.2.2 Interregional analysis

The hybrid framework also provides insight into interregional energy transfers for a specific construction project. This could help clients, project managers, and other project-related stakeholders better understand the energy interactions among different regions.

Especially by specifying the origin of building materials in the developed framework, it could alleviate the environmental pressure at the regional level by reallocating suppliers at different regions. Figure 8.3 shows the result of interregional analysis for three projects. It can be seen that local energy supply is dominant in project construction, accounting for more than 80% of total energy consumption. In addition, the geographic connection is another factor influencing energy transmissions. Hunan and Guangxi, as the most geographically closely neighbors, are the other two major energy exporters for construction projects in Guangdong because of the convenience in materials transportation. Similarly, Henan and Shaanxi are the other two significant contributors to the embodied energy use of construction projects in Sichuan.

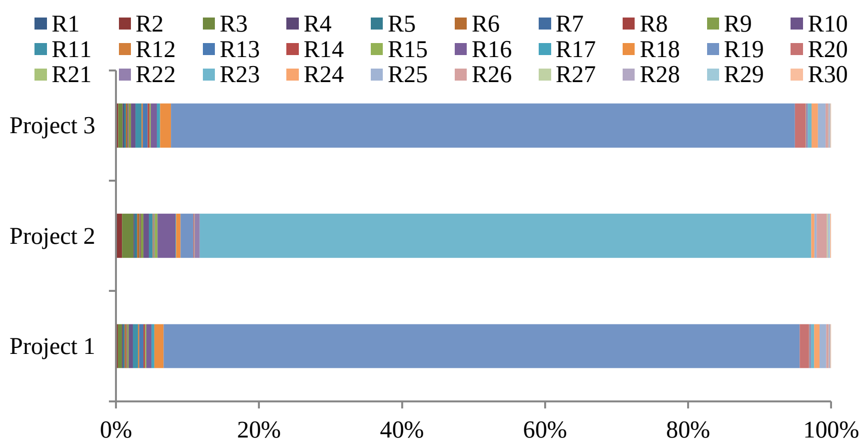


Figure 8.3 Interregional analyses for three projects

8.3.2.3 Sectoral analysis

By integrating the process-based data of material production, electricity use, and transportation, the sectoral energy input for three projects is shown in Figure 8.4. In addition to traditional energy-intensive sectors such as sector 12, 13, and 14, it can be found that energy use embodied in electricity supply and transportation also plays an important role during the embodied phase. In order to further explore the contribution from specific building material rather than strictly following the sector classification of the multi-regional input-output table, the hybrid framework also provides in-depth energy analysis of primary building materials (see Figure 8.5).

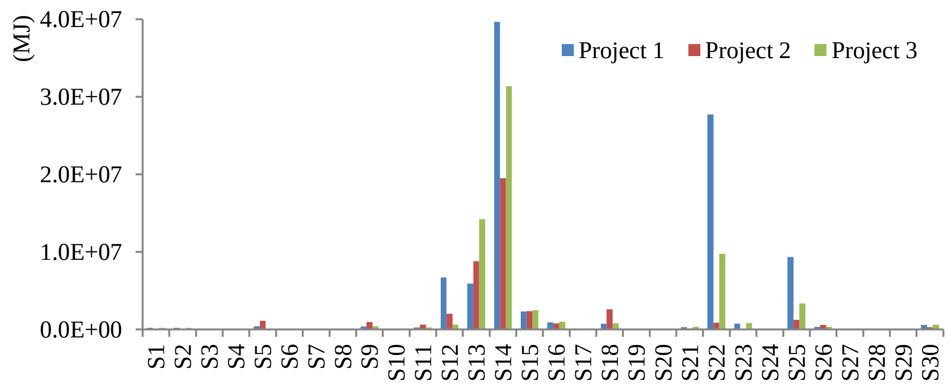
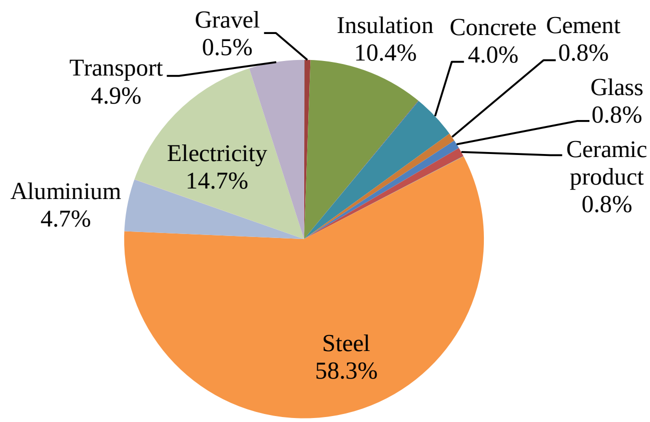
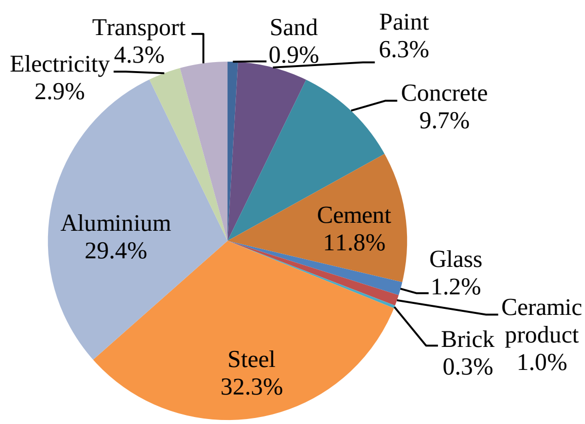


Figure 8.4 Sectoral analyses for three projects

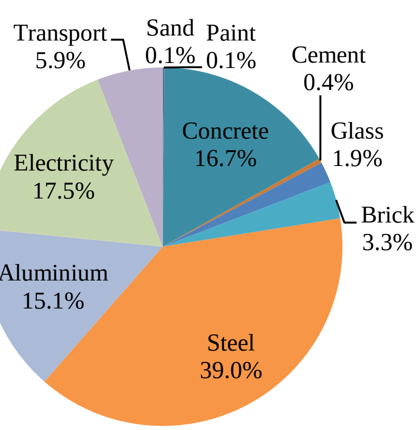
In general, the productions of steel, concrete, and aluminum as well as electricity use are the major contributors for overall energy consumption during the project construction process. More specifically, project 1 is more steel-intensive where the energy use embodied in the steel production accounts for almost 60% of total consumption. In contrast, concrete and cement together consume only 5% of total energy use in project 1, whereas it is approximately 20% in project 2 and 3. Moreover, it was found from the literature review that the estimation of energy use embodied in the transportation process was relatively small according to previous literature (Thormark, 2000, 2002; Verbeeck and Hens, 2010). However, the multi-regional framework not only calculated the energy use embodied in direct transportation of materials from offsite factory to construction site but also takes account of the indirect construction related transportation through the whole supply chain. The corresponding result indicated that the proportion of energy use embodied in transportation was around 5%. Such proportion might be even underestimated on the assumption that all the materials used in target construction projects are from local suppliers. In fact, the real result could be even higher when cross-regional materials were procured.



Project 1



Project 2



Project 3

Figure 8.5 Percentage of embodied energy use for construction materials

8.3.2.4 Optimization analysis

Based on the fact that it is difficult for the local or central government to promote sectoral energy efficiency in a very short time through technology promotion and structure improvement, the purpose of the optimization analysis is to upgrade the energy structure by using materials in regions with higher level of energy efficiency and manufacturing technology. In general, the total energy consumption in this study comprises four categories of energy sources: materials production, electricity use, transportation, and others consumptions. Electricity supply is commonly provided by local power plants. Consequently, reducing the energy consumption from electricity use should be more dependent on advanced and coal-clean technology implemented during electricity production process rather than changing the supplier. Moreover, the category of other consumptions include energy use embodied in the construction related service and other sectoral indirect inputs. Energy interactions in this category are complicated and their contributions to the total energy consumption are negligibly small. Therefore, this study only focused on optimizing the energy use embodied in the primary materials production and transportation, which can be expressed as:

$$Z = \sum_{i=1}^{n} \min(E_{m,i} + E_{t,i})$$

Where $E_{m,i}$ and $E_{t,i}$ is the embodied energy use of production and transportation for material i, respectively. According to Figure 8.5, cement, concrete, steel, aluminum, and copper are the major contributors to total energy consumption during building construction process and were therefore selected for further optimization. The transportation distance from the investigated construction project to the origin of materials is estimated by Google Maps. In summary, the major purpose of optimization is to maximize energy reduction by re-selecting the origin of materials. For instance, regarding the alternative region k, the results of such reselection can be analyzed under four scenarios (see Table 8.5).

Table 8.6 Different scenarios and their implications

	$E_{m,i}$	$E_{t,i}$	Implication
Scenario 1	↑	↑	Exclude region k
Scenario 2	↓	↑	If $\sum(E_{m,i}+E_{t,i})$ decreased, Region k is identified as alternative option; If not, exclude region k
Scenario 3	↑	↓	If $\sum(E_{m,i}+E_{t,i})$ decreased, Region k is identified as alternative option; If not, exclude region k
Scenario 4	↓	↓	Region k is identified as alternative option

It can be seen that in the scenario 1 and 4, the determination process is straightforward. In contrast, scenario 2 and 3 are more complex, which have to seek for the optimal point by comprehensively considering energy efficiency gains from purchasing materials in region k and the energy increment due to the increased distance of transportation. Figure 8.6 shows the percentage changes of the embodied energy use for five primary materials regarding different origins. It is obvious that concrete is more sensitive to the change of origins. On the other hand, materials supplied by regions far away from the investigated projects such as R8 (Heilongjiang) and R30 (Xinjiang) are more energy-intensive because of long-distance transportation. However, the results of optimization analysis indicate that a number of energy-efficient alternatives exist for further consideration of energy reduction during the construction process. However, it is also necessary to take regional resource characteristic into consideration before determining the optimized origins. More specifically, it is unlikely to provide the required materials for a certain region where they are rarely produced, even if the computational result has identified it as the most energy-efficient materials supplier. Therefore, the top 10 origins for these 5 types of materials have been investigated by referring to the China Cement Almanac, China Steel Yearbook, and the Yearbook of Nonferrous Metals Industry of China (see Table 8.6). According to the statistic classification, the steel here mainly includes finished steel products, steel bar, rebar, strip, etc.

By comprehensively considering the results of optimization analysis and reality of regional resource characteristics, optimized strategies are given in Table 8.7. It can be found that local suppliers are still recommended as the major source for material supply after optimization. Generally, construction projects are encouraged to import typical energy-intensive materials (e.g. steel, aluminum, and copper) from energy-efficient regions to achieve further embodied energy reductions. According to the relative change of total embodied energy consumption, by importing aluminum and copper from Henan and Jiangsu, the energy saving potential in project 1 and 3 is comparatively small with a reduction of 0.6% and 1.8%, respectively. In contrast, the energy use embodied in Project 2 has been reduced significantly by procuring materials in regions with higher energy efficiency. More specifically, the typical energy-intensive materials such as cement, steel, and aluminum in project 2 are encouraged to be imported from Guangdong, Jiangsu, and Henan. Such optimization of the material origin could reduce more than 15% of the total embodied energy consumption. However, it should also be noted that energy reduction strategies provided by the optimization process are case-specific, which to a large extent dependent on the basic profile of the investigated construction project, including the geographical connection with other regions and quantity of the target material used.

In summary, energy saving strategies provided by the multi-regional hybrid framework provides a possible solution for energy consumption optimization at the project level. By comprehensively balancing the energy consumption embodied in the material production and transportation process, the origins of materials are optimized to further reduce the total energy consumption for the target construction project.

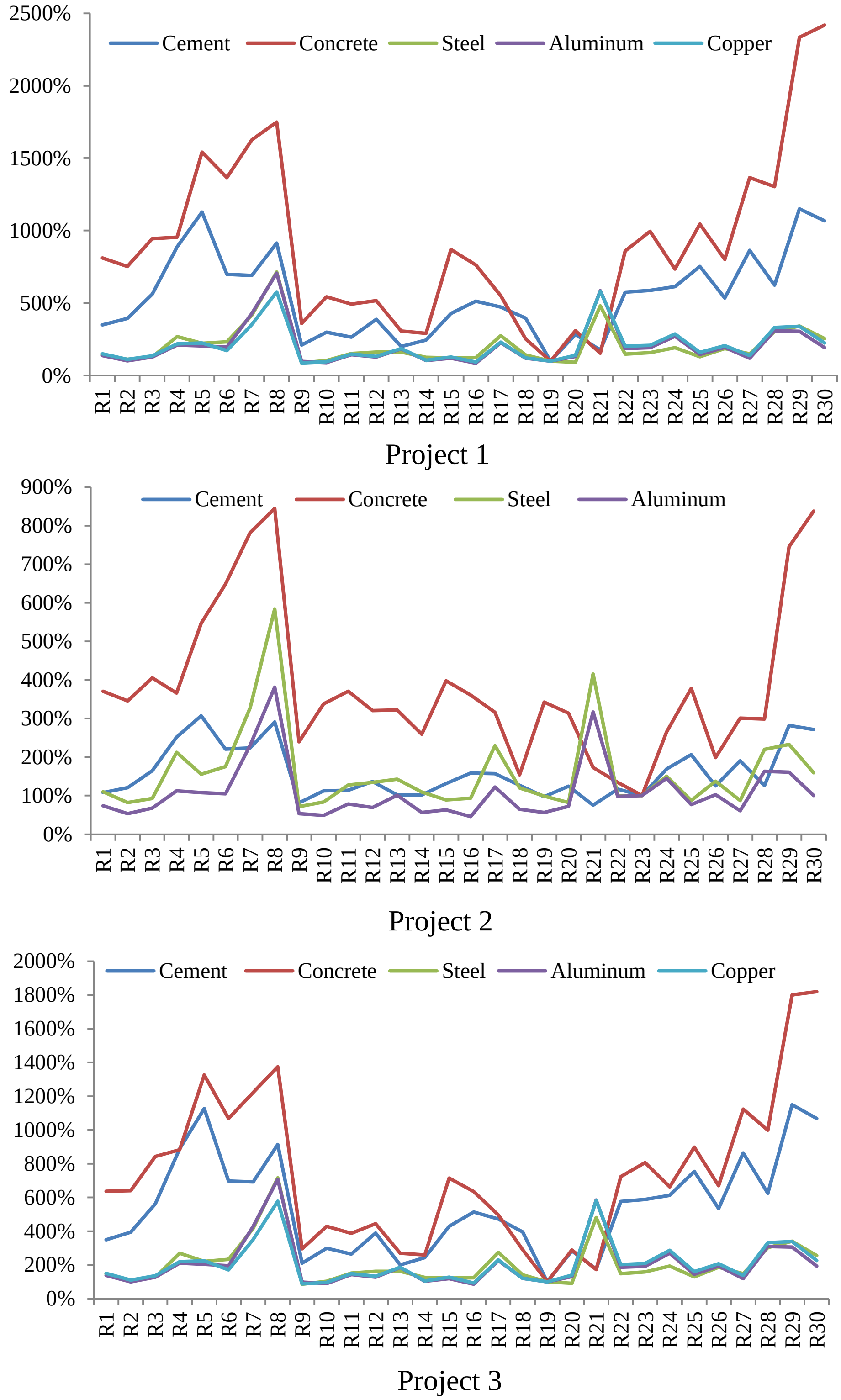


Figure 8.6 Percentage changes of the embodied energy consumption for materials procured in different regions

Table 8.7 Top 10 origins for primary construction materials

	Cement	Concrete	Steel	Aluminum	Copper
1	R10 (Jiangsu)	R10 (Jiangsu)	R3 (Hebei)	R16 (Henan)	R14 (Jiangxi)
2	R15 (Shandong)	R15 (Shandong)	R6 (Liaoning)	R15 (Shandong)	R15 (Shandong)
3	R16 (Henan)	R16 (Henan)	R10 (Jiangsu)	R5 (Inner Mongolia)	R27 (Gansu)
4	R23 (Sichuan)	R23 (Sichuan)	R15 (Shandong)	R28 (Qinghai)	R12 (Anhui)
5	R3 (Hebei)	R3 (Hebei)	R4 (Shanxi)	R27 (Gansu)	R11 (Zhejiang)
6	R19 (Guangdong)	R19 (Guangdong)	R23 (Sichuan)	R29 (Ningxia)	R10 (Jiangsu)
7	R11 (Zhejiang)	R11 (Zhejiang)	R5 (Inner Mongolia)	R4 (Shanxi)	R25 (Yunnan)
8	R12 (Anhui)	R12 (Anhui)	R16 (Henan)	R25 (Yunnan)	R17 (Hubei)
9	R18 (Hunan)	R18 (Hunan)	R17 (Hubei)	R24 (Guizhou)	R5 (Inner Mongolia)
10	R17 (Hubei)	R17 (Hubei)	R2 (Tianjin)	R23 (Sichuan)	R19 (Guangdong)

Source: the China Cement Almanac, China Steel Yearbook, and the Yearbook of Nonferrous Metals Industry of China

Table 8.8 Optimization strategies for three projects

	Optimized strategy	Original energy intensity	Optimized energy intensity	Changes
Project 1	Using aluminum produced from Henan	6.31	6.27	-0.6%
Project 2	Using cement from Guangdong Using steel from Jiangsu Using aluminum produced from Henan	6.18	5.23	-15.4%
Project 3	Using aluminum produced from Henan Using copper from Jiangsu	3.37	3.31	-1.8%

8.4 Summary of the Chapter

This chapter verified the reliability of the developed multi-regional hybrid framework in real construction projects. Comparative analysis has been conducted between previous research and this study based on the same construction profile to examine the reliability of the framework. The results show that although gaps exist in the value of traditional methods and the improved hybrid framework, they are still in the same order of magnitude. In addition, the embodied energy consumption calculated by the hybrid framework is smaller than the results obtained in the process-based model. This might be caused by a more detailed collection of case-specific data in the original research and a higher level of manufacturing and energy productivity of the region where the target project located. An empirical study has been further implemented to validate the feasibility of the framework. Results show that besides a basic embodied energy assessment for the target project, the developed framework is capable of providing interregional and sectoral analysis of embodied energy consumption. By comprehensively considering energy efficiency gains from purchasing materials in energy-efficient regions and the energy increment due to the increased distance of transportation, the framework can also optimize the origin of materials to achieve further energy reduction at the project level.

Chapter 9 Policy Implications and Recommendations

9.1 Introduction

This chapter aims to present policy implications and recommendations by utilizing the analysis results obtained in this study according to different investigation levels. At the national level, guidance will be given for the central government based on energy incremental trajectory and driving forces of the construction sector. At the regional level, several specific regulations have been presented from the regional and sectoral perspectives, and such regulations will benefit the policy-making process for the central and local government. At the project level, recommendations are initially given for different stakeholders. Then, a discussion has ensued regarding the energy reduction potential of innovative technologies in the construction sector.

9.2 National Level Implications

From 1990 to 2010, energy consumption in the construction industry changed dramatically due to the booming property market in China. It is likely that this trend will continue for a long time due to the rapid urbanization process and resulting increase in standard of living. According to the findings introduced in Chapter 4, although the change in energy intensity contributed markedly to the energy reduction of the construction industry at the aggregate level, it is still insufficient to offset the rapid growth in final demand. Therefore, it is important to adopt more ambitious strategies to offset further increases.

In principle, reductions in energy intensity are the result of technological improvement and energy structural optimization—this is the major tool used for energy savings in the construction industry. The projection for the 13th Five-Year Plan shows that by further improving the sharing for renewable and clean energy sources, energy use would be reduced by 22 Mtce (2.1%) in 2020.

The structural optimization in production from 1990-2010 was enabled by both improvements in energy productivity in the heavy industry as well as movement of energy-intensive sectors towards energy-efficient service sectors. The proportion of the service industry increased from 31.5% to 43.1% in the past two decades. This is projected to be nearly half of the national total economic output in 2020. Had such a situation stayed constant, the total energy reduction from the structure shift would be expected to be 238 Mtce (22.7%). This would make it the most important factor for energy reduction in 2020.

Based on the analysis results at the national level, it is clear that the energy increase in China's construction industry is mostly driven by the growth of final demand. Such high demand is the result of the investment-driven and rigid demand for residence. However, it is really difficult to predict the volume of final demand for the construction industry. On one hand, in the foreseeable future, the trends in population growth will slow due to the family-planning policy started in the 1980s. As a result, such supply shortage in property market will be alleviated. Moreover, with several rounds of macro-control on property market by the central government from the year 2005, profit margins have been further narrowed. This suppresses the enthusiasm of investors and returns the market to rationality. On the other hand, although total population decreases in China, the cityward migration associated with rapid urbanization would also generate stronger demand for urban residential buildings, which may result in larger energy footprints for per unit building floor area compared to rural residential buildings. Besides, the rising middle class in urban areas also yields demand for more spacious houses. Such comfort-oriented purchases would also cause new constructions, and thus increase building energy consumption.

In summary, although China's construction industry has shown consistent increases from 1990 to 2010, the role of driving factors has changed across different time periods. The structural change in energy and production has gradually switched their roles from energy-driven factors to energy-reducing factors. This is due to the consistent efforts in structural optimization by the central government. It is also worth noting that the urbanization rate in China will reach a historic high of 51.5% at the end of the 12th Five-Year Plan. Therefore, focus should not only remain on structural optimization and energy intensity improvements but also controlling or restricting the volume of consumption demand by the central government.

More specifically, the central government should first encourage industrial sectors to adopt advanced production technologies. Technical innovation effectively improves energy productivity and efficiency. Since construction activity is highly related to the number of energy-intensive sectors due to its heavy use of cement and steel (e.g. manufacture of non-metallic mineral products and smelting and pressing of metals), more energy-efficient and value-added products should be advocated to these energy-intensive suppliers for reducing energy intensity. For instance, prefabricated products provide a controlled condition to facilitate the standard design of building materials, units, and components—these advances could not only improve energy efficiency but also achieve higher added value during the construction process.

Second, as a typical fossil energy-oriented sector, the construction industry should take action to optimize its energy consumption structure. In fact, the change in energy structure is also one major factor leading to energy increase in the past two decades. This highlights the deficiency that such factors had on energy use in the construction industry. One effective way to achieve this optimization is to improve the share of environmentally-friendly energy. This would replace the conventional carbon-intensive energy with renewable and clean energy sources. For instance, shale gas is a promising energy source which is abundant in China. According to Wang et al. (2014), this energy source is projected to replace coal power and change the US energy landscape in the future.

Third, the central government should consistently put great efforts into industrial structural upgrading—not only by switching the economy from heavy manufacturing to service based, but also transiting the entire supply chain toward a more sustainable and high value added economy. More specifically, it is crucial to set measurable targets at the beginning of the 13th Five-Year Plan. According to the quantitative analysis in this study, the optimistic scenario indicates that the percentage change of energy increments in 2020 is 22% of 2010 level by conducting an ambitious structural optimization in production and energy consumption. Accordingly, given the consistently positive effect from the implementation of energy reduction policies and ambitious of the central government in energy reduction as well as the declined trend of incremental energy consumption, it is reasonable to expect that the percentage change of the incremental energy consumption from the construction sector could be restrained below 25% at the end of the 13th Five-Year Plan. Such target is to large extent dependent on technology innovations and a favorable environment created by the central government for further upgrades.

Fourth, the central government should restrict irrational increases from speculations. Consistent efforts on the macro-control of property markets are required to further narrow down profit margins. This policy is expected to suppress the enthusiasm of investors and return the entire market to rationality.

9.3 Regional Level Implications

China is now in a rapid development period of urbanization. According to the results in Chapter 5, gross fixed capital formation is the major contributor to the energy use embodied in the final demand of the regional construction sector. In fact, the investments in fixed capital formation are closely related to infrastructure construction, retrofit, refurbishment, and real estate development. Such construction activities are the result of rapid urbanization in China. This inevitable trend is bound to produce large energy demands. Therefore, implementing a fair and equitable energy reduction policy by considering both direct and indirect energy input as well as the interrelationship at the regional and sectoral levels is of crucial importance.

9.3.1 Regional Policy Implications

A combination of various strategies can be established at the sub-region level of China with regard to the construction sector (see Table 9.1). Based on the region classification in Chapter 5, the corresponding strategies can be implemented according to their energy consumption status (see Figure 9.1).

Table 9.1 Energy saving strategies

	Strategy
Energy intensity	① Adopting advanced production techniques
	② Developing less energy-intensive and high value-added products in identified primary energy suppliers
	③ Changing the production process from extensive mode to intensive mode
	④ Improving energy productivity
	⑤ Innovative construction techniques (precast construction)
Energy consumption structure	⑥ Improving the share of renewable and clean energy sources
	⑦ Using less energy-intensive fuels
	⑧ Adopting clean-coal technologies
Production structure	⑨ Switching from energy-intensive industry toward energy-efficient lighter industry;
	⑩ Shifting economic growth pattern from resource-intensive oriented to resource efficient

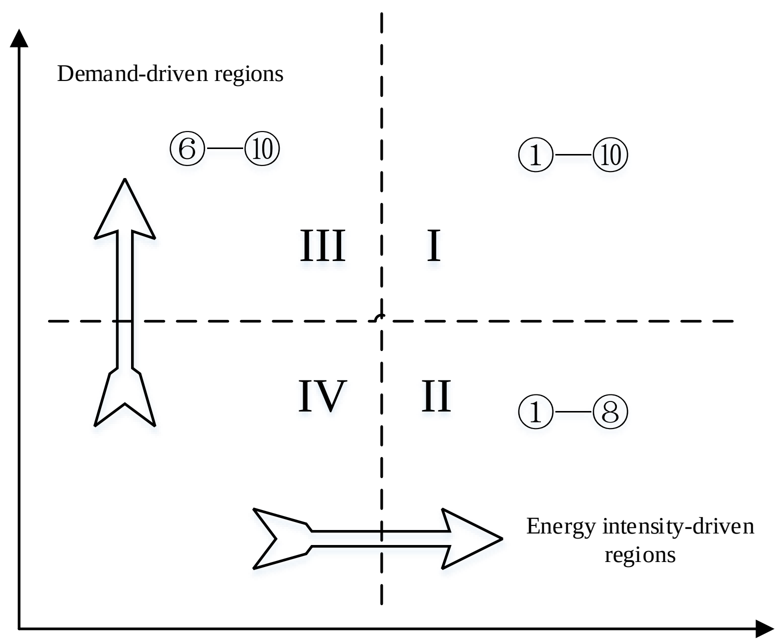


Figure 9.1 Policy implications for regions with different energy consumption status

The increase of final demand and energy intensity were the major factors that contribute to the growth of embodied energy consumption for the regions in the first quadrant. Therefore, attention should not only be given to improve energy efficiency but also to optimize the energy and production structure, which could offset the energy increment from the rapid growth of final demand. Considering that the application of renewable energy in the building field accounts for only approximately 2% of all energy sources, one effective policy is to optimize the energy consumption structure. It can be achieved by improving the share of renewable and clean energy sources in the construction industry, especially in the regions with abundant renewable energy resources, which can help to compensate for the rapidly increasing energy demands from China's urbanization. The regions in the second quadrant were driven mostly by the high energy intensity with smaller effects from the increasing volume of final demand. Consequently, authorities should enhance the application of high-efficiency technology and encourage innovative construction techniques. For instance, construction industrialization, which refers to the standard design and production of building materials, units, and components, is an effective method to reduce negative environmental impact due to its high-level quality control. More importantly, housing industrialization is also a critical issue for the development of urbanization in China, which has been emphasized through a series of national guidance and policies, including the Report at the Eighteenth National Congress (CPC, 2012), National Plan on New Urbanization 2014-2020 (GOSC, 2014), and Plan on Green Building (MOHURD, 2013). The volume of final demand was the primary factor that causes the energy increment for the regions in the third quadrant. Therefore, the policy for the local government should be geared toward optimizing the energy and production structure, which is expected to balance the energy increment from the increase of the final demand.

In addition, the local government should be the leading authority responsible for managing energy reduction in the regional construction sector since the characteristic of energy flows through the supply chain is more self-sufficient than interregional energy transmissions. Formulating energy conservation policies will be more effective by considering regional technological differences and the resource-carrying capacity of the local economy instead of implementing a national policy by the central government. In addition, the primary energy suppliers for the construction sector in northern, western, and eastern China are Hebei, Inner Mongolia, and Henan. Thus, these provinces are the most important regions for the sustainable development of the construction sector in China. From the production-based perspective, building products manufactured from these regions should be restricted by imposing strict policies. From the consumption perspective, regions on the eastern coast and southern area of China import energy from several resource-abundant regions. Such energy mobility requires the local governments in these developed areas to assume additional responsibilities to reduce the volume of energy use in the construction sector. The local government should take responsibility for production technology improvements because most significant energy contributions came from the local economy according to the structural analysis results in Chapter 6. An effective method is to switch the traditional resource-intensive model to standard, resource-efficient, and modular construction processes. Precast construction techniques provide a controlled condition to facilitate the standard design of building materials, units, and components. These advances can help achieve direct energy reduction in the first stage of the upstream production process. The Ministry of Housing and Urban–Rural

Development should assume additional responsibilities in promoting its application in building practices.

9.3.2 Sectoral Policy Implications

The results of sectoral analysis in Chapter 5 revealed the fossil fuel energy-oriented characteristic of the construction sector in China. In fact, the primary building materials (e.g., cement, steel, and aluminum) are highly related to a number of energy-intensive sectors, such as manufacturing of non-metallic mineral products (S13), smelting and pressing of metals (S14). Therefore, from a macroscopic view, central or local government should restructure the economic growth pattern by consistently shifting the production structure from energy-intensive industry towards energy-efficient industry to achieve structural energy savings. The national energy administration and relevant industrial departments should also conduct energy reduction measures at the sectoral level. Focus should be placed on optimizing the energy consumption structure and improving the proportion of renewable and clean energy in these sectors. In addition to natural gas and electricity, shale gas is also an important energy source with considerable potential as a clean fuel for construction. From a microscopic view, the selection of building materials plays a major role in energy and emission reduction. Traditional resource-intensive materials should be replaced with energy-efficient and environment-friendly materials to reduce overdependence on heavy industries. Accordingly, encouraging local governments to use less energy-intensive materials in the construction sector is critically important, which can guide traditional energy or resource consumption behavior toward a greener and less energy-intensive direction.

9.4 Project-Level Recommendations

9.4.1 Recommendations for Different Stakeholders

This study proposed a multi-regional hybrid framework to assess the embodied energy consumption of construction projects. The benefits and recommendations from the project-level investigation can be inspected according to different stakeholders.

For regional policy makers, the developed framework could serve as a benchmark tool to quantify the embodied energy consumption of the different types of construction projects. Such preliminary estimation could assist policy makers have an overview of energy consumption intensity of the local construction sector. It could enable decision makers to directly identify the essence of energy-related problems and explore detailed information on upstream energy interactions, which will positively improve the overall energy performance in the local construction sector. Moreover, the local government could evaluate the energy reduction status at the design stage of a particular project by comparing its embodied energy intensity with the baseline obtained from the regional benchmark. Consequently, the local government could make a detailed financial support plan for different intensity levels, which could help clients recover the cash flow at the beginning of construction projects. Such advance subsidies are extremely important for clients, especially at the design stage, considering that a rapid return of the cash flow can benefit the operation of property companies. Ultimately, examining the actual embodied energy intensity is essential during project delivery, which enables the local government to determine whether to withdraw the initial financial support or pay the remaining subsidies.

For clients, this framework provides a quick assessment tool to effectively assess and manage the energy consumption of a specific construction project at the design stage. It could facilitate clients to apply the three-star green building evaluation standard with robust and concrete evidences. Furthermore, clients can employ the energy optimization strategies provided by this hybrid framework to rethink the material suppliers at the design stage by extensively considering the balance between the economic and environmental impacts.

For contractors, embodied energy analysis and optimization analysis in the developed framework provide contractors an understanding of the embodied energy use from regional and sectoral perspectives. Such exploration could assist project managers establish an overall map of the embodied energy consumption of the target project and provide possible alternatives to further reduce energy by reallocating the origin of materials. Furthermore, the information of onsite electricity use obtained from the framework could provide guidance for project managers to further reduce the onsite energy use.

In summary, the multi-regional embodied energy assessment framework is an effective tool to pre-estimate the embodied energy use at the design stage of a project, which could give incentives for industry practitioners to consider sustainability. It further facilitates the implementation of green building standards, and promotes the development of a cleaner production in China’s construction industry.

9.4.2 Recommendations for Innovative Construction Technologies

9.4.2.1 Building Materials

According to the results of empirical studies conducted in Chapter 8, building material production contributed the most in total embodied energy consumption, where steel and concrete generated nearly two thirds of the overall consumption. In fact, the findings obtained in Chapters 5 and 6 indicated that the production of these materials were closely related to the upstream processes, such as steel processing and cement production, which are typical energy-intensive economic sectors. Therefore, the adoption of advanced technologies is critically important to improve productivity and energy efficiency for material production. More energy-efficient and value-added products should be advocated to these energy-intensive suppliers to reduce energy intensity. Using low-carbon and energy efficient materials is encouraged as alternatives during building construction. To illustrate, the adoption of materials, such as glulam timber mullions, light-frame wood, and cement stabilized rammed earth for exterior walls was proved capable of generating less environmental impact during the building embodied phase (Azari-N and Kim, 2012; Frenette et al., 2010; Reddy and Kumar, 2010).

9.4.2.2 Renewable and Clean Energy

One effective method to achieve the embodied energy reduction during the building material/product manufacturing process is to improve the share of clean and renewable energy. Apart from implementing traditional clean energy, such as natural gas and electricity, shale gas is also an important energy source with considerable potential as a clean fuel for construction. According to Chang et al. (2014a), this clean energy is abundant in China, which is a promising energy source for heavy industries. Furthermore, it is projected to replace coal power and change the US energy landscape in the future (Wang et al., 2014).

9.4.2.3 Industrialized Building System

Some integrated strategies and technologies are implemented in the current construction field to improve the life-cycle environmental performance of buildings. One effective solution is the adoption of precast construction or industrialized building system, which has become increasingly important in the entire construction industry. Prefabricated construction refers to the practice of producing construction components in a manufacturing factory, transporting complete or semi-complete components to construction sites, and finally assembling these components to construct buildings (Tam et al., 2007). Compared with conventional construction technologies, prefabrication provides controlled conditions for bad weather and for ensuring quality, facilitates the compression of project schedule by changing workflow sequencing, and reduces the waste of materials (Li et al., 2014). Thus, prefabricated construction does not only reduce waste, noise, dust, operation cost, labor demand, and resource depletion, but also improves the quality control process, as well as ensure the health and safety of workers (Jaillon and Poon, 2009; Li et al., 2011; Lu et al., 2011).

The effectiveness of adopting prefabrication technique to reduce embodied energy of buildings has been validated in some studies. The results of previous research revealed that the precast construction can reduce approximately 20% of the total embodied energy consumption (Cao et al., 2015; Chen, 2010; Zhang and Skitmore, 2012). To further examine the possible energy reduction potential of such innovative construction technology, an empirical study has been conducted using the hybrid framework developed in this study. To achieve this goal, a typical prefabricated building located in Guangdong has been investigated. The target building is semi-prefabricated and comprises three types of prefabricated components, namely, precast façade, staircase, and slab. Table 9.2 shows the basic building profiles. It is apparently a residential building with a frame shear structure. Two types of precast façade exist. One is a 160 mm-thick semi-prefabricated type, which leaves the remaining part for onsite pouring. It can be used as a basic formwork to combine with cast-in-situ concrete. This type of façade provides less support for structural load, but reduces time and cost consumption for the formwork installation. The other type is a 310-mm manufactured façade in the offsite factory, which can be assembled directly with steel connectors. Such type of prefabrication is used as one of the major structural components. The floor slab is semi-prefabricated with laminated technology. Half of the slab (80 mm) is manufactured in the offsite factory, and the remaining part is built with cast-in-situ concrete. The implementation of such construction technology aims to reduce the overdependence on formwork use, alleviate the demand for man power, improve the construction efficiency, and ensure high-quality control during building construction.

Table 9.2 Basic profile of building cases

		Project
Building information	Location	Shenzhen
	Building Type	Residential
	Structure	Frame shear structure
	Gross floor area (m2)	216200
	Basement	2 floors
	Height	26-28 floors
Prefabrication techniques	Construction method	Semi-prefabrication
	Volume of prefabrication (m3)	7850

	Prefabrication rate (% by volume)	10
	Precast facade	✓
	Semi-precast slab	✓
	Precast balcony	
	Precast staircase	✓

Table 9.3 Material inventory flow for the target building

	Physical quantity
Concrete	100587.3 m3
Steel	11380.1t
Cement	13930.9t
Aluminum	175.5t
Block	51935.0t
Sand	41792.8t
Ceramic	13628.4t
Paint	595.5t
Glass	128.8t

Inputting the information on material inventory data and the geographic location into the developed framework enables the calculation of the embodied energy intensity of the target project, that is, 5.04 GJ/m^2. Compared with the result of the traditional process-based computational model (4.51 GJ/m^2), the completeness of system boundary in the hybrid framework enables the improvement of the result accuracy by quantifying energy inputs in the higher order of the upstream production process. To further explore the environmental benefits of prefabricated buildings during the embodied phase, conducting a comparative analysis with previous research is required. The building selection criteria for the subsequent comparison include the following:

(1) The building selected for further comparison should be in China. The consistency of geographical location provides similar levels of economic development and energy efficiency, which ensures the comparability of chosen cases.

(2) All selected buildings should be built with similar building type, structure system, and other relevant profiles that may cause the change in the amount of materials used.

(3) The direct energy input to the onsite construction only accounts for an extremely small proportion during the embodied phase (Hong et al., 2015; Liu et al., 2012b; Scheuer et al., 2003); this study assumes that the effect of variations in onsite construction management skill is negligibly small on the total embodied energy use.

(4) To alleviate the effect of method diversities on energy consumption assessment, this study employed the hybrid framework developed in this study to calculate the embodied energy intensity.

Based on the aforementioned criteria, three buildings have been selected for further comparison (see Table 9.4). All buildings are apparently distributed in two provinces, namely, Henan and Guangdong. They were all residential buildings with frame-shear wall structure. Table 9.4 shows that the investigated prefabricated building is energy efficient, which can reduce 10.4% to 17.8% of the total embodied energy consumption of the conventional buildings.

Table 9.4 Results of comparative analysis

	Project 1	Project 2	Project 3
Source	Li and Li (2005)	Hong et al. (2014)	Hong et al. (2015)
Location	Henan	Guangdong	Guangdong
Building type	Residential	Residential	Residential + commercial
Structure	Frame shear structure	Frame shear structure	Frame shear structure
Gross floor area (m2)	5240	20105	11508
Energy intensity (GJ/m2)	5.95	5.62	6.13
Energy increase	15.3%	10.4%	17.8%

An extensive consideration on the entire life cycle of precast construction allows such innovative construction technology to possibly contribute to the reduction of embodied energy consumption from the following three aspects:

(1) Material and waste reduction. By providing the conditioned control and improving the quality during the production process, the adoption of prefabricated technique can therefore reduce the use of building materials and mitigate the generation of construction waste. Specifically, several types of materials and resources can be saved during the manufacturing process.

Timber: Steel formwork is widely used for prefabrication manufacturing to achieve mass production in the offsite plant. Such reuse of steel formwork could significantly mitigate the usage of wooden formwork in the conventional construction process. Moreover, the semi-precast slab itself can be used as the formwork with the remaining part built by cast-in-situ concrete. Such procedure can reduce the overdependence on traditional wooden formworks and enhance the quality of the slab system. These characteristics may further reduce the consumption of timber in the precast construction. In fact, the use of timber can be reduced by 71%–87% according to previous investigations (Cao et al., 2015; Zhang and Skitmore, 2012).

Insulation: The insulation used in the prefabricated exterior wall is protected by two layers of concrete, which favorably extends its service life and reduces the maintenance or replacement works during the building operation phase. Therefore, the recurrent embodied energy consumption could be further reduced in this method.

Water: Compared with the traditional water curing in the conventional construction, the water consumption can be significantly reduced by implementing the steam curing technique for prefabricated components in the offsite plant. The adoption of such technique enables the acceleration of the strength formation of concrete without the excessive use of water. A 25.8% to 70% reduction of water consumption is estimated during the building construction phase according to previous studies (Cao et al., 2015; Zhang and Skitmore, 2012).

Waste: Compared with the conventional construction method, which may require additional resource input because of the unexpected damage of onsite materials, the offsite technique provides a controlled environment with skilled workers and standard waste management procedures. It can facilitate the further processing of waste in the offsite factory and avoid the unpredictable conflicts in the traditional onsite construction. Table 9.5 presents the difference of wastage rate between the conventional and prefabrication buildings. The energy reduction potential from the minimization of waste ranged from 4% to 81% of the total life-cycle energy consumption according to different studies (Cao et al., 2015; Hong et al., 2016; Treloar et al., 2003; Zhang and Skitmore, 2012).

Table 9.5 Waste rate of building materials

	Conventional construction			Prefabrication
	Blengini (Blengini, 2009)	Poon et al. (Poon et al., 2001)	Tam et al. (Tam et al., 2007b)	
Concrete	7%	3%–5%	4%–7%	0.5%–3.5%
Steel bar	7%	1%–8%	3%–8%	0.2%–4%
Timber	7%	5%–15%	4%–23%	0.6%–12%
Block/brick	10%	4%–8%	5%–8%	0.6%–4%

(2) Onsite energy reduction

Using precast technique during the building construction process could reduce the frequency of vertical transportation, which can therefore save the electricity consumption for crane operation. This possibility is mainly explained by the advanced assembly of miscellaneous construction materials, such as rebar and window frame for prefabricated components during their offsite production process. Such pre-installation allows tower cranes to lift only bulky components instead of separate materials in the traditional method.

(3) Recycle and reuse

Considering that the prefabricated elements' relatively straightforward disassembly during the building demolition phase, the recycling process of prefabricated buildings exhibits a high-energy saving potential. According to Hong et al. (2016), despite considering the energy input from the secondary processing, the recycling process still presented a reduction potential ranging from 16% to 24%.

9.5 Summary of the Chapter

This Chapter presents policy implications and recommendations by considering the key findings obtained in this study. At the national level, recommendations have been given for the central government, including the adoption of advanced production technologies, optimization of energy structure, and promotion of industrial structural upgrading. At the regional level, some appropriate strategies were provided at China's sub-regional level by comprehensively considering its characteristics. At the project level, recommendations have been presented for different stakeholders**,** including discussions on innovative technologies in the construction sector.

Chapter 10 Conclusions

10.1 Introduction

This chapter summarizes the key research findings and suggests future research directions based on limitations presented in this study. The research aim and objectives are first reviewed to examine whether they have been achieved. The key research findings are then presented from three levels: national level, regional level, and project level. Third, the significance and contributions to the existing knowledge are concluded, and limitations and future research directions are discussed.

10.2 Review of Research Objectives

Construction projects in China have generated substantial adverse environmental impacts because of rapid urbanization and extensive development. Therefore, it is critically important to comprehensively understand not only the direct energy input to the construction site but also the indirect energy transmissions in the upstream process of the supply chain. To achieve this, the energy consumption embodied in the regional construction sectors has been analyzed at sectoral and regional level. Macro-level analysis can provide valuable insights into the energy interactions through the whole supply chain and facilitate policy makers to achieve equitable energy reduction policies in different regions, whereas micro-level simulation could help stakeholders better understand the energy consumption structure of a specific project in advance, enabling clients and contractors to optimize and reduce energy use at an early stage of construction. In summary, to address research questions in this study, the primary aim was to explore the direct and indirect energy transmissions embodied in China's construction sector at the regional and sectoral level, and build a multi-regional based hybrid framework for assessing embodied energy consumption at the project level.

(1) To explore the driving forces behind the increase in energy use of the construction sector and investigate energy consumption trajectory in the past two decades.

(2) To quantify embodied energy use of the construction sector at the regional and sectoral level.

(3) To decompose energy transmissions and identify critical energy paths in the entire supply chain from the sectoral and regional perspectives.

(4) To develop a multi-regional hybrid framework for assessing embodied energy consumption at the project level by integrating regional average data and case-specific process data.

(5) To verify and validate the reliability of the developed framework in real building cases through data from project level.

To achieve these objectives, Chapter 1, Chapter 2, and Chapter 3 identified motives and barriers existing in the embodied energy analysis of construction projects, serving as a theoretical foundation and solid reference for further in-depth analysis. To achieve Objective 1, Chapter 4 decomposed the time-series data to explore the driving forces behind the energy increment of the national construction sector. The critical driving factors have been presented and investigated individually for their effects on total energy consumption, and the energy consumption trajectory of the 13th Five-Year Plan (2015-

2020) has been projected based on a number of assumptions. To achieve Objective 2, Chapter 5 investigated embodied energy use due to interregional trade in the construction sector at the regional and sectoral level. The findings of this chapter also provide a database of region-based sectoral energy intensities for the further establishment of the hybrid framework. To achieve objective 3, the upstream supply chain has been decomposed up to 5 tiers in Chapter 6 in order to study the effect of system completeness on the accuracy of final result. The key energy paths with largest reduction potential have been explored and served as the theoretical foundation for constructing computational skeleton for the hybrid framework. To achieve object 4 and 5, Chapter 7 and 8 constructed and validated the embodied energy assessment framework at the project level. The region-based sectoral energy intensity database obtained in Chapter 5, the computational module constructed in Chapter 6, and the building information module for the target project have been integrated into the hybrid framework. Comparative analyses and empirical studies were conducted to verify the reliability and feasibility of the developed framework in real construction projects.

10.3 Summary of Research Findings

10.3.1 Findings from literature review

The literature review provides an insight into the difficulties and gaps of applying embodied energy analysis in construction projects.

(1) There is a lack of a comprehensive understanding of the direct and indirect energy transmissions derived by the construction sector in China. A systematic analysis of the

embodied energy consumption of the construction industry at the sectoral and regional level could help decision makers achieve equitable energy reduction policies.

(2) A large number of uncertainties lie in the data collection, system boundary, and data quality. Because of confidentiality for clients and contractors, collecting sufficient data to describe the project investigated is very difficult. As a result, related studies have to search for balance between data completeness and loss of accuracy. Consequently, it is necessary to establish a comprehensive embodied energy assessment model with a consistent computational framework. On one hand it can provide the solution with a complete system boundary, while on the other hand it can also determine the embodied energy for a specific project with relatively higher accuracy at the pre-construction stage.

(3) The computational structures and boundary definitions applied to previous studies were not consistent. The data used for EE research in the construction sector are almost secondary data, which lacks transparency and reliability. Especially for data based on outdated technology and manufacturing levels in the input-output analysis, it may result in an underestimation or overestimation of the results in the embodied energy assessment. Therefore, a solid, transparent, and reliable database needs to be established with updated information, which could not only alleviate the difficulties in data collection but also reflect the level of local production technology and regional characteristics.

10.3.2 Findings at the national level

At the national level, a systematic review of the total embodied energy consumption and the driving forces behind the increase of energy use in China's construction industry have been quantified and investigated by using MRIO model and SDA. The findings are as follows:

(1) The energy use embodied in the entire construction industry is 793.74 Mtec, which is equal to 29.6% of China's total national energy consumption. As a typical demand-driven sector, the gross fixed capital formation represents the highest relative contribution in all final demand categories. In addition, coal and crude oil are extensively consumed during the production of building material, reflecting the fossil fuel oriented characteristic of the construction industry.

(2) The driving factors during the past two decades represent a competition between the effects of increasing demand and a reduction in energy intensity. In contrast, the effects of structural optimization in energy, production, and final demand were comparatively minor. The results also indicated that the construction industry is a typical fossil fuel-oriented sector in which the consumption of coal has increased almost 6-fold from 2002 levels due to the flourishing property market.

(3) The projection of energy use changes in the construction industry from 2010 to 2020 shows that the structural optimization in energy, production and final demand are three major factors causing energy reduction. This is because of the consistent efforts in structural optimization and technological improvement by the central government.

(4) The scenario analysis firstly explored the positive effect of the structural optimization on energy reduction from a production-based perspective. Result shows that the percentage change of energy increments in 2020 is 22% of 2010 level in the optimistic scenario. Secondly, results from the level of sector aggregation have been examined

under 18, 8, and 4-sector format scenarios. The results revealed that more aggregates would increase uncertainty to some extent and result in a misinterpretation of the importance of the underlying factors. Therefore, it is advisable and necessary to perform decomposition analysis based on sufficient detailed economic data.

10.3.3 Findings at the regional level

At the regional level, the direct and indirect energy use of the construction sector has been further inspected from regional and sectoral perspectives. MRIO model has been adopted to quantify interregional and inter-sectoral energy transmissions. SPA has been used to further decompose the indirect energy inputs through the upstream production process. The results can be regarded as a solid reference to re-recognize the spatial and sectoral characteristics of embodied energy requirements of the construction sector. The findings are as follows:

(1) Based on the value of construction energy intensity, China (except Tibet) can be divided into seven areas. Regions with high-energy intensity are concentrated in the central part, whereas the less energy-intensive regions are located on the southern and eastern coasts. By taking account of different driving forces for energy increment, all regions are further divided into four groups. Such classification enables central or local government to implement specific energy reduction targets.

(2) Five sectors, namely manufacturing of non-metallic mineral products (S13), smelting and pressing of metals (S14), transportation, storage, post, and telecommunications (S25), chemical industry (S12), mining and processing of non-metal ores (S5), and power sector (S22) contribute 80% of all embodied energy input to the construction industry. Besides,

the service sector is also highly related to the upstream process of building construction, which consumes energy by providing consulting, financing and real estate services.

(3) Energy imports of the construction industry represent a resource-dependent characteristic with distribution of energy flows from resource-abundant areas in the central part to resource-deficient areas in the eastern coast. By contrast, energy exports are discrete, which mainly transfer energy in the form of labor mobility and service supply.

(4) The inspection of the entire structure of energy flow tree indicates that the energy paths in the first stage consume the highest amount of energy. This implies that there is a large potential for further direct energy reductions. Sectoral interactions begin to cross the breadth of the entire economy in the second stage. This emphasizes the importance and necessity of investigating the higher order upstream process.

(5) The regional analysis explored the self-sufficiency characteristic for energy consumption in the regional construction sector. Hebei and Inner Mongolia comprised the major energy suppliers for the construction industry in northern China. Henan was identified as a hub for energy imports to the construction industry in the east and west of China.

(6) The sectoral analysis obtained the critical determinants hidden in the higher order of supply chain. The manufacture of non-metallic mineral products (S13), the smelting and pressing of metals (S14), and transportation, storage, posts and telecommunications (S25) were identified as the major energy suppliers in the first stage. The chemical industry

(S12), the production and distribution of electric power and heat power (S22), and mining industries exert the most significant indirect impact on the construction industry.

(7) A systematic analysis of the changes in the threshold and system boundary demonstrated that a higher value of the threshold (0.005%-0.01%) is preferred because of its advantages in simplifying the computational process while retaining the most valuable energy information. Depending on the specific research objectives, the system boundary could narrow into the first 2 tiers which contain almost 50% of the energy flow information or expand towards the first 6 tiers by representing 80% of the total energy consumption.

10.3.4 Findings at the project level

At the project level, a multi-regional framework has been established to assess the embodied energy consumption for a specific construction project. Comparative analyses and empirical studies verified the reliability and feasibility of the developed framework in real construction projects. The findings are as follows:

(1) The developed framework enables exploration of the ‘hidden’ embodied energy that has been theoretically ignored due to cut-off requirements in the process analysis. In fact, such hidden energy consumption includes the energy use embodied in materials with lower energy intensity or smaller quantities and other construction related services, which together accounts for a significant proportion (22.7%-40.7%) of the total energy use.

(2) The integration of case-specific process data and regional characteristic in the developed framework enabled to reflect the effects of changes in geographical location,

building type, and building structure on the total embodied energy consumption of different case buildings.

(3) According to empirical analyses, the developed framework was capable of providing valuable information on interregional energy transfers and embodied energy use of primary building materials for the target construction project. It could alleviate environmental pressures at the regional level by reallocating suppliers in different regions.

(4) By comprehensively analyzing the energy consumption in material production and transportation processes, materials with less embodied energy intensity were identified for each case. Results of optimization analysis indicated that localization strategy was still recommended for procurement of most materials after optimization. Only several typical energy-intensive materials (e.g. steel, aluminum, and copper) were encouraged to be purchased in other energy-efficient regions to achieve further energy reduction.

10.4 Contributions of the Research

10.4.1 Contributions to Current Knowledge

First, this research has contributed to the literature of embodied energy analysis in the construction field by examining the benefits and obstacles for its application at the industrial and project levels. The research findings and gaps identified in previous studies could provide a solid reference for future studies in similar analysis of embodied energy in the construction sector. Second, this study systematically quantified the effects of driving factors from insight into consumption and production based. The primary driving factors responsible for the energy increase and reduction have been listed in different investigation periods which could facilitate the central government to steer the entire supply chain of the construction sector toward a more sustainable and high value added economy. Third, this research has enriched the existing body of knowledge in the construction field by providing a comprehensive understanding of the current energy consumption status of regional construction sectors. Interregional energy transfers have been systematically analyzed, which could not only sharpen the understanding of the overall map regarding energy flows from regional construction sectors but also serve as a basis for regional energy policy making and implementation. Fourth, the indirect energy input in the upstream supply chain was systematically decomposed and the specific energy paths with the largest environmental improvements were also extracted. Such decomposition could provide insights into energy interactions through the upstream process at the sectoral and regional level, helping policy makers to achieve an equitable energy reduction policy. Lastly, the multi-regional hybrid framework could provide valuable information for preliminary embodied energy use at an early stage of construction, which can provide stakeholders with an advanced indication of the sustainability for a specific construction project. Energy saving strategies provided by the developed framework could optimize the energy structure and promote the cleaner production at the project level.

In summary, this research contributes to the knowledge of sustainable construction and fills the knowledge gap in systematically understanding the current energy consumption status of regional construction sectors from regional and sectoral perspectives. In addition, recognizing the hidden linkage in the interregional trade of China’s construction sector is of great importance to help policy makers achieve a fair and equitable energy reduction policy.

10.4.2 Practical Contributions to the Industry

This study proposed a multi-regional hybrid framework for assessing the embodied energy consumption of construction projects, which could facilitate industrial practitioners to effectively assess and manage the energy consumption of a specific construction project at an early stage. Embodied energy analysis and optimization analysis in the developed framework enable decision-makers to understand the embodied energy use from a regional and sectoral perspective. Such exploration could help project managers establish an overall map on embodied energy consumption of the target project and provide possible alternatives for further energy reduction by reallocating the origin of materials. The developed framework could also serve as a benchmark tool for quantifying the embodied energy consumption of different types of construction projects. In addition, differences regarding the embodied energy use of projects with similar type and structure but located in different regions further demonstrate the importance of considering the regional characteristics and technology differences for embodied energy analysis at the project level.

In summary, the multi-regional embodied energy assessment framework is an effective tool to pre-estimate the embodied energy use at the initial stage of a project, which could give incentives for industry practitioners to consider sustainability. It also facilitates the implementation of green building standards, and promotes the development of cleaner production in China’s construction industry.

10.5 Limitations of the Research

Despite the theoretical and practical contributions to the existing studies, it is worth noting that the findings obtained in the present research are subject to a number of limitations.

First of all, given the difference between building and civil engineering construction, the hybrid framework designed in this study unable to describe some specific differences in embodied energy consumption. Such limitation is mainly from the inherent methodological assumption in the computational structure module in the hybrid framework. The scope of the construction sector defined in the multi-regional input-output table considered construction activities in both building and civil engineering construction, which is unable to analyze each construction type separately.

Secondly, the scale of input-output tables in time-series decomposition analysis is inconsistent with the number of total sectors in the multi-regional input-output table. Although uncertainty analysis has been conducted to evaluate the effect of the sector aggregation on the final results, it would be preferable if all the data analysis methods (e.g. SDA, MRIO analysis, SPA) had been implemented under the same computational framework. The major reason for this limitation comes from the problem of data availability. In China, the edition of single region input-output (SRIO) table by National Bureau of Statistic is a systematic process with enormous labor and resource input. It has been compiled every five years since 1987, and the extended table is published in every five years starting from 1992. Given the fact that the time and cost consumption for collecting the regional monetary transactions in MRIO table is much higher than the single region I-O table, it is understandable that the compilation of MRIO table may take even more time, which results in the scarcity of MRIO tables in time series. Therefore, to investigate the trajectory of energy changes and explore driving factors in different time periods, single region input-output (SRIO) tables were employed for time series analysis.

Thirdly, this study lacks of authoritative process-based energy intensity database for primary materials at the regional level. This study adopted adjustment coefficients to simulate the region-based material embodied energy intensity based on the national measuring data obtained from previous research. Such a subjective assumption may have resulted in the possibility of underestimation or overestimation of the total embodied energy for a specific project. Although the College of Architecture and Environment of Sichuan University is currently developing a Chinese Life Cycle Database (CLCD), a database at the regional level has not yet been developed.

Fourthly, the size of case studies for comparative and empirical analyses is not large enough to capture all types of construction projects in China’s 30 regions. A sufficient and extensive study of cases with diverse construction features and locations could further reduce sampling errors and demonstrate the reliability and feasibility of the proposed framework in reality.

10.6 Future Research Direction

Firstly, a further disaggregation of the construction sector needs to be conducted to differentiate building types in the multi-regional input-output analysis. It can improve the applicability of the developed framework to a broader range of construction types, making this framework be more specific to a certain construction type.

Secondly, the decomposition of driving forces for the construction sector at the national level could further narrow the research scope into a certain region if time-series MRIO tables are available. It would be meaningful to conduct an in-depth investigation of internal driving factors at the regional level, since levels of economic development and production technology are unbalanced amongst different regions of China. Such region-based understanding could facilitate local governments to adopt more appropriate energy reduction measures and accelerating energy conservation process for China's construction industry.

Apart from the energy assessment of construction projects during the embodied phase, the system boundary could also be expanded to take account of the operational phase. Note that the operational energy consumption is to a large extent dependent on the local geographic climate, insulation materials adopted, and other design parameters. It is therefore critically important to take the region-specific and project-specific characteristics into consideration. Future research could focus on the conceptualization of a multi-regional life cycle energy assessment framework for construction projects, which considers the energy use in both the embodied phase and operation phase.

In addition, more materials under the six chosen sectors could be considered and substituted by the process-based energy intensity data in the hybrid framework, if project-specific data are available for future research. Although this would increase the time and workload for data processing, it could to some extent improve the accuracy.

Last but not least, although the present study is conducted in the context of China, the theoretical framework conceptualized in this research could be generalized into other regions or countries. A benchmark could be also established based on the developed framework for construction projects in China, which would contribute to measuring embodied energy consumption of various types of construction projects in different regions.

Appendix I: Region Division in Multi-Regional Based Input-Output Table

	Region
R1	Beijing
R2	Tianjin
R3	Hebei
R4	Shanxi
R5	Inner Mongolia
R6	Liaoning
R7	Jilin
R8	Heilongjiang
R9	Shanghai
R10	Jiangsu
R11	Zhejiang
R12	Anhui
R13	Fujian
R14	Jiangxi
R15	Shandong
R16	Henan
R17	Hubei
R18	Hunan
R19	Guangdong
R20	Guangxi
R21	Hainan
R22	Chongqing
R23	Sichuan
R24	Guizhou
R25	Yunnan
R26	Shaanxi
R27	Gansu
R28	Qinghai
R29	Ningxia
R30	Xinjiang

Appendix II: Sector Classification in Multi-Regional Based Input-Output Table

	Sector
S1	Farming, Forestry, Animal Husbandry and Fishery
S2	Mining and Washing of Coal
S3	Extraction of Petroleum and Natural Gas
S4	Mining and Processing of Metal Ores
S5	Mining and Processing of Nonmetal Ores
S6	Manufacture of Foods and Tobacco
S7	Manufacture of Textile
S8	Manufacture of Textile Wearing Apparel, Footwear, Caps, Leather, Furs, Feather(Down), and Related Products
S9	Processing of Timber, Manufacture of Furniture
S10	Manufacture of Paper, Printing, Manufacture of Articles For Culture, Education, and Sports Activity
S11	Processing of Petroleum, Coking, Processing of Nuclear Fuel
S12	Chemical industry
S13	Manufacture of Non-Metallic Mineral Products
S14	Smelting and Pressing of Metals
S15	Manufacture of Metal Products
S16	Manufacture of General and Special Purpose Machinery
S17	Manufacture of Transport Equipment
S18	Manufacture of Electrical Machinery and Equipment
S19	Manufacture of Communication Equipment, Computers and Other Electronic Equipment
S20	Manufacture of Measuring Instruments and Machinery for Culture Activity and Office Work
S21	Other Manufacturing
S22	Production and Distribution of Electric Power and Heat Power
S23	Production and Distribution of Gas and Water
S24	Construction
S25	Transportation, Storage, Posts and Telecommunications
S26	Wholesale Trade and Retail Trade
S27	Hotel and Restaurants
S28	Tenancy and Commercial Services
S29	Research and Experimental Development
S30	Other Services

Appendix III: Sector Classification in 28-Sector Format

	Name
S1	Agriculture
S2	Mining and washing of coal
S3	Extraction of petroleum and natural gas
S4	Mining and processing of metal ores
S5	Mining and processing of nonmetal ores
S6	Manufacture of foods and tobacco
S7	Manufacture of textile
S8	Manufacture of textile wearing apparel, footwear, caps, leather, furs, feather(down) products
S9	Processing of timber, manufacture of furniture
S10	Manufacture of paper, printing, manufacture of articles for culture, education, and sports activity
S11	Processing of petroleum and coking
S12	Chemical industry
S13	Building materials and non-metallic mineral products
S14	Smelting and pressing of metals
S15	Manufacture of metal products
S16	Manufacture of general and special purpose machinery
S17	Manufacture of transport equipment
S18	Manufacture of electrical machinery and equipment
S19	Manufacture of communication equipment, computers and other electronic equipment
S20	Manufacture of measuring instruments and machinery for culture activity and office work
S21	Other manufacturing
S22	Production and distribution of electric power, heat power, gas, and water
S23	Construction
S24	Transportation, storage, posts and telecommunications
S25	Wholesale trade, retail, hotel, and restaurants
S26	Culture, education, health, and research
S27	Finance and insurance
S28	Other services

Appendix IV: Sector Classification in 18-Sector Format

	Name
S1	Agriculture
S2	Mining and washing of coal
S3	Petroleum and natural gas mining and processing
S4	Mining and processing of metal ores
S5	Mining and processing of nonmetal ores
S6	Manufacture of foods and tobacco
S7	Manufacture of textile
S8	Manufacture of textile wearing apparel, footwear, caps, leather, furs, feather (down) products
S9	Processing of timber, manufacture of furniture
S10	Manufacture of paper, printing, manufacture of articles for culture, education, and sports activity
S11	Chemical industry
S12	Building materials and non-metallic mineral products
S13	Other manufacturing
S14	Production and distribution of electric power, heat power, gas, and water
S15	Construction
S16	Transportation, storage, posts and telecommunications
S17	Wholesale trade, retail trade, hotel, and restaurants
S18	Other services

Appendix V: Sector Classification in 8 and 4-Sector Format

	Name
S1	Agriculture
S2	Mining and quarrying
S3	Energy-intensive manufacturing industry
S4	Energy-efficient manufacturing industry
S5	Production and Distribution of Electric Power, Heat Power, gas, and water
S6	Construction
S7	Transportation, Storage, Posts and Telecommunications
S8	Other Services

	Name
S1	Agriculture
S2	Industry
S3	Construction
S4	Service

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