Extraction, Use and Disposal of Construction Materials in Great Britain and Thailand

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Declaration

I hereby certify that this thesis is the result of my own investigations and calculations. No part of it has been submitted for any degree other than 'Doctor of Philosophy' at the Newcastle University and all references are appropriately acknowledged.

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Abstract

Construction growth has become a causal factor in economic competitiveness with rapid urbanisation. Consequently upstream businesses, such as cement and concrete manufacture, also expand. Sustainability balances economic, environmental and societal issues and although this philosophy is well developed in the European Union (EU), there seems to be less practical awareness amongst the ten countries in the Association of Southeast Asian Nations (ASEAN). This thesis investigates and compares the flow of key mineral-based components of national construction materials (cement, aggregates and concrete) from extraction to disposal in two case studies: Great Britain (EU) and Thailand (ASEAN), from the perspective of sustainable resource and waste management.

The study considers material needs and wastes arising associated with future and expected demolition of residential accommodation, measured as national floor area including future concrete demand and concrete waste from national housing, as concrete is mostly used in the Thai residential sector. To compare the difference between the two national and continental strategies in more depth, it also identifies and evaluates policies and taxations influenced by EU regulation that enable Great Britain to achieve the highest rates of recycled aggregates (29%) and the 70% reuse and recycling rate of construction and demolition waste (C&D waste). Then, options for Thai policy integrally relating to construction materials and waste are developed using lessons learned from the EU and Great Britain.

Material Flow Analysis (MFA) is used to combine results from both national cement and concrete industries, together with primary and recycled aggregates from the aggregate market made for annual concrete manufacturing in Great Britain, and primary aggregates only for Thailand. Government and manufacturing data for 2012 were used for calculating national cement production by chemical calcination. Then, all MFA outcomes (cement production, virgin and recyled aggregates including waste and emissions) of each nation are presented using Sankey diagrams. This research also considers national estimates of future and prospective demolition of floor area including future concrete demand and waste in the residential sector using Stock Dynamic Analysis (SDA) with Gross Domestic Product (GDP) to indicate demand.

Great Britain with its 61.9 million and Thailand with 64.5 million inhabitants had quite similar populations in 2012. MFA results show that more than 30% of Thai cement and clinker were exported as cementitious products to ASEAN trading countries, in particular, which is double the annual amount of domestic cement used for concrete manufacturing in the whole of Great

Britain. Moreover, the results also show that Thailand used six times more indigenous minerals for cement manufacturing and exporting than Great Britain. The 2012 Thai concrete stock is approximately 3.8 times (256.14 million tonnes: Mt) greater than Great Britain (67.73 Mt). For aggregates used for concrete production, Great Britain uses both primary (48.04 Mt) and recycled aggregates (5 Mt) while Thailand consumes only primary aggregates (214.66 Mt).

The results of SDA show that Thailand uses a large amount of concrete for the housing sector presently due to a shorter lifetime of housing compared to Great Britain. Using 50 years of Thai housing lifespan to compare with Great Britain scenarios, concrete waste generation in Thailand will peak mostly around 2050. This period will produce a similar amount of concrete waste to a scenario of 100 years lifespan in Great Britain (2100). In addition to longer lifetime of housing, an increase in renovation activities and higher quality of housing construction like Great Britain can extend the time of demolition activities and can delay the problem of concrete waste that needs to be disposed of properly in Thailand.

Thailand has no strategy for encouraging recycling of construction materials, with no registered data and no integrated sustainability policy. In the foreseeable future, Thailand may experience problems such as rapidly depleted resources and improper C&D waste management. In contrast, Great Britain has experience in managing C&D waste (particularly concrete waste) as well as conservative consumption of natural resources, involving environmental taxes with cement and associated natural resources used only within the country. Contractors are also encouraged to use recycled aggregates for construction activities, including producing new concrete following a standard from the British Standards Institute (BSI, BS EN 12620:2013 Aggregates for Concrete), with other supporting organisations such as the Mineral Products Association (MPA) and Waste Resource Action Programme (WRAP). However, with the above strategies, Great Britain still has not achieved the anticipated target of recycled aggregate use.

Shortly, the ASEAN countries will form the ASEAN Economic Community (AEC) aiming to achieve a single market and production base. Therefore, there is an opportunity to report on cement and other material requirements and wastes in construction, including comparing awareness and performance of natural resources and waste management practices of two main trading regions. Capitalising on the experiences from the Great Britain case study to cope with rapid economic growth and societal change, this thesis gives some valuable insights into the use of appropriate tools for policy-makers that consider the construction industry and its raw materials including its waste management systems for Thai national policy but also other ASEAN countries.

Acknowledgements

As receiving a Thai government scholarship, I am very grateful to accept the opportunity to pursue my doctorate study at Newcastle University from (1) the Royal Thai Government, (2) Office of The Civil Service Commission, (3) Office of Educational Affairs at the Royal Thai Embassy, United Kingdom and (4) the Pollution Control Department. The academic and international experiences make me very proud to be Thai and give me a great desire to contribute all my knowledge and skills to support my beloved country, following the royal initiative of His Majesty King Bhumibol Adulyadej.

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Lastly, my eternal gratitude is to my beloved parents for their unconditional love, profound understanding and the greatest encouragement during all the ups and downs throughout this marathon journey. Thanks to my adoptive parents (Margaret and John), dearest brother and sisters, together with my bosses, university staff and friends (especially Dr Phatthanawan Promnim and Dr to be Amornphat Tadsanaprasittipol) for their prompt support, endless care and motivation. Furthermore, to my precious brother, Dr Sani M. Makarfi, our mission 'Every day is Monday' allows me to think of him just on Monday. Because of him that helps me get through tough days and reminds me of who I am.

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Abbreviations

ASEAN	The Association of Southeast Asian Nations
AEC	The ASEAN Economic Community
Al_2O_3	alumina
ALSF	The Aggregates Levy Sustainability Fund
BGS	The British Geological Survey
BIM	Building Information Modelling
BMA	Bangkok Metropolitan Administration
BSI	British Standards Institution
C&D waste	construction and demolition waste
CaO	lime
CD&E waste	construction, demolition and excavation waste
CEAT	The Consulting Engineer Association of Thailand
CEnv	The Chartered Environmentalist
CF	Carbon Footprint
CIOB	The Chartered Institute of Building
CKD	cement kiln dust
CO_2	carbon dioxide
COE	The Council of Engineers of Thailand
CSI	The Cement Sustainability Initiative
CU	concrete in use
DCLG	The Department for Communities and Local Government
Defra	The Department for Environment, Food & Rural Affairs
EPR	The Environmental Permitting Regulations
ESEA	The European Strategy for Environmental Accounting
EU	The European Union
EWC	The European Waste Catalogue
FAU	floor area in use
Fe_2O_3	Ferric oxide
GDP	Gross Domestic Product
GGBS	ground granulated blast furnace slag
GIS	Geographical Information Systems
HMRC	Her Majesty's Revenue and Customs
IOA	Input-Output Analysis
ISO	The International Organization for Standardization

JISC	The Japanese Industrial Standards Committee
Kg	kilogram
kg/m^3	kilograms per cubic metre
km^2	square kilometres
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
m^2	square meters
MFA	Material Flow Analysis
MFCA	Material Flow Cost Accounting
MFMs	Material Flow Methodologies
MIOTs	Monetary Input-Output Tables in money terms
MJ/kg	megajoules per kilogram
MPA	The Mineral Products Association
Mt	million metric tonnes
NGO	Non-Governmental Organization
NICs	The employers' national insurance contributions
NIEA	The Northern Ireland Environment Agency
OECD	The Organisation of Economic Co-operation and Development
ONS	The Office of National Statistics
PA	Process Analysis
PIOTs	Physical Input-Output Tables in physical units
PPP	purchasing power parity
SDA	Stock Dynamic Analysis
SEEA	The System of Integrated Environmental and Economic Accounting
SETAC	The Society of Environmental Toxicology and Chemistry
SiO_2	silica
SPC	The Statistical Programme Committee
UK	United Kingdom
UNCED	United Nations Conference on Environment and Development
UNCEEA	United Nations Committee of Experts on Environmental-Economic Accounting
UNSC	The UN Statistical Commission
US	United States
WRAP	The Waste Resource Action Programme

Chapter 1 Introduction

The Chapter introduces the key areas that inspire and contribute to this thesis through section 1.1. Based on the understanding and identified research gaps, section 1.2 specifies the context, aim and objectives of the thesis structure.

1.1 Introduction

In all countries, the construction business and demand for construction materials have directly fluctuated with the national economy. The regional economic development of Southeast Asian countries, known as the Association of Southeast Asian Nations (ASEAN), also drives the demand for construction and materials. However, these countries have no systematic planning and no supporting data together with integrated policy of natural resources and construction and demolition waste (C&D waste), compared to the European Union (EU). In Great Britain, as an EU country, waste management is highly regulated with encouragement of recycling, and the mining of primary construction aggregates is discouraged through environmental taxation. These policies encourage sustainable use of non-renewable resources, underpinning a change in the culture of construction in Great Britain.

As shown in **Figure 1-1**, this thesis uses Thailand to represent ASEAN countries, where there are no policy or environmental tax drivers to influence behaviour in the construction and associated waste sectors. The situation in Thailand is compared with Great Britain as an example of good practice in the EU. Although Great Britain is an important country that can meet EU targets for recycled aggregate uses and C&D waste management, the use of recycled aggregates in the concrete industry is lower than it might be, due to the lack of confidence among consumers (The European Environment Agency, 2008). Appropriate approaches relating to these EU operations are of major importance for ASEAN countries, especially for Thailand, given the rapid growth of urbanisation. Great Britain strives to reach a goal that minimises inappropriate resource use, minimises waste, and maximises benefits through raising environmental taxes; Thailand and other ASEAN countries have yet to start on that journey.

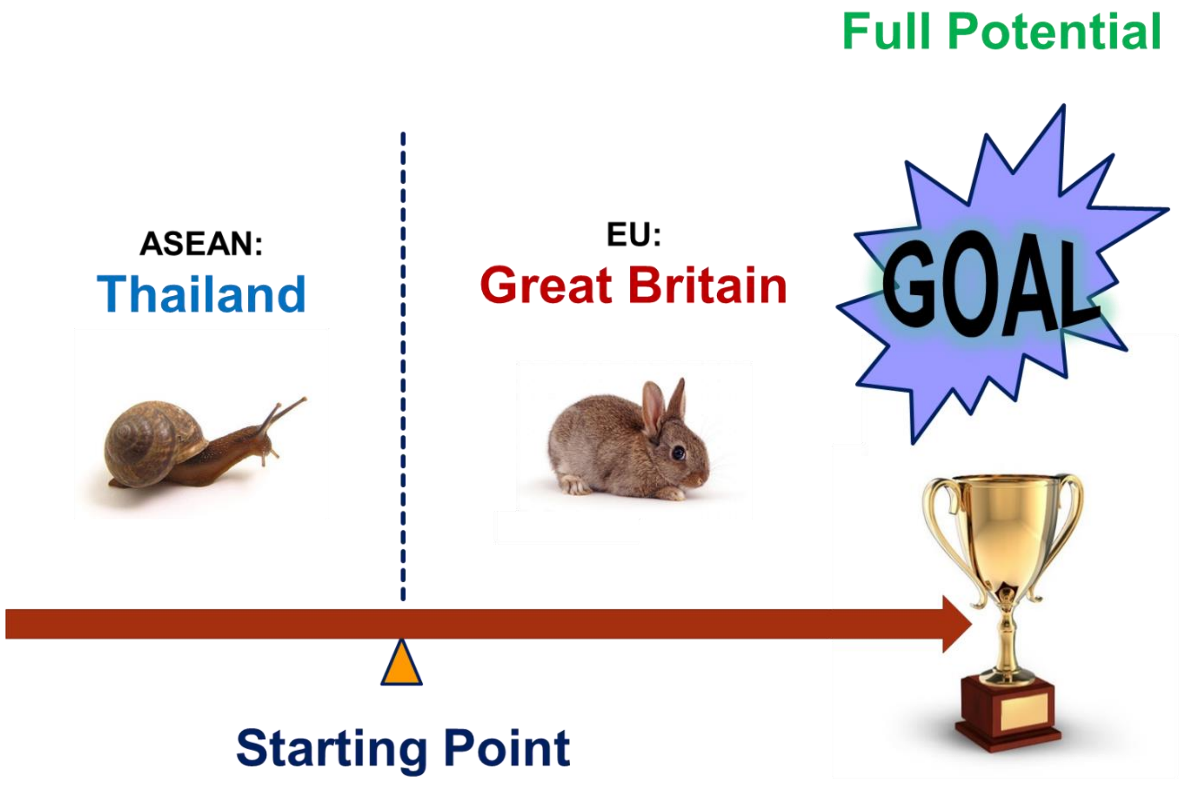


Figure 1-1 Thesis concepts in policies and environmental taxes relating to construction materials and construction and demolition waste management, leading to best practice in the use of non-renewable resources.
Sources: Author

1.2 Aim and Objectives

Concrete is an essential material for the global construction industry, especially for developing countries, since these countries consume increasing amounts of concrete to support their national economic expansion, increased urbanisation, and to improve the well-being of their population. The more concrete is manufactured, from non-renewable resources, to reach demands for construction presently, the more concrete waste, directly impacting on the environment, will be generated in the future. Furthermore, the other main limitation of concrete waste management in developing countries is lesser concern in policy and regulation, including no main responsible organisation and no environmental tax to minimise waste.

This study aims to investigate the experiences of the EU and Great Britain from the practical insights of laws and regulations relating to natural resources and environmental management of construction materials. The influence of the EU and Great Britain strategies for the better management of annual and future concrete stock leads to a better understanding of material supplies and sustainable disposal chains for developing urban societies with a rapid economic growth and societal changes, such as Thailand and the other nine ASEAN countries. By understanding the flow of construction materials through society, the benefits of appropriate policy and taxation can be demonstrated for Thailand.

The objectives required for this study are:

(1) to collect data on domestic cement production in Great Britain and Thailand,

(2) to calculate the quantity of the raw material use based on calcination characteristics for both national cement industries,

(3) to compare the flows of cement, aggregates and concrete used in each country,

(4) to carry out a material flow analysis of existing and future stocks of concrete and associated raw materials and wastes in Great Britain and Thailand,

(5) to develop stock dynamic analysis for housing in Thailand and Great Britain,

(6) to interpret the Material Flow Analysis (MFA) and the Stock Dynamic Analysis (SDA) to extract key information affecting policy development,

(7) to develop an outline policy appropriate for Thailand and other ASEAN countries.

Chapter 2 Construction Industries in Great Britain and Thailand

This chapter explains the five main parts of the construction industries of Great Britain and Thailand. These parts are the cement industry, aggregate market, concrete industry, construction industry and waste management. All these details are presented in terms of their basic structure, before more detailed discussion in other chapters relating to the two case studies.

2.1 Great Britain

2.1.1 Cement Industry

It can be stated that the origin of the modern cement manufacturing techniques came from England. Portland cement, its colour resembles Portland stone, was invented by Joseph Aspdin using calcined impure limestone and clay, who patented it in 1824 (Manning, 1995; Domone and Illston, 2010). Consequently, this invention started the large scale production of cement. Because of a too low calcining temperature, his cement had poor quality (Kurdowski, 2014). Using previous experiences of many predecessors in England, in 1845, Isaac Charles Johnson found the correct proportion of clinker minerals and also chose a higher burning temperature (Bogue, 1947; Lea, 1971). However, it is still unclear between Aspdin and Johnson who is the first pioneer for this efficient condition because some authors argued that the higher temperature in a calcination process was suggested by Aspdin (Kurdowski, 2014). Since then cement manufacturing in European countries has been continuously developed, and the most rapid evolution was after the Second World War (Kurdowski, 2014).

Since the 20th century, concrete has been the most valuable construction material and the core part of the infrastructure. Consequently, cement, a hydraulic binding agent in concrete, is the essential component. In Great Britain, the cement production industry is represented by the Mineral Products Association (MPA), the principal trade association for many construction materials in the UK. According to the crisis of climate change and high greenhouse gas emissions in cement manufacturing processes, MPA is addressing the challenge to sustain its members' commercial enterprises, and developing a strategy to cut 81% of greenhouse gases, especially carbon dioxide (CO_2) by 2050 compared with 1990 levels (MPA, 2013d). This planned reduction uses combined strategies such as (1) more alternative waste-derived fuels, (2) more carbon-neutral biomass fuels, (3) lower carbon cements, (4) fewer indirect CO_2 emissions by improving electrical efficiency and by the de-carbonisation of the electricity sector, (5) carbon capture and storage, (6) reduced transport emissions, and (7) robust carbon accounting.

2.1.1.1 Clinker Manufacturing

For the mineral market, mining and quarrying was worth £24 billion or 2.55% of the UK GDP in 2012 (ONS, 2013a). Providing calcareous, aluminous, siliceous and ferrous elements for clinker manufacturing, the important indigenous clinker minerals, a part of this market, are limestone (mainly), chalk, cement clay, and shale. In 2012, recorded data showed that Great Britain used 10.64 Mt of these main minerals for clinker, and these were lower in quantity than in the past (**Figure 2-1**). This is because the amount of clinker minerals produced for the cement industry is directly proportional to cement production, and consumption slightly decreased during the same period.

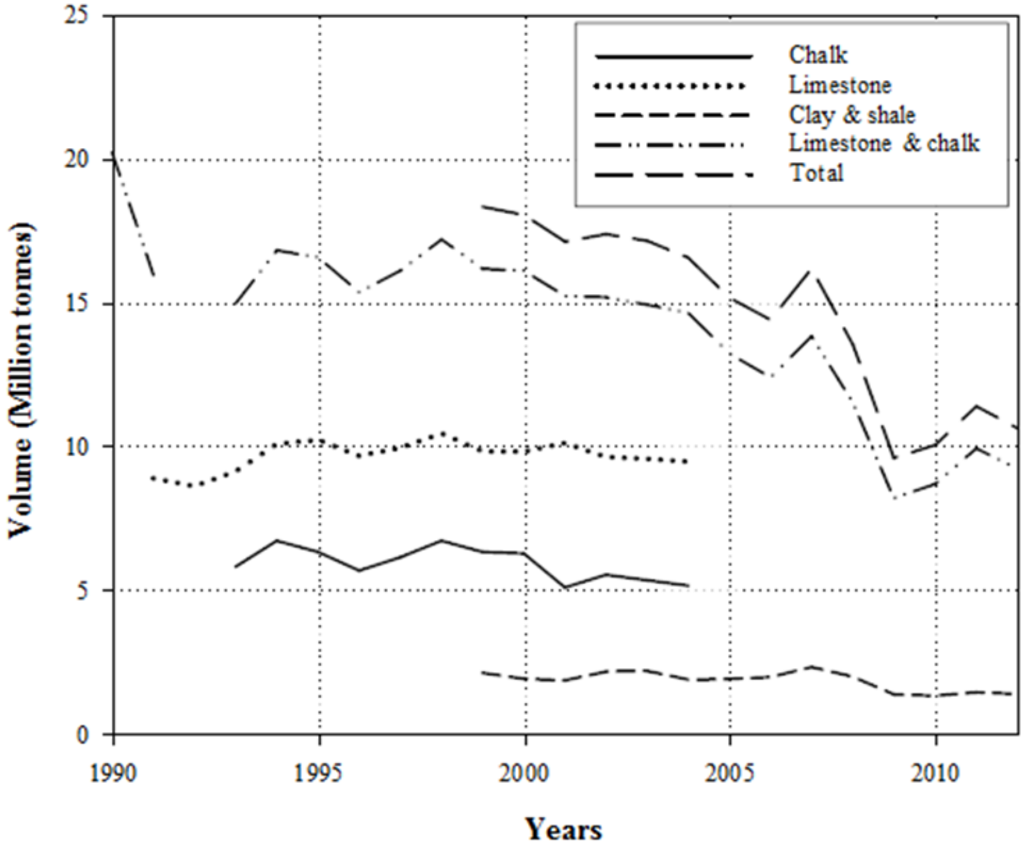


Figure 2-1 Clinker minerals in Great Britain
Sources: Author based on BGS (2003), (2004), (2005), (2006), (2007), (2008b), (2009), (2010), (2011), (2012), (2013), (2014c) and ONS (2000), (2001), (2002), (2003), (2004), (2005), (2006), (2007), (2008b), (2009b), (2010c), (2011d), (2012e), (2014d)
Note: Continuous data are not available as reported categories changed with time

2.1.1.1.1 Emissions

In the manufacturing stage, it is noteworthy that emissions from cement processes make more serious impacts for the environment than any other construction material, affecting global warming, ocean acidification, and photo-oxidant formation (Kofoworola and Gheewala, 2008). Cement industries generate a large amount of CO_2, because manufacturing processes need to burn minerals and fossil fuels, including electricity used in plants. Moreover, transportation of both raw materials and final products is one of the causes of CO_2 emission. CO_2 emission of global cement industry mainly comes from mineral calcination, more than the CO_2 derived from associated combustion of fossil fuels and waste derived fuels, by around two times (National Ready Mixed Concrete Association, 2012). For the UK, CO_2 emissions (kilograms; Kg) per tonne of Portland cement are shown in **Figure 2-2**.

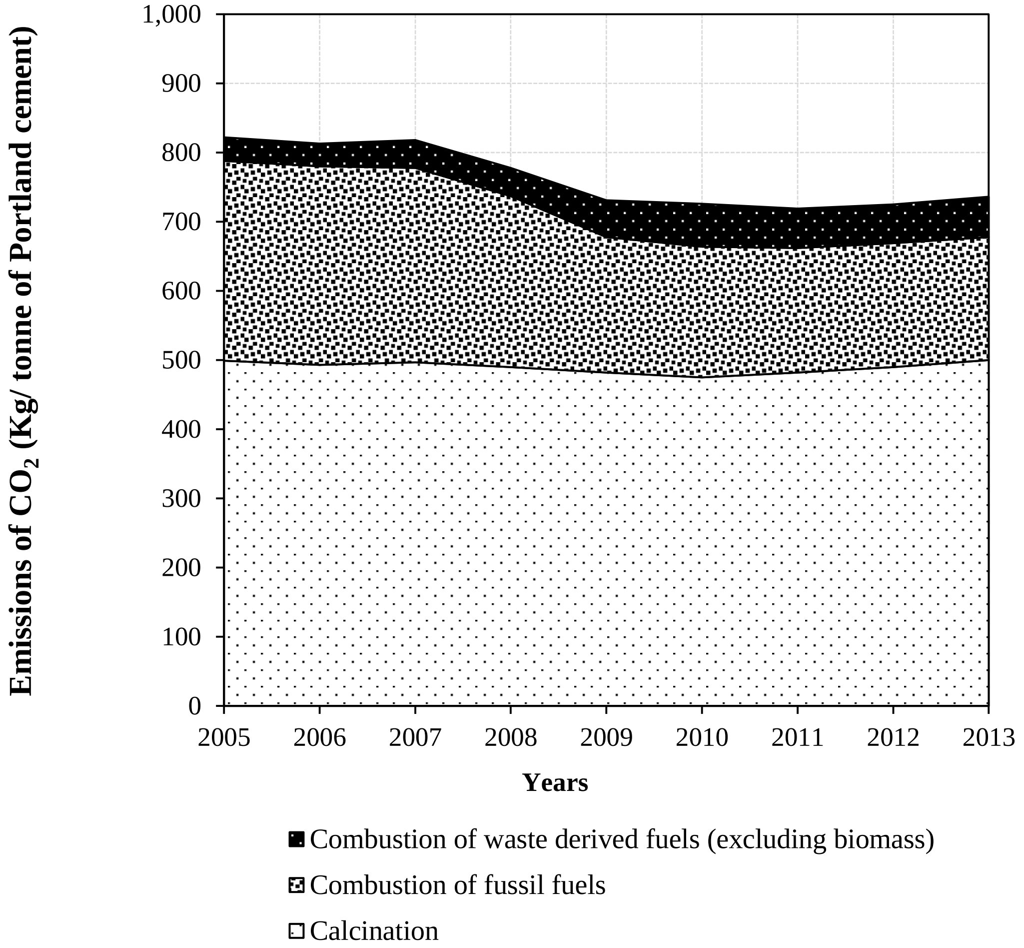


Figure 2-2 UK cement industry emissions (CO_2 (kg) per tonne of Portland cement), based on 1998
Source: Author based on MPA (2014c)

2.1.1.1.2 Fuels

In addition to efforts to reduce conventional fuels such as coal for saving natural resources and reducing greenhouse gas emissions, waste-derived fuels have been increasingly used since 1998 (MPA, 2013c; MPA, 2014c). Examples of waste-derived fuels or alternative fuels can be separated into three main types, as (1) liquid waste fuels, (2) solid waste fuels and (3) gaseous waste (**Table 2-1**, Alsop (2014)). Wastes and by-products used as fuel and raw materials comprised 40% of fuels used for Great Britain cement manufacturers in 2012 (**Figure 2-3**). Then, these fuels rose slightly to around 44% of total fuels or 1.5 million tonnes in 2013 (MPA, 2013c). They can be fed into the burning chamber or directly fed into the burning zone in the cement kiln or the pre-heating system (Kääntee *et al.*, 2004).

Table 2-1 Alternative fuels in cement industry

Liquid waste fuels	Tar, chemical wastes, distillation residues, waste solvents, used oils, wax suspensions, petrochemical waste, asphalt slurry, paint waste, oil sludge
Solid waste fuels	Petroleum coke, paper waste, rubber residues, pulp sludge, used tires, battery cases, plastic residues, wood waste, domestic refuse, rice chaff, refuse derived fuel, nut shells, oil-bearing soils, sewage sludge
Gaseous waste	Landfill gas, pyrolysis gas

Source: Taken from Alsop (2014)

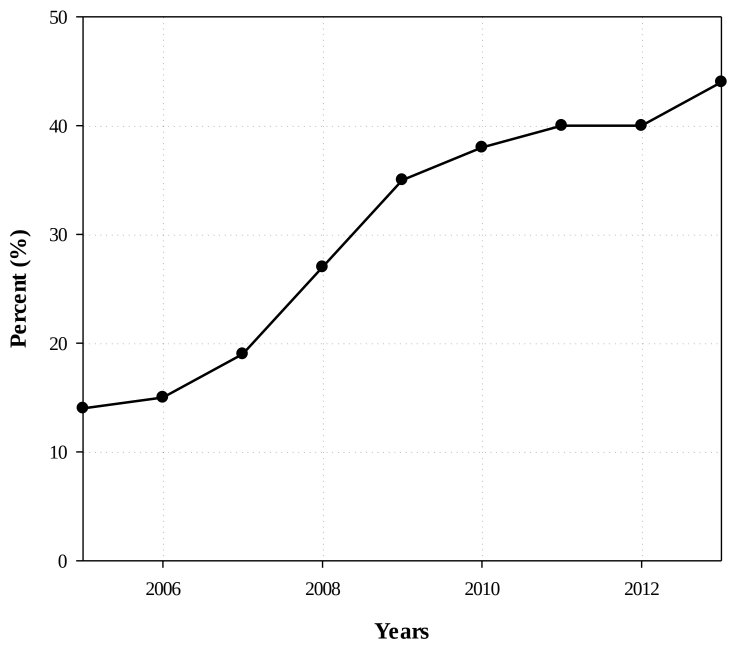


Figure 2-3 Proportion of fuel comprising waste material in the UK cement kiln sites, based on 1998
Sources: Author based on MPA (2013c) and (2014c)

2.1.1.2 Cement Manufacturing

Almost all kiln, grinding and blending sites (including blending only) are located in Great Britain (**Figure 2-4**). MPA Cement, a part of MPA, represents four main cement manufacturers for the concrete industry, namely CEMEX UK Cement, Hanson Cement, Lafarge Tarmac and Hope Construction Materials. Details of Great Britain cement plants with their clinker capacity, process types and locations are shown in **Table 2-2**. This table also shows that Great Britain still has mixed processes of cement manufacturing as dry, semi-wet and semi-dry processes with similar capacity. Since 2009, cementitious production and consumption in Great Britain have reduced around 30% and the volume of cement additives used is directly affected by cement consumption (**Figure 2-5**). Comparing with cement consumption per capita in some main European countries in 2012, the UK consumed cement around 50% lower than the European average, or 154.84 kilograms (kg) per capita as shown in **Figure 2-6**.

	Company	Site
1	CEMEX	Rugby
2	CEMEX	South ferriby
3	CEMEX	Tilbury
4	Hanson	Ketton
5	Hanson	Padeswood
6	Hanson	Ribblesdale
7	LAFARGE TARMAC	Aberthaw
8	LAFARGE TARMAC	Barnstone
9	LAFARGE TARMAC	Cauldon
10	LAFARGE TARMAC	Cookstown
11	LAFARGE TARMAC	Dunbar
12	LAFARGE TARMAC	Tunstead
13	LAFARGE TARMAC	Belfast
14	LAFARGE TARMAC	Northfleet
15	LAFARGE TARMAC	Scot Ash
16	LAFARGE TARMAC	Seaham
17	LAFARGE TARMAC	West Thurrock
18	HOPE Construction Materials	Hope
19	HOPE Construction Materials	Dewsbury
20	HOPE Construction Materials	Theale
21	Kerneos	Purfleet

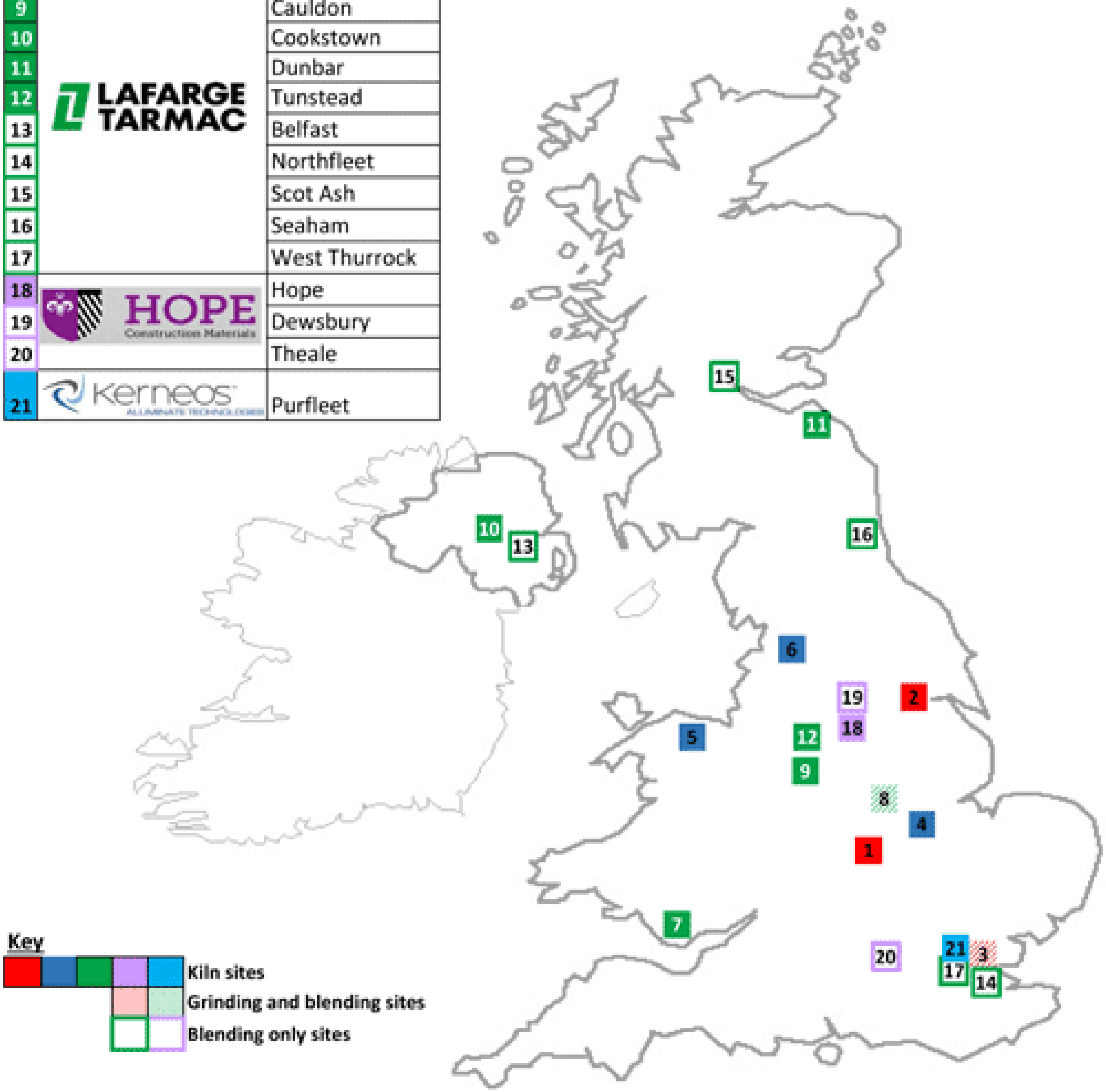


Figure 2-4 Site locations of UK kiln, grinding and blending, including blending only
Source: Taken from MPA (2014a)

Table 2-2 Great Britain cement plants with details

Cement Companies	MPA	Plant	Cement clinker capacity (Thousand tonnes/ year)	Process
Lafarge Tarmac	Staffordshire	Cauldon	900	Dry
	Vale of Glamorgan (South Wales)	Aberthaw	500	Dry
	East Lothian (Scotland)	Dunbar	900	Dry
	Derbyshire	Tunstead	1,095	Dry
	Kent	Northfleet		Grinding and Blending
	Nottinghamshire	Barnstone		Grinding and Blending
	Fife (Scotland)	Scot Ash		Blending
	County Durham	Seaham		Blending
	Essex	West Thurrock		Blending
Hanson Cement	Rutland	Ketton	1,390	Dry
	Lancashire	Ribblesdale	750	Dry
	Flintshire (North Wales)	Padeswood	820	Dry
	North Lincolnshire	South Ferriby	750	Semi-dry
CEMEX UK Cement	Warwichshire/ Bedforshire	Rugby	1,500	Semi-wet
	Essex	Tilbury		Grinding and Blending
Hope Construction Materials	Peak District National Park	Hope	1,300	Dry

Source: Modified from BGS (2014b)

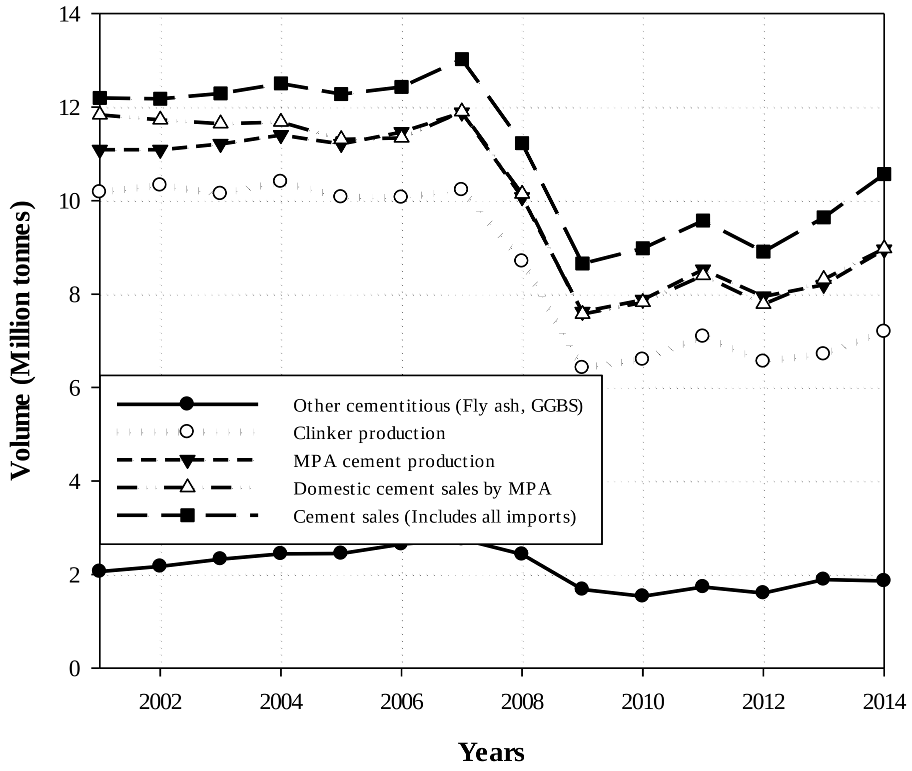


Figure 2-5 Great Britain cement production and sales including additive
Source: Author based on MPA (2015c)

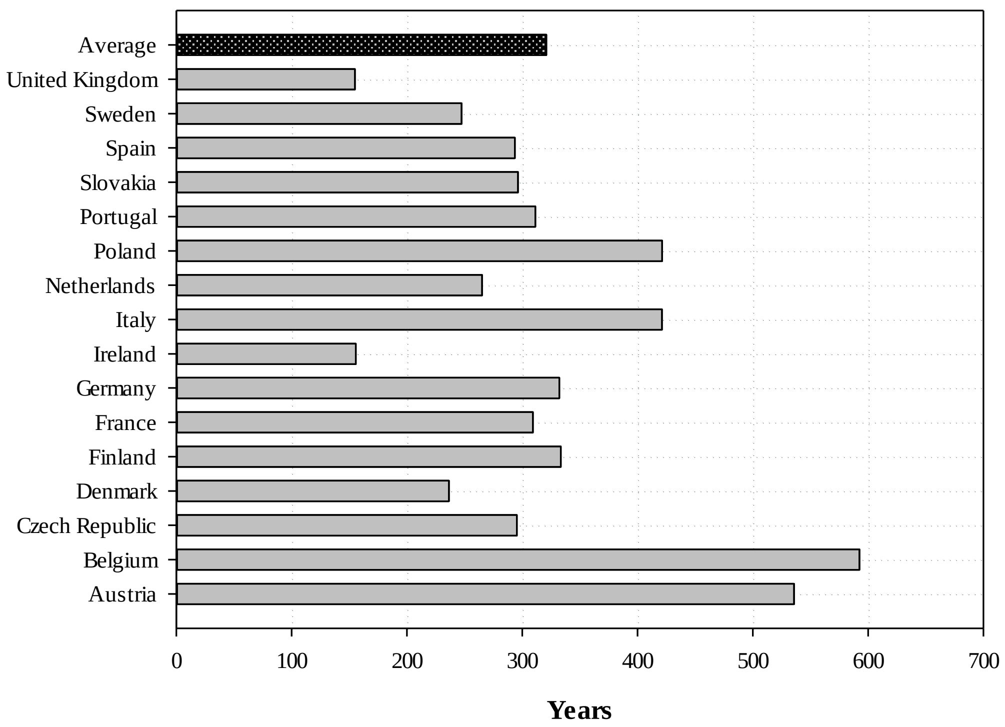


Figure 2-6 Cement consumption per capita in main EU countries (2012)
Source: Author based on European Ready Mixed Concrete Organization (2013)

Moreover, Great Britain uses almost all its domestic production with the very little volume of exported and imported cement. As noted, the import volume was slightly higher than exports and the main cement organisations importing mostly are unrelated to MPA (**Figure 2-7**). Portland cement is the dominant type of cement for international trade exchange (**Figure 2-8**). Domestic cement consumption in Great Britain is mainly used for the concrete industry (85% England, 10% Scotland and 5% Wales; **Figure 2-9**).

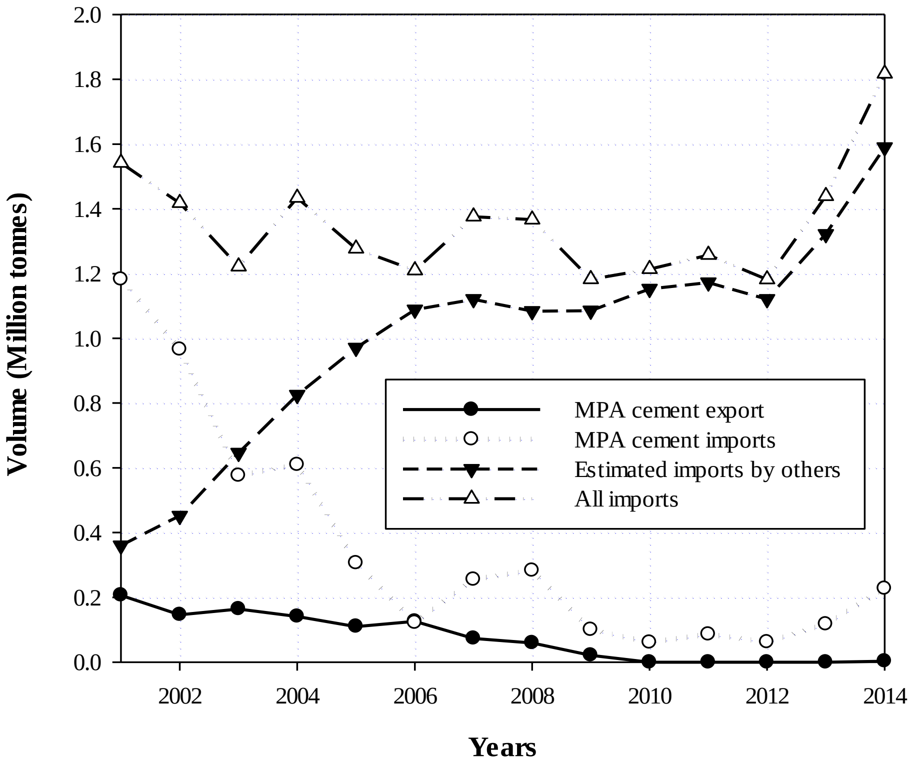


Figure 2-7 Great Britain cement import and export
Source: Author based on MPA (2015c)

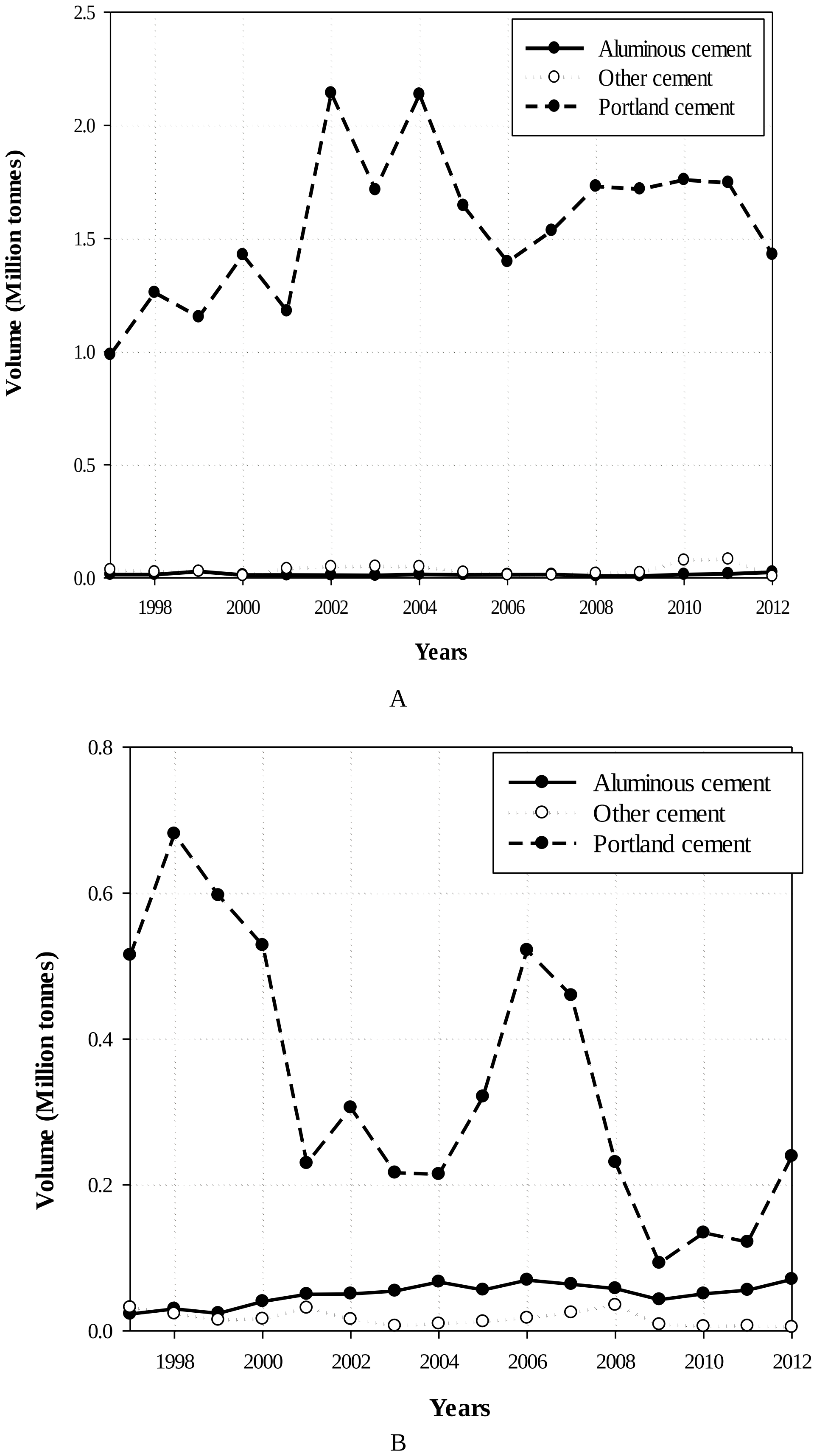


Figure 2-8 Imported (A) and exported (B) cement in Great Britain
Sources: Author based on BGS (2003), (2004), (2005), (2006), (2007), (2008b), (2009), (2010), (2011), (2012), (2013) and (2014c)

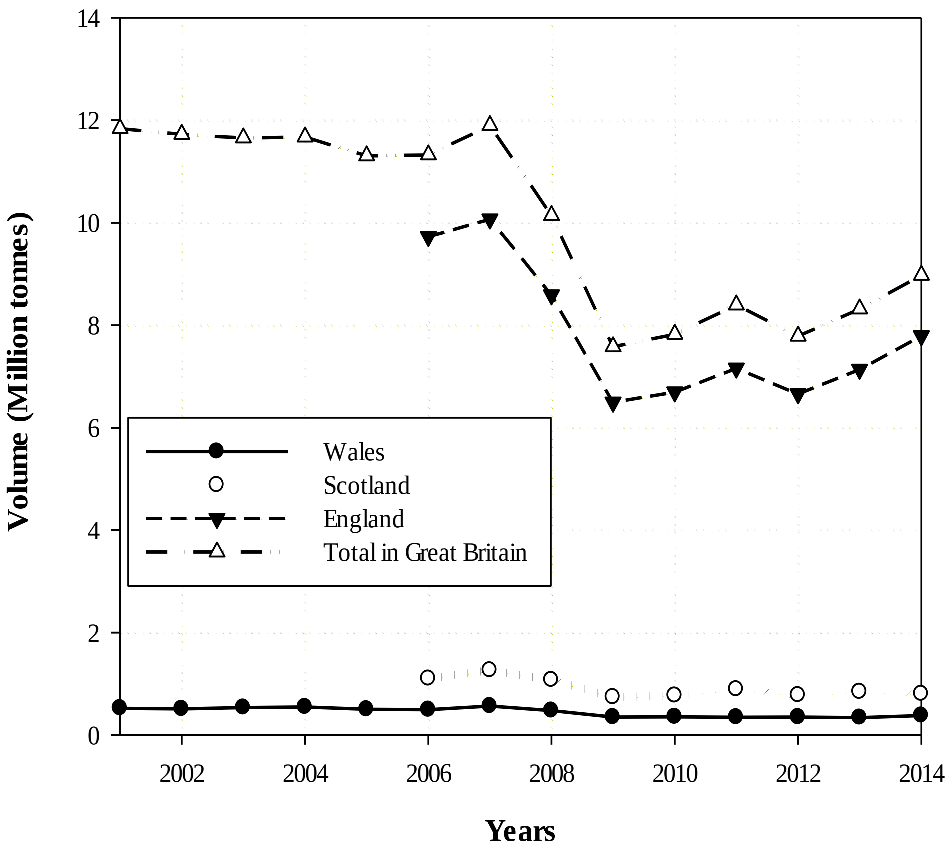


Figure 2-9 Great Britain regional cement sales
Source: Author based on MPA (2015b)

2.1.1.2.1 Cement for Concrete

The concrete industry is the main channel of cement sales in Great Britain. Domestic cement consumption is largely separated into 55% ready mix concrete, followed by 23% precast concrete products, 19% merchant and 3% other uses (**Figure 2-10**).

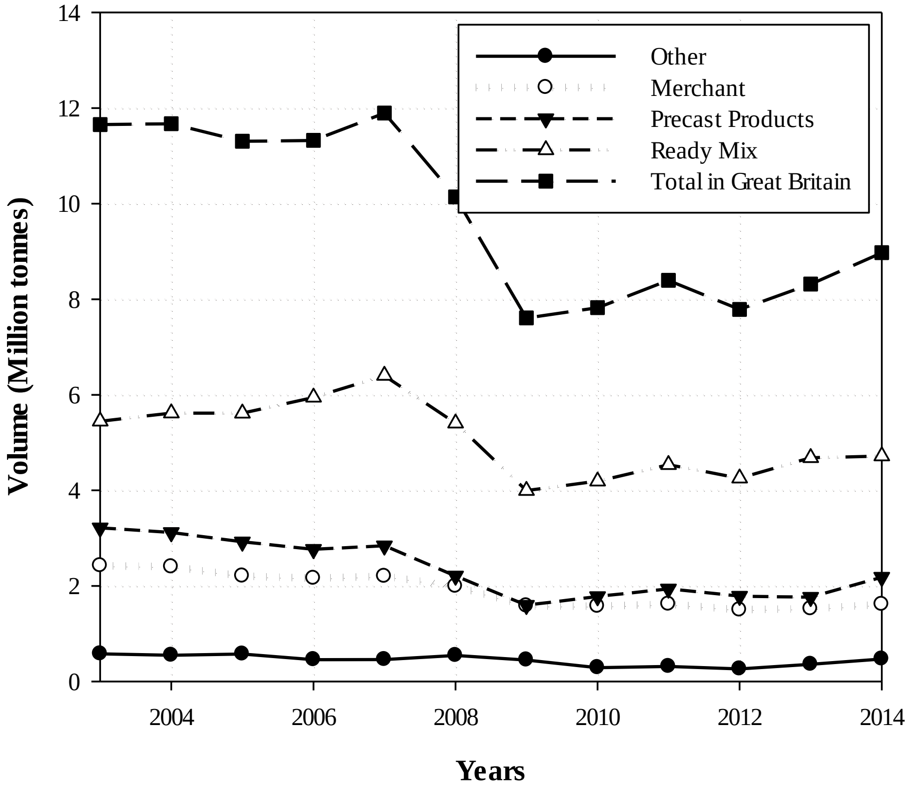


Figure 2-10 Cement sale channels in Great Britain
Source: Author based on MPA (2015a)

2.1.1.2.2 Cement for Mortar

In 2012, Great Britain used 2.20 Mt cement for mortar or around 20% of its cementitious product (MPA, 2014b). This high cement requirement may come from the common use of construction methods using brick and block as a double layer that needs more binding (Mortar Industry Association, 2013).

2.1.1.2.3 Cement for Other Uses

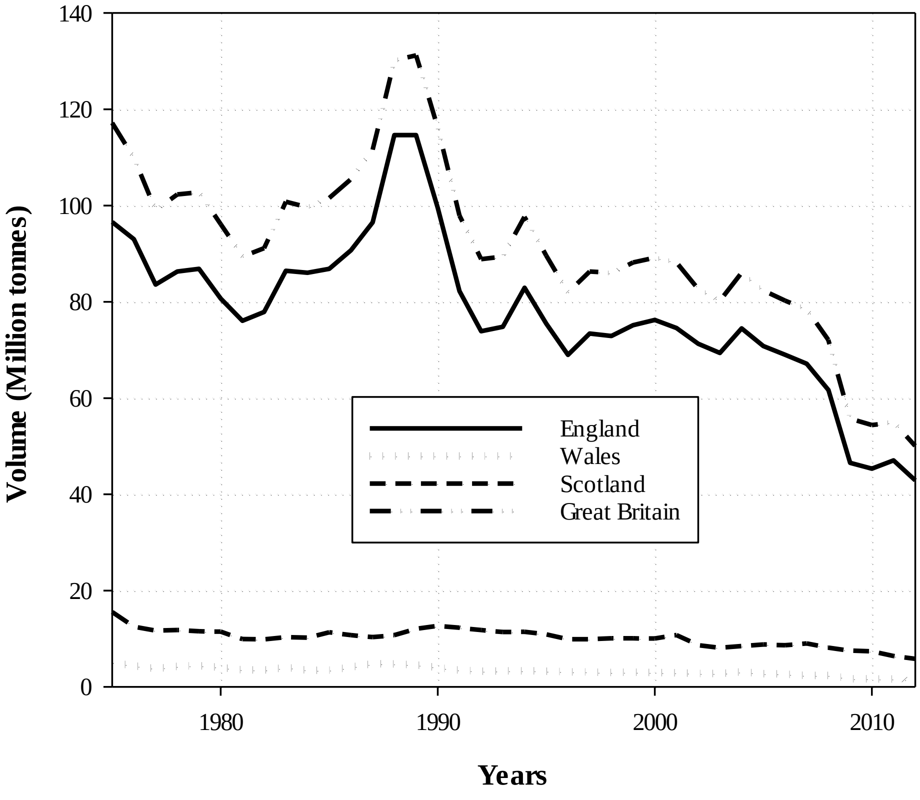
For other uses of cement, the remaining 5% is estimated for other benefits such as soil and pH stabilisation (WBCSD, 2009b). However, in Great Britain, MPA (2015a) reported cement usage for other purposes is around 3%.

2.1.2 Aggregate Market

2.1.2.1 Primary Aggregate Production

Although the UK has over 350 quarry companies in the MPA, mostly located in Great Britain, 80% (200 million tonnes) of total aggregate supply is produced by only seven dominant companies (The European Environment Agency, 2008; Seely, 2011). Aggregate production, fine (4 millimetres (mm) particle size and smaller) and coarse (more than 4 mm particle size), is made in all regions of Great Britain. Depending on the fluctuations of domestic demand, England produces and consumes most, around 82-88% sand and gravel, and 61-75% crushed rock. The second aggregate producer and consumer is Scotland: 8-14% sand and gravel with 11-26% crushed rock. The remaining production comes from Wales: around 3-4% sand and gravel and 12-17% crushed rock (**Figure 2-11**).

For the international trading of aggregates, Great Britain exported little volume (<5%) of indigenous primary aggregates compared to domestic consumption. This international trade seems to show the same trends of import and export for clinker and cement; that is little export and import. However, the export volume of all types of primary aggregates was higher than import (**Figure 2-12**).



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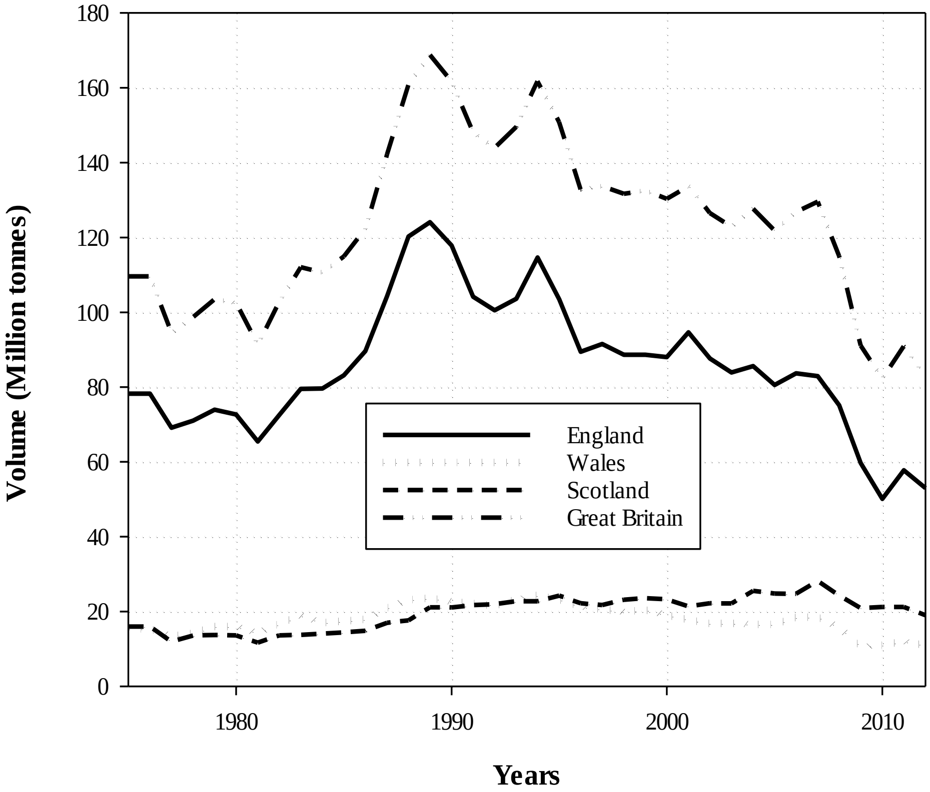
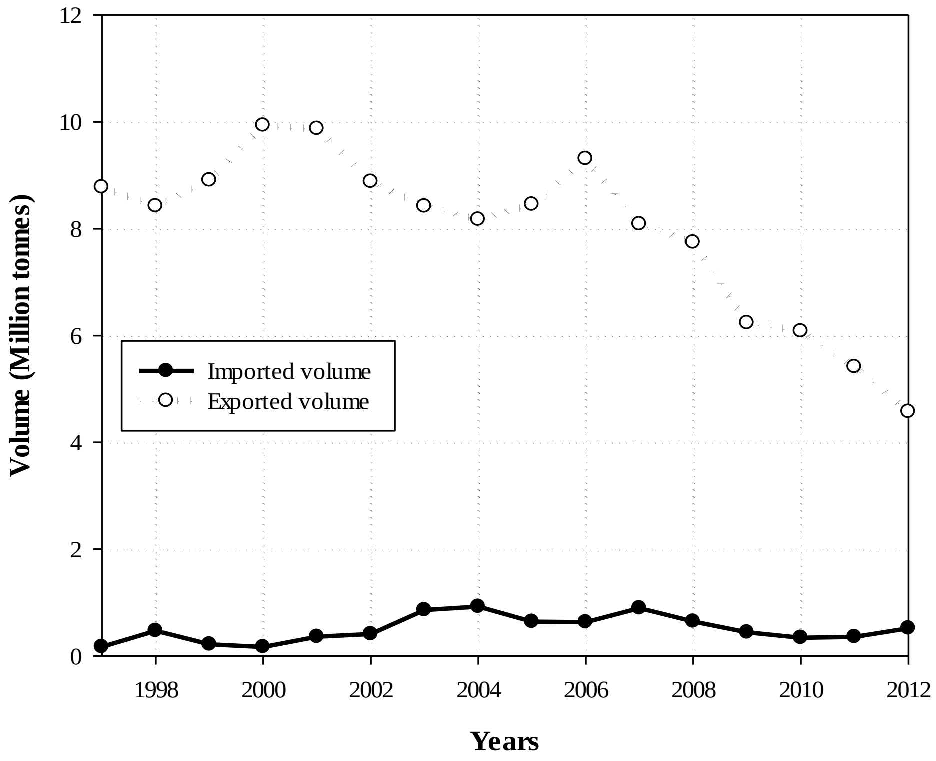


B

Figure 2-11 Total production of primary sand and gravel (A) and crushed rock (B), by end-use in Great Britain

Sources: Author based on BGS (2003), (2004), (2005), (2006), (2007), (2008b), (2009), (2010), (2011), (2012), (2013) and (2014c)



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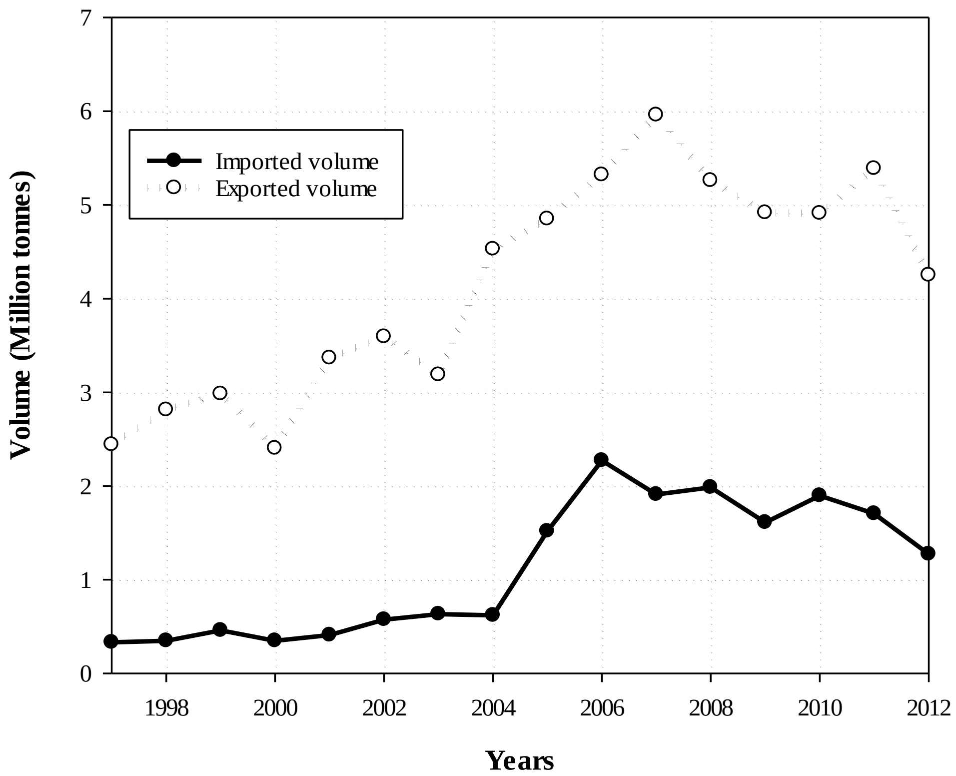


B

Figure 2-12 Total import and export of sand and gravel (A) and crushed rock (B) in UK
Sources: Author based on BGS (2003), (2004), (2005), (2006), (2007), (2008b), (2009), (2010), (2011), (2012), (2013) and (2014c)

2.1.2.2 Recycled and Secondary Aggregate Production

Aiming for resource efficiency, Great Britain has achieved the highest recycled and secondary aggregates rate in the EU, accounting for 29% of total aggregates in the aggregate market of Great Britain or three times higher than the European average consumption (The European Environment Agency, 2008; The Concrete Centre, 2009; MPA, 2013c). These aggregates come from (1) natural, (2) recycled and (3) manufactured materials (**Table 2-3**).

Table 2-3 Aggregates from natural, recycled and manufactured materials

Recycled Aggregates	**Secondary Aggregates**	
	Manufactured Aggregates	**Natural Aggregates**
• Recycled aggregate (RA) • Recycled concrete aggregate (RCA) • Recycled asphalt • Recycled asphalt planings (RAP) • Spent rail ballast	• Blast furnace slag • Steel slag • Pulverized fuel ash (PFA) • Incinerator bottom ash (IBA) • Furnace bottom ash (FBA) • Used foundry sand • Spent oil shale • Recycled glass • Recycled plastic • Recycled tyres	• Slate aggregate • China clay sand • Colliery spoil

Source: Taken from BGS (2008a) and WRAP (2015a)

The efficiency cycle of C&D waste by WRAP (2011) can be used to explain the recycled activities of aggregates from concrete waste as **Figure 2-13**. Recycled aggregates arise from construction and demolition of buildings, structures, or civil engineering works including asphalt from resurfacing roads and railway track ballast. After the demolition stage, mainly providing waste volume, concrete waste can be recycled and used in-sites to build the new building in combination with primary materials and/or recycled off-site at recycled aggregate sites. The benefits of reused aggregate from old concrete on-site saves natural resources and reduces transport and dust (Di Maio *et al.*, 2012).

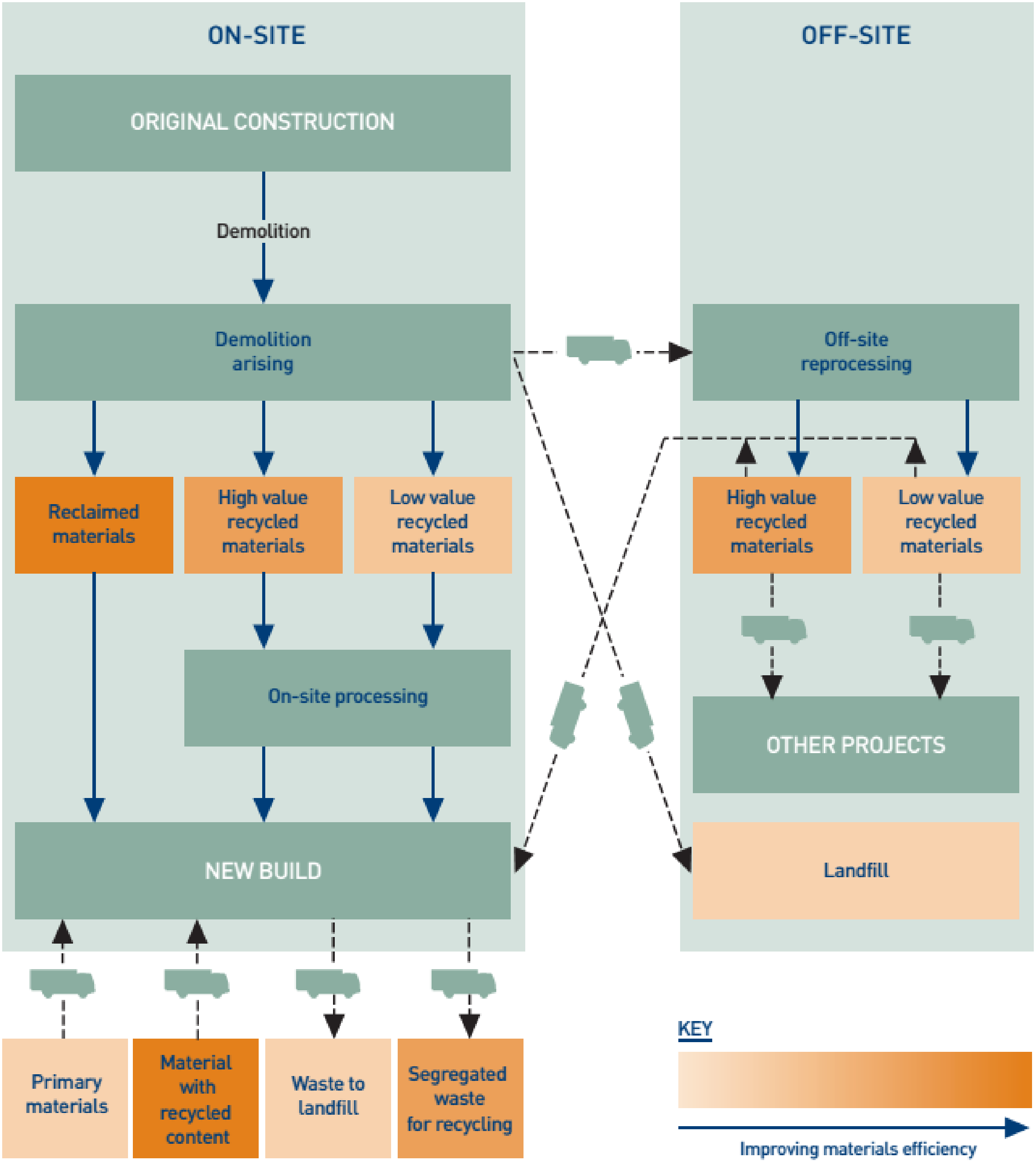


Figure 2-13 The efficiency cycle of C&D waste
Source: Taken from WRAP (2011)

Reducing the size of concrete waste and removing metal are main manufacturing processes of recycled aggregates in off-site operation. To obtain the size of recycled aggregate as required, screening of recycled aggregate into different fractions is the final process (**Figure 2-14**). Examples of recycled aggregate products as coarse and fine recycled concrete aggregates from Thompsons of Prudhoe at Springwell Quarry, Gateshead, Newcastle upon Tyne, can be seen in **Figure 2-15**. At the end of concrete waste separation in both sites' operation, the remaining will be sent for disposal at landfill as inert waste.

As stated by Symonds Group Ltd. et al (1999), primary aggregates can be substituted by recycled aggregates to reduce extracted and processed activities from quarries and relieve biodiversity issues, including to preserve non-renewable resources and to minimise landfill space. In addition, the transportation cost of these materials can be reduced by using recycled aggregates from local areas. On the other hand, processing of recycled aggregates can cause air pollution and make noise as the major environment and health concerns. Therefore, some researchers such as Monier *et al.* (2011) concluded that the environmental benefits of recycled concrete for coarse or fine aggregates are probably moderate.

A filling material in quarries and earthwork construction such as roads, yards and building foundations that include a concrete component is the main use for coarse recycled concrete aggregates (Monier *et al.*, 2011; MPA, 2013b). Fine recycled concrete aggregates can be used to replace primary sand in mortars. However, this affects the mortar water content and its workability directly in terms of strength and shrinkage due to high water absorption. It causes increasing risk of settlement and dry shrinkage cracking and its use needs to be avoided in structural concrete (Monier *et al.*, 2011).

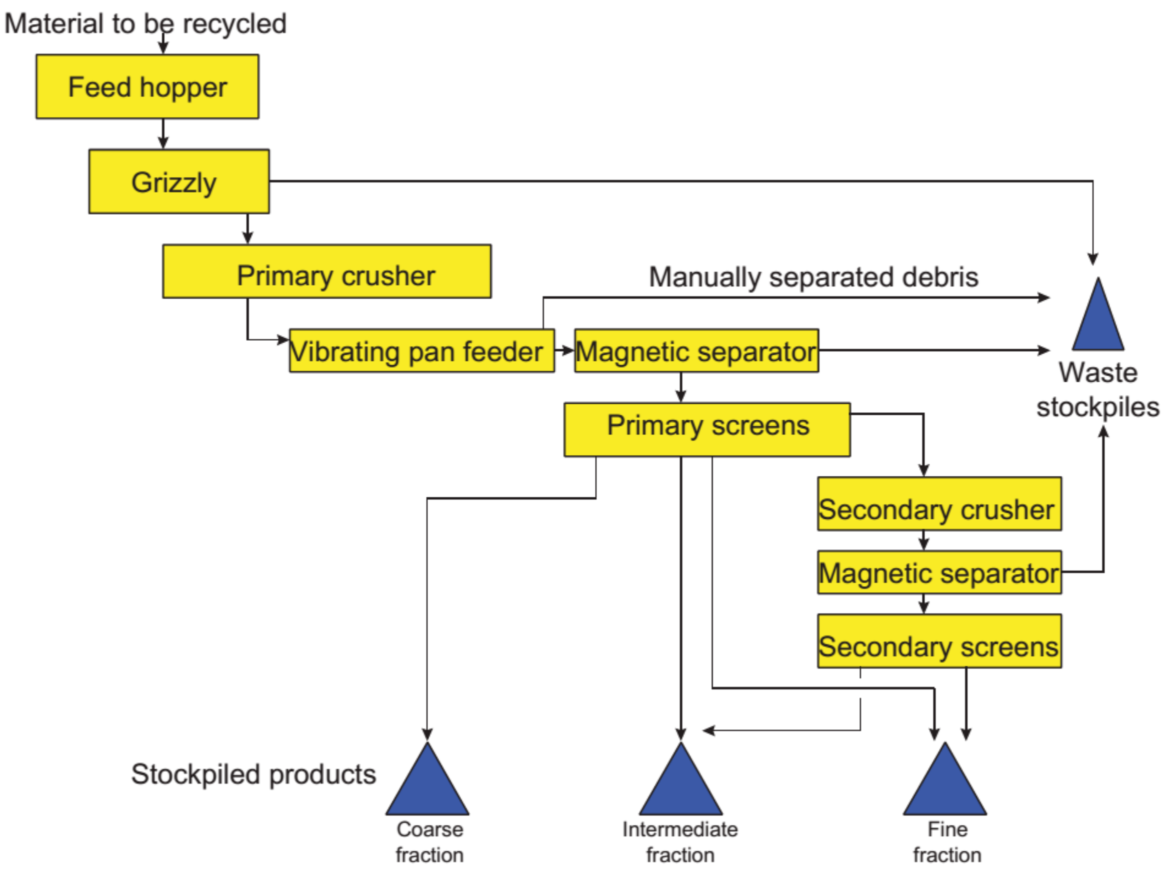


Figure 2-14 Generalised flow diagram for an aggregates recycling operation
Source: Taken from Wilburn and Goonan (1998)

Coarse Recycled Concrete Aggregates

Fine Recycled Concrete Aggregates

Figure 2-15 Coarse and fine recycled concrete aggregates from Thompsons of Prudhoe at Springwell Quarry, Gateshead, Newcastle upon Tyne on 9th September 2014

2.1.2.3 Aggregate Consumption

2.1.2.3.1 All Purposes of Aggregates for Construction

The majority of primary aggregates used in 2012 came from crushed rock (44%). Primary sand and gravel were used with 21% from land mining and 6% from marine-dredged material. Great Britain used almost three times more primary aggregates than recycled and secondary aggregates (29%, **Figure 2-16**). Moreover, Great Britain used primary aggregates mostly for concrete (around 36%), followed by 23% road, 14% other screened and graded, and 13% other constructional purposes, 4% fill, 4% mortar, 4% armour stone and gabions, and 2% rail ballast (**Figure 2-17**).

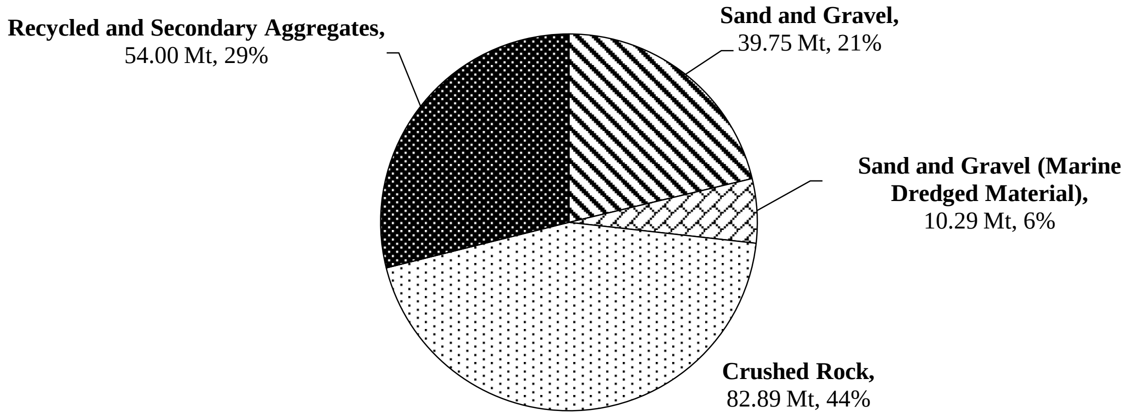


Figure 2-16 Aggregate produced for Great Britain construction (2012)
Sources: Author based on MPA (2013c) and ONS (2014d)

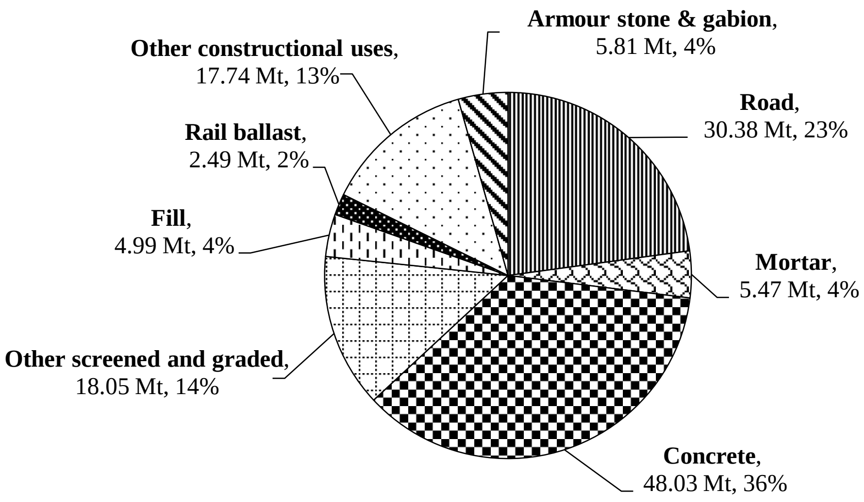


Figure 2-17 Primary aggregate uses in Great Britain in 2012
Source: Author based on ONS (2014d)

In 2012, the consumption of primary aggregates in the UK was half of the average of the majority of European countries (2.39 tonnes per capita, **Figure 2-18**). Additionally, Defra (2015a) reported that due to the UK extracting a significantly lower amount of non-metallic minerals in 2012, the UK's domestic material consumption, around 9.3 tonnes per capita, was the third lowest figure in the EU-27 (the EU average was 13.5 tonnes per capita).

In Great Britain, the consumption of crushed rock in 2012 had reduced over the last two decades by around one-third. The main types of crushed rock are limestone, igneous rock and sandstone. Previously, limestone was the main source of crushed rock, until 2010, after which limestone and igneous rock were consumed in the same volume. Like crushed rock, sand and gravel quantity had reduced, and the volume of sand and gravel have been similar since 1959. The summary consumption of all primary aggregates for construction in Great Britain is shown in **Figure 2-19**.

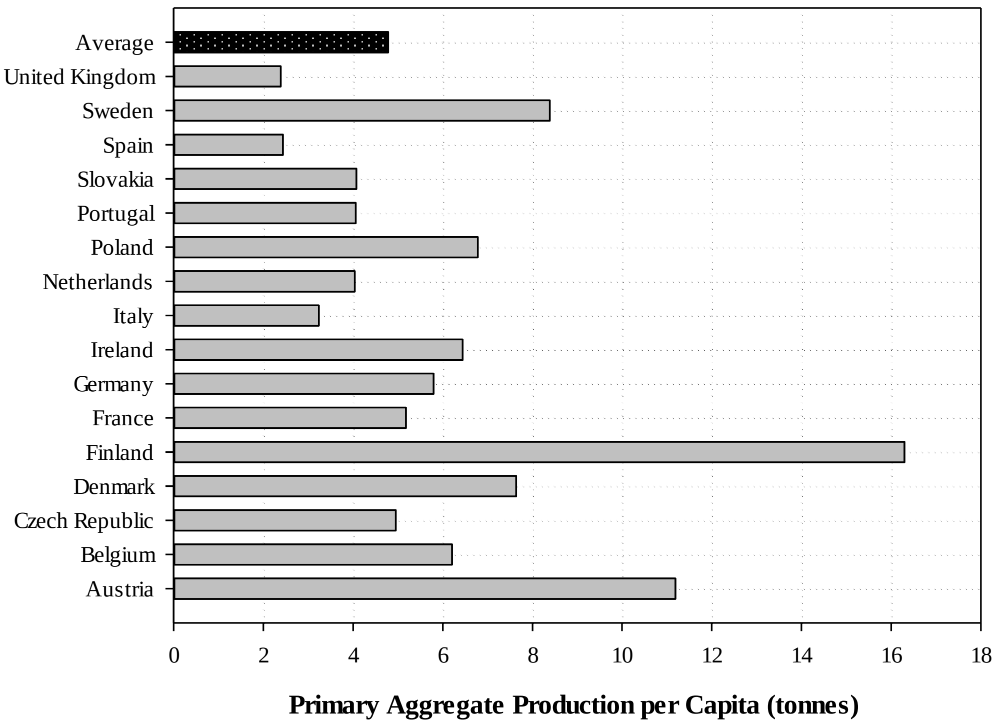
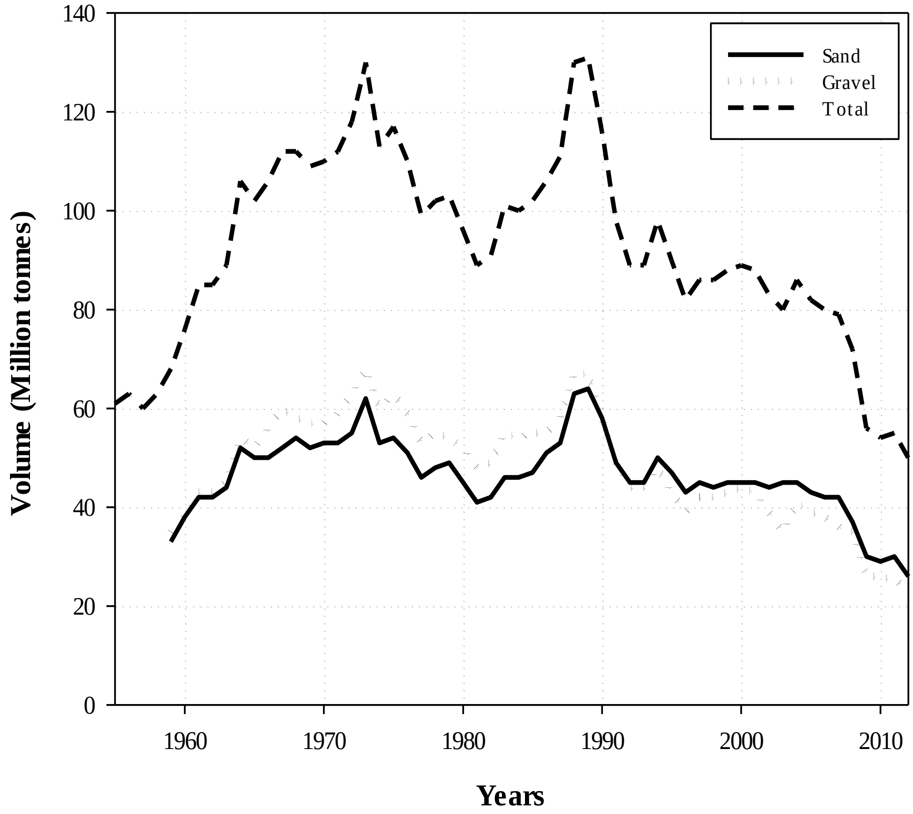


Figure 2-18 Primary aggregate production per capita in main EU countries (2012)
Source: Author based on UEPG (2015)



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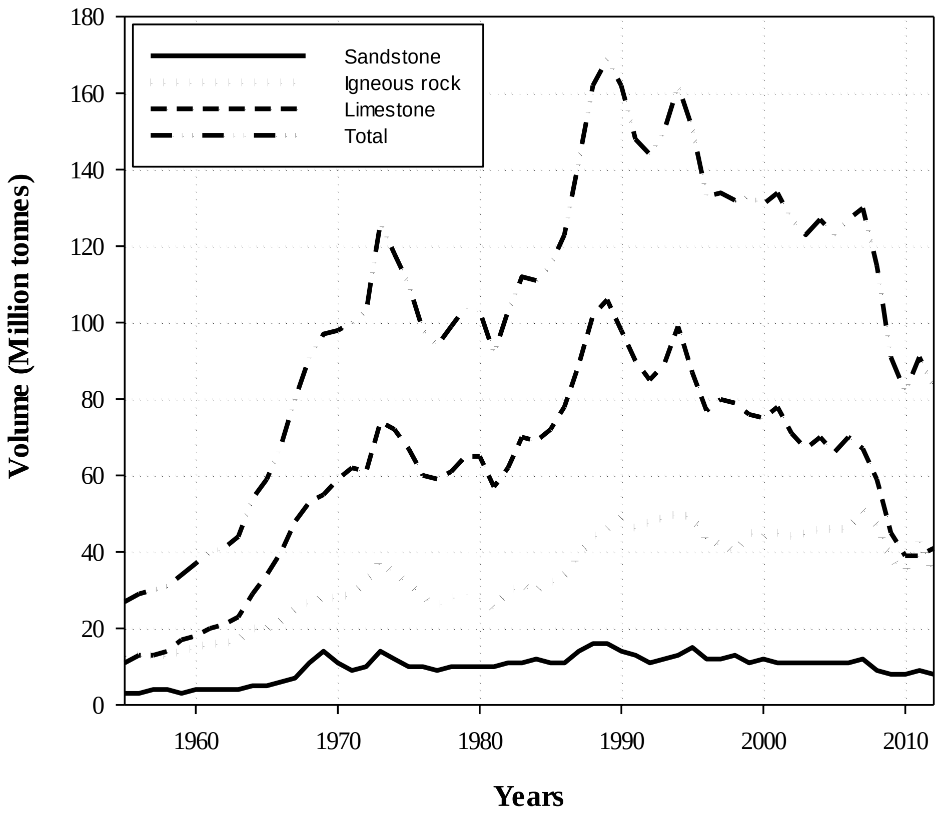


B

Figure 2-19 Great Britain consumption of sand and gravel (A) and crushed rock (B) for construction
Sources: Author based on BGS (2003), (2004), (2005), (2006), (2007), (2008b), (2009), (2010), (2011), (2012), (2013) and (2014c)

2.1.2.3.2 Aggregates for Concrete

(1) Primary Aggregate

In Great Britain, approximately similar amounts of crushed rock, gravel and sand are used for the concrete industry (**Figure 2-20**). Not only does England produce the most aggregate in Great Britain, this region uses more in each type of aggregate for concrete and mortar purposes than any other region because of its greater population and broader territory (around 75-90%, **Figure 2-21**). Moreover, another factor is the limited transportation of heavy aggregates, because of high transportation costs. The important type of crushed rock for concrete is around 70% limestone (including dolomite), followed by 25% igneous rock and 5% sandstone (**Figure 2-22**). Like other construction materials, England consumed more sand for mortar than other regions (more than 80%), shown in **Figure 2-23**.

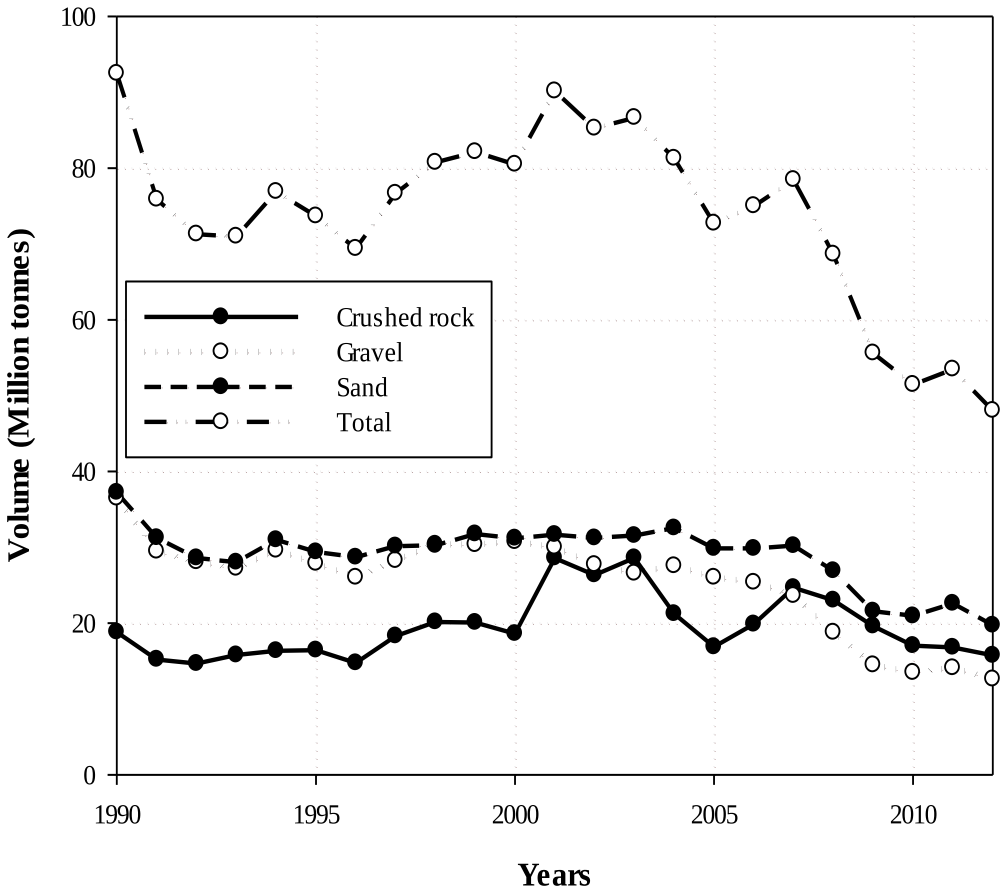
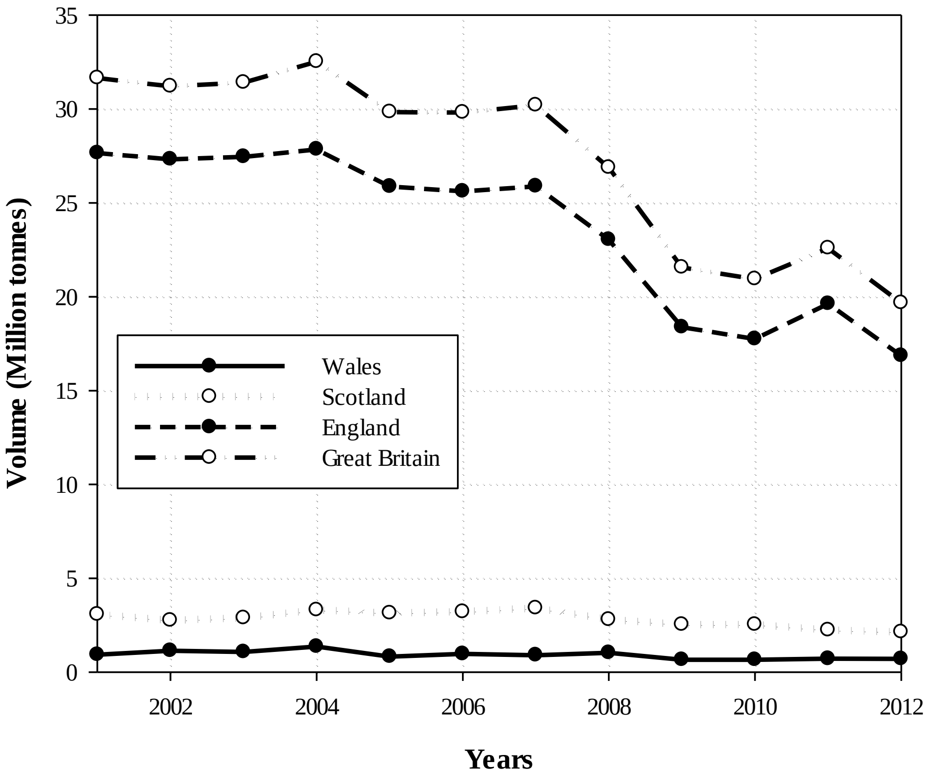


Figure 2-20 Crushed rock, gravel and sand for concrete in Great Britain
Sources: Author based on BGS (2003), (2004), (2005), (2006), (2007), (2008b), (2009), (2010), (2011), (2012), (2013) and (2014c)



35
30
25
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Volume (Million tonnes)
Years
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Scotland
England
Great Britain

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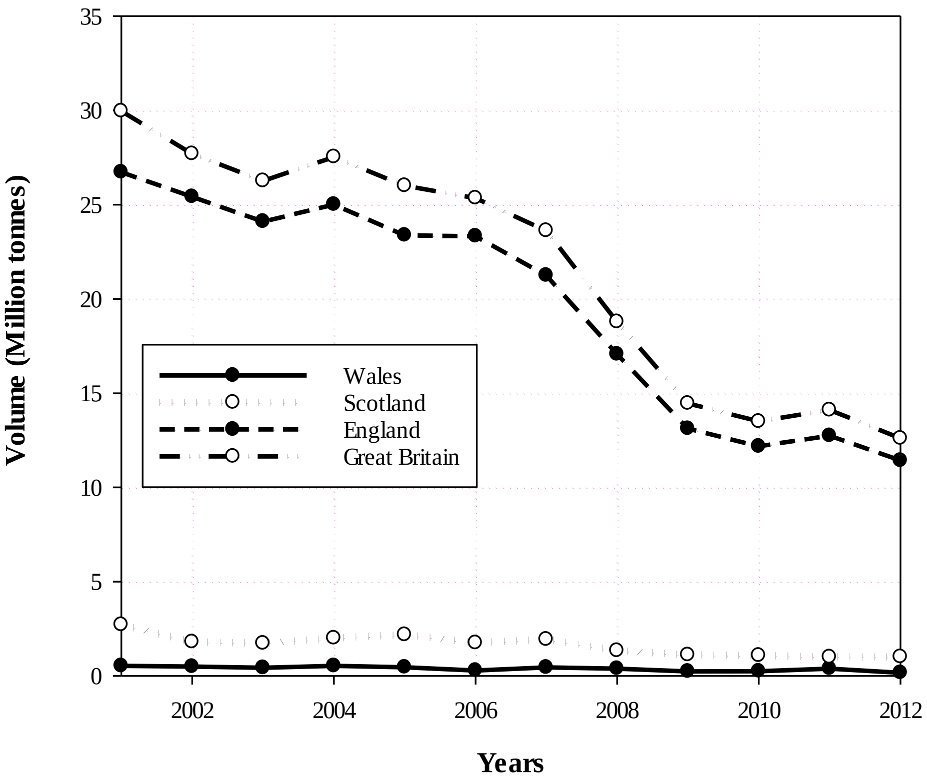

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Volume (Million tonnes)
Years
Wales
Scotland
England
Great Britain

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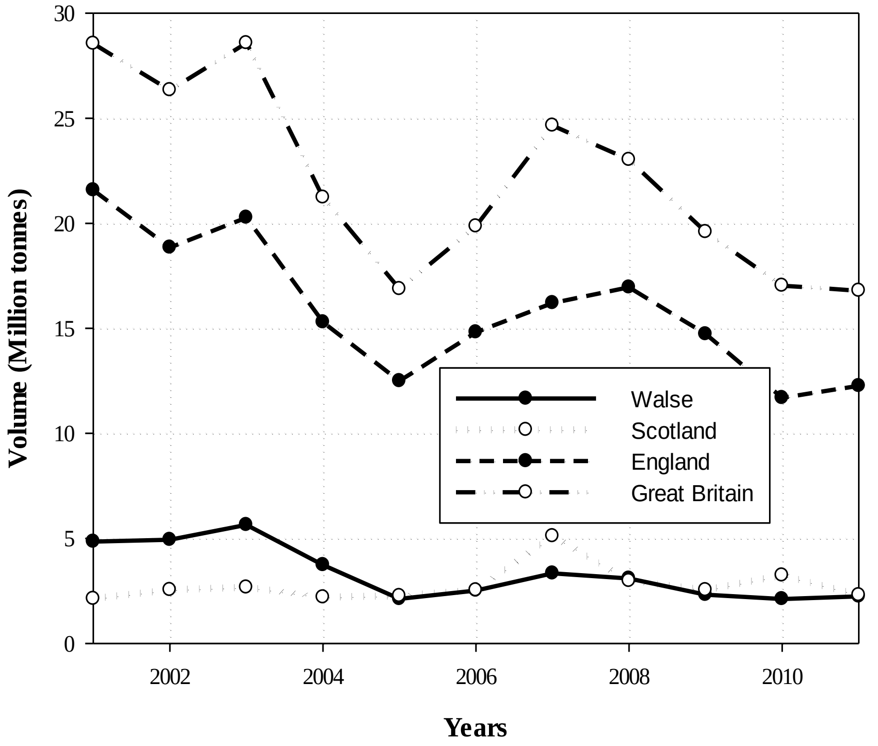


C

Figure 2-21 Concrete aggregates from sand (A), gravel (B) and crushed rock (C) in Great Britain
Sources: Author based on BGS (2003), (2004), (2005), (2006), (2007), (2008b), (2009), (2010), (2011), (2012), (2013) and (2014c)

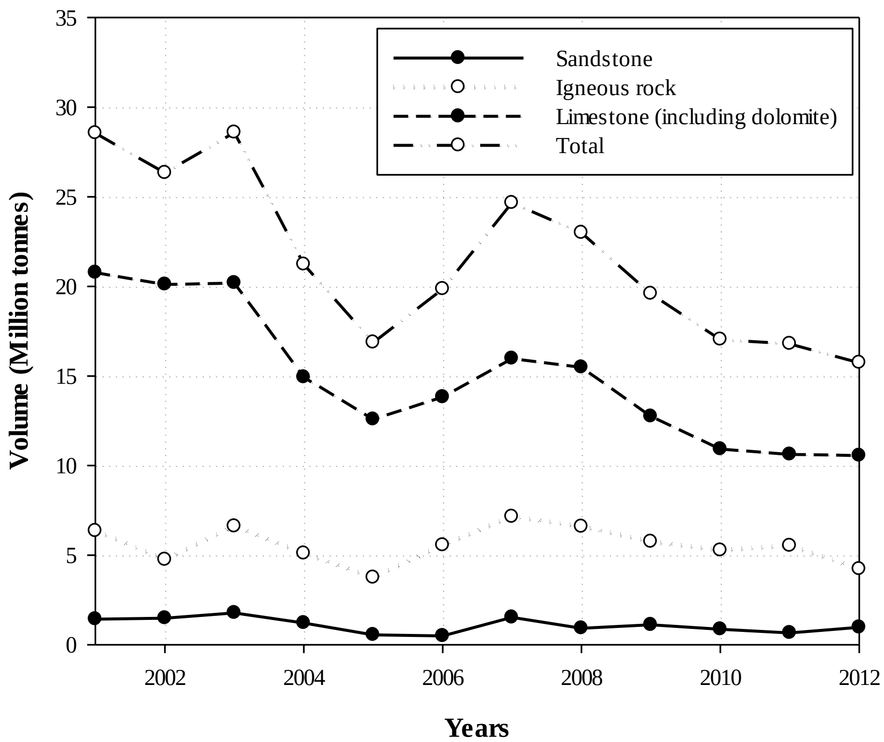


Figure 2-22 Types of concrete crushed rock aggregates in Great Britain
Sources: Author based on BGS (2003), (2004), (2005), (2006), (2007), (2008b), (2009), (2010), (2011), (2012), (2013) and (2014c)

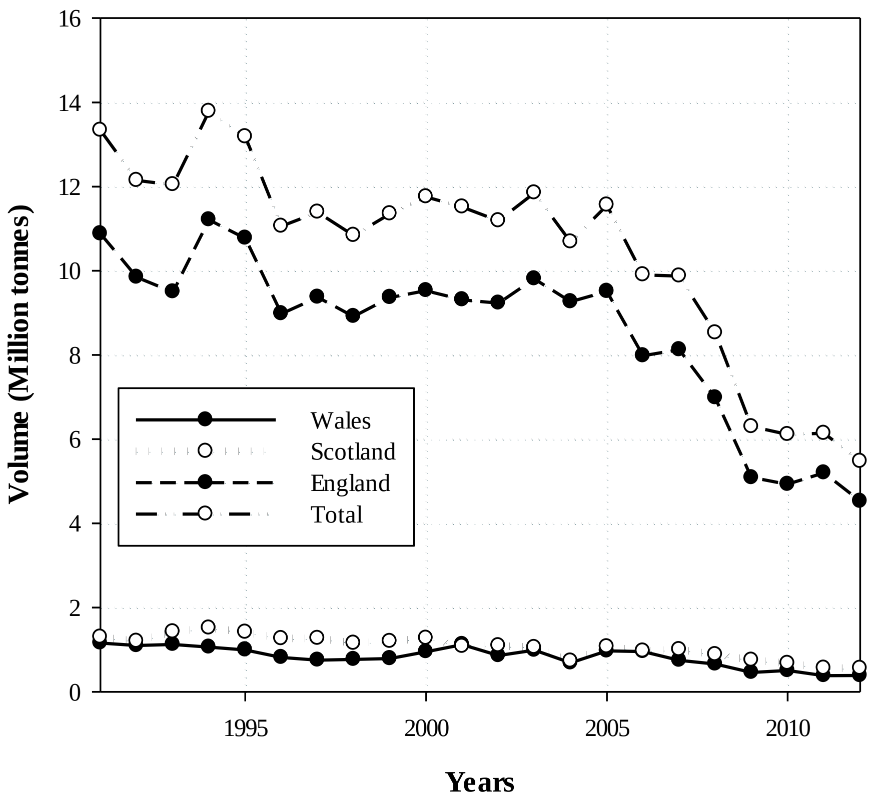


Figure 2-23 Sand for mortar use in Great Britain
Sources: Author based on BGS (2003), (2004), (2005), (2006), (2007), (2008b), (2009), (2010), (2011), (2012), (2013) and (2014c)

(2) Recycled and Secondary Aggregates

The ratio of recycled and secondary aggregates in 2005 according to DCLG (2007) was 85% of recycled aggregates from C&D waste and 15% from secondary aggregates. These alternative aggregates can replace coarse primary aggregates in concrete or be used for other constructions. Using roads for transportation, The Concrete Centre (2010b) suggested that the utilisation of recycled aggregates with a lower carbon option should be within 10 miles (or 15 kilometres) of their origins.

The Great Britain aggregate market has used recycled aggregates for construction activities since 1955. Its use has increased steadily from 1988 until 2009 after which it dropped and reduced (**Figure 2-24**). One main reason probably comes from the Aggregate Levy launched in 2002. As seen, this reduces the use of primary aggregates, and recycled and secondary aggregates increased steadily. During 2008 to 2012, MPA (2013b) reported that Great Britain used around 4-6 Mt recycled and secondary aggregates for concrete purpose.

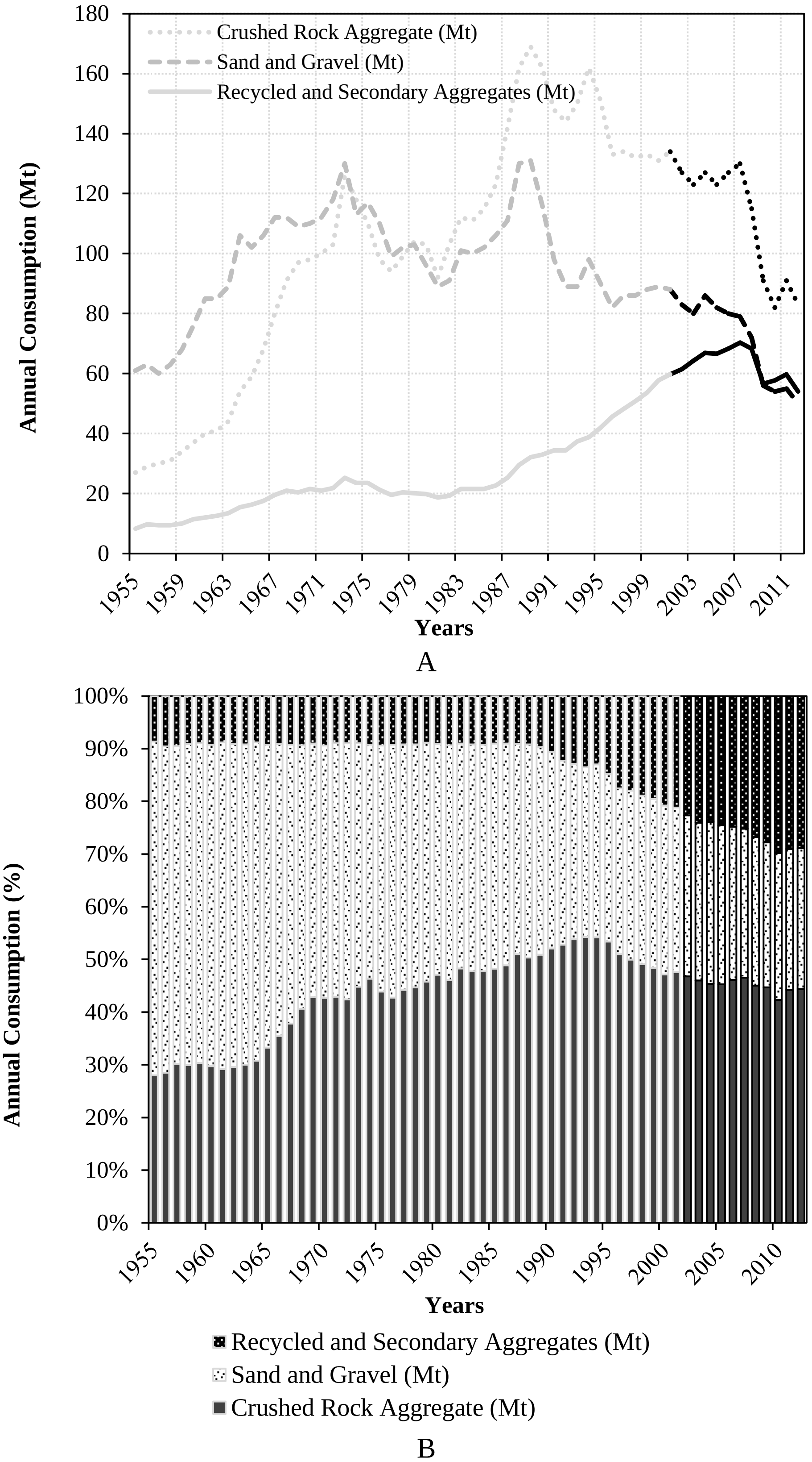


Figure 2-24 Great Britain estimated consumption of primary and recycled/ secondary aggregates in volume (A) and percent (B)
Source: Author based on BGS (2006), (2014c) and MPA (2014b)

2.1.3 Concrete industry

There are three main types of concrete: (1) ready-mixed concrete or poured concrete, (2) precast concrete and (3) site-mixed concrete. Ready-mixed concrete is mixed at the factory and then delivered to the construction sites where it is cast. Precast concrete is mixed and cast in the plant before transporting to the construction sites. Combining both types of concrete is a usual method in developed countries, where cement is directly made for the concrete industry and then sold as ready mixed and precast concrete (Sjunnesson, 2005). Great Britain's cement production was delivered to make concrete by 1,000 ready mixed plants and 800 precast concrete factories (The Concrete Centre, 2009). In 2012 Great Britain used cement as follows: 54.56% for ready- mixed concrete (4.25 Mt), 22.85% precast concrete (1.78 Mt) and only 1.5 Mt or 19.26% cement for site-mixed concrete, with 0.26 Mt or 3.34% for other uses (**Figure 2-10**).

To encourage more use of recycled and secondary aggregates, the Sustainable Concrete Forum (SCF) created the Resource Efficiency Action Plan (REAP) to contribute to the UK government requirements to be a low carbon and sustainable construction strategy (MPA, 2013a). SCF has several members, relating to construction materials, including (1) MPA-Cement, (2) British Precast Concrete Federation (BPCF), (3) MPA-British Ready-mixed Concrete Association (MPA-BRMCA), (4) Cement Admixtures Association (CAA), (5) Cementitious Slag Makers Association (CSMA), (6) Mineral Products Association (MPA), (7) MPA-The Concrete Centre (MPA TCC) and (8) UK Quality Ash Association (UKQAA).

There are some important fundamental concepts in REAP relating to recycled and secondary aggregates (British Ready-Mixed Concrete Association, 2014). For example, (1) recycling of ready-mixed concrete to reduce the extraction of primary aggregates by providing a guidance by BRMCA and TCC for the best practice of recycled and secondary aggregates in ready-mixed concrete before 31 December 2016, and (2) preventing against traditional issues that may restrict recycling of concrete, the Sustainable Concrete Design Guide encourages awareness and promotes the updated best practice for appropriate recycling of crushed concrete among designers. TCC planned to update this guide by 31 December 2018. Then, (3) raising awareness in other stakeholders, such as proprietors, construction and demolition contractors, of opportunities and circumstances beneficially to reuse foundations and concrete frame.

The British Ready-Mixed Concrete Association (2012) stated that there is little waste associated with ready-mixed concrete since the precise volume required can be delivered with no packaging. The small amounts of concrete that are returned, and any washout, are normally processed to reclaim the aggregate or left to harden for use as recycled concrete aggregate. The same organisation noted that secondary and clean recycled concrete aggregates are safe to use as a component of ready-mixed concrete, following the appropriate British Standards and industrial protocols. Moreover, The Concrete Centre (2013) targeted to increase the proportion of recycled/ secondary aggregates in Great Britain to 25% of total aggregates in precast concrete by 2012 based on 2008 but only 21.3% of aggregates used in 2012 were recycled or secondary origin in this concrete type as the significant volume of these materials is in the precast concrete sector.

2.1.4 Construction Industry

2.1.4.1 Overview of Construction Industry in Great Britain

The expenditure of construction sectors in Great Britain was £115.59 billion in 2012 (ONS, 2014b). The value of new construction of Great Britain (£70.95 billion) was around 1.6 times higher than repair and maintenance value (£44.64 billion). It means that repair and maintenance are significant construction activities in Great Britain. Moreover, The Cabinet Office (2011) stated that central government is the industry's biggest customer due to some 40% of the whole construction being in the public sector.

To classify sub-sectors for new, repair and maintenance construction (**Table 2-4**), there are three main types of construction, with corresponding value: (1) non-residential building £50.91 billion (public £15.71, private £35.2 billion), (2) residential building £42.77 billion (public £11.61, private £31.16 billion) and infrastructure £21.88 billion. **Table 2-4** also shows that in 2012 public residential building had repair and maintenance activities greater in value than new construction. In contrast, private residential building, infrastructure and non-residential building were popular in new construction. Moreover, in 2012, Great Britain construction spent more money for specialised construction activities (£56.75 billion or 49.09%), following by 28.17% construction of buildings (£32.56 billion) and 22.74% civil engineering (£26.28 billion).

Table 2-4 Great Britain private contractors: Value of work done in 2012, by trade of firm and type

£ Billion

Firm Trade	New						Repair & Maintenance						All Work
	Residential Building		Infrastructure	Non-Residential Building		All	Residential Building		Infrastructure	Non-Residential Building		All	
	Public	Private		Public	Private		Public	Private		Public	Private		
Construction of buildings	2.30	7.17	2.40	3.91	6.92	**22.70**	3.24	3.22	0.32	1.47	1.62	**9.86**	**32.56**
Civil engineering	0.36	2.55	8.03	2.79	4.20	**17.93**	0.41	1.28	5.17	0.77	0.73	**8.35**	**26.28**
Specialised construction activities	1.35	6.43	3.53	4.08	14.93	**30.32**	3.96	10.52	2.43	2.72	6.80	**26.42**	**56.75**
Total	**4.01**	**16.14**	**13.96**	**10.78**	**26.06**	**70.95**	**7.60**	**15.02**	**7.92**	**4.96**	**9.14**	**44.64**	**115.59**

Source: Author based on ONS (2014b)

Using the number of Great Britain firms by sizes and trades in 2012 (**Figure 2-25**), micro firms with 0-13 employees employed the most people, having 95.40% or 235,727 companies with 492,749 employees (42.69%). Although the small (14-34 employees), medium (35-299 employees) and large (more than 300 employees) firms were fewer in number than the micro firms (3.19%, 1.31% and 0.10% respectively), the number of employees were greater: 159,942 people (13.86%) for small, 238,419 people (20.66%) for medium and 262,998 people (22.79%) for large firms. As clearly seen in **Figure 2-26** and **Figure 2-27**, although the number of other private contractor firms (small, medium and large firms) are significantly less than the micro-group, there are more employees in these bigger firms in Great Britain. In 2012, most construction firms in Great Britain were located in England (89%) and the South East region of England had the most construction firms (20%), followed slightly by Scotland (7%) and Wales (4%, **Figure 2-28**).

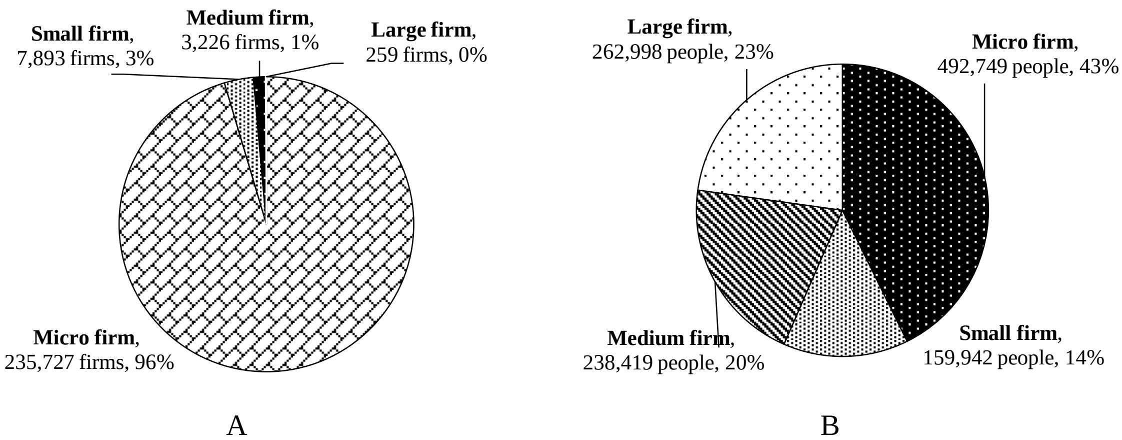


Figure 2-25 Numbers (A) and employees (B) of private contractors by firm sizes in Great Britain (2012)
Source: Author based on ONS (2014b)

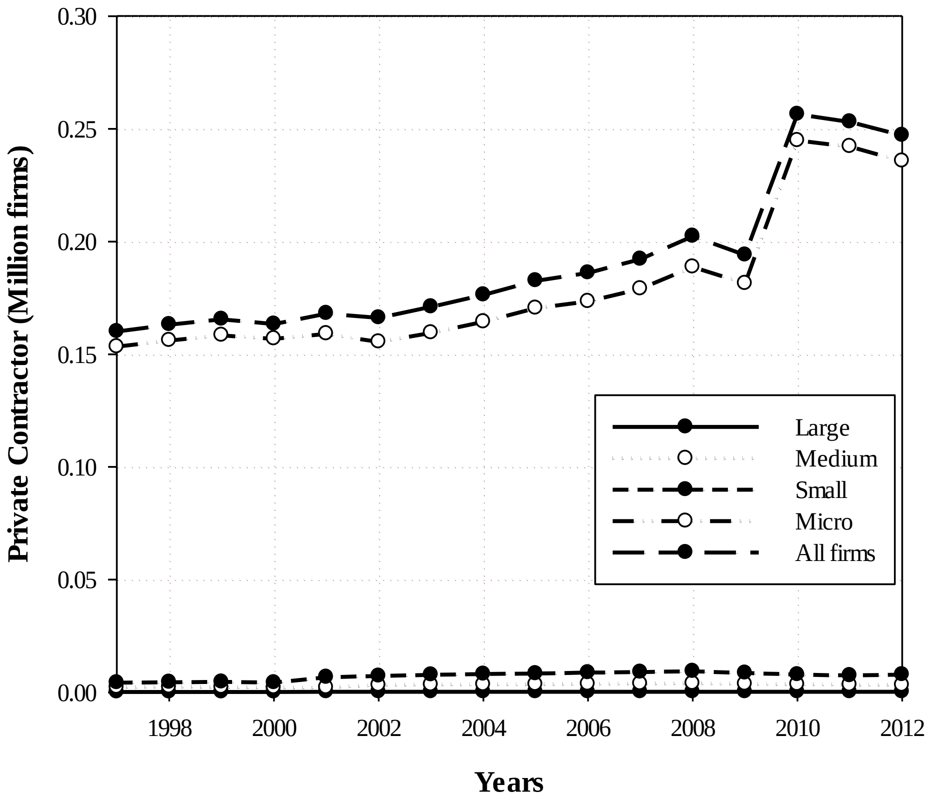


Figure 2-26 Numbers of private contractor firms in Great Britain
Source: Author based on ONS (2014b)

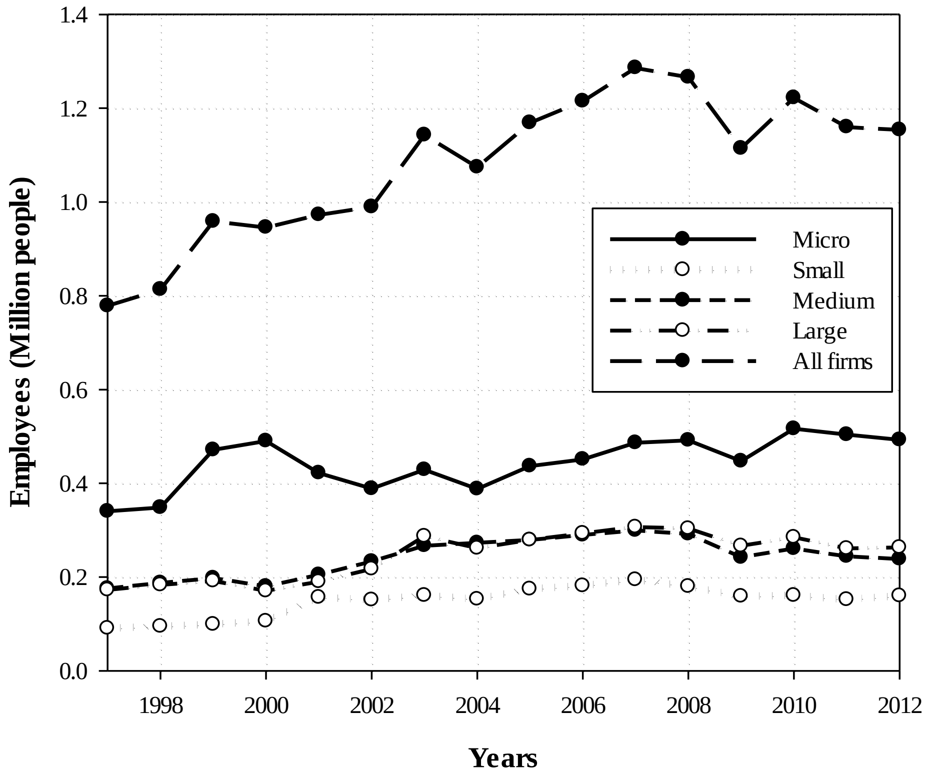
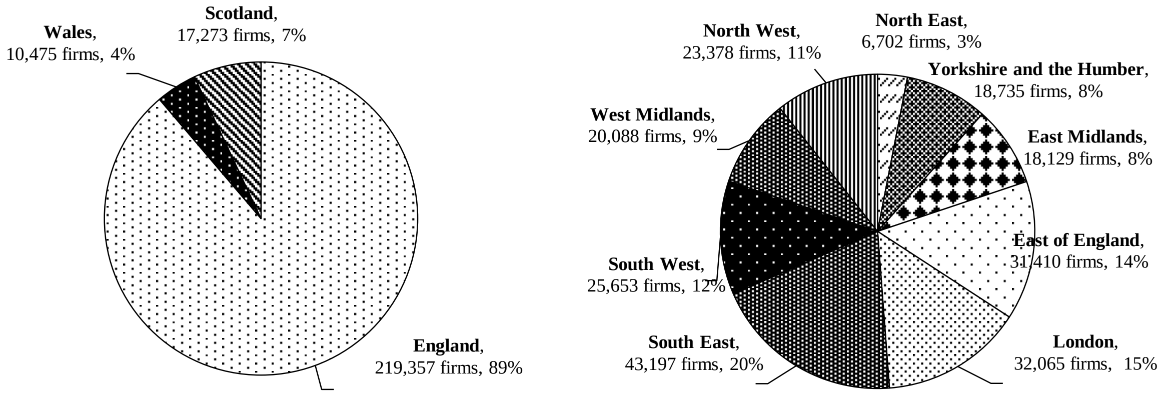


Figure 2-27 Total employees of private contractor firms in Great Britain
Source: Author based on ONS (2014b)



A B

Figure 2-28 Number of construction firms in Great Britain (A) and Number of construction firms in Britain (B)
Source: Author based on ONS (2014b)

For the value of work done in 2012 (**Table 2-5**), micro firms earned 31.93% income (£36.90 billion), followed closely by 29.46% large firms (£34.06 billion), 24.26% medium firms (£28.04 billion) and 14.35% small firms (£16.59 billion). This means a few large firms (only 0.10%) in Great Britain can earn similar revenue to the combined micro companies, which were the largest firm group (95.40% of total firms). Using construction value to measure construction activities, Great Britain's new construction is focussed on non-residential building, followed by residential building and infrastructure (**Figure 2-29**).

Table 2-5 Great Britain private contractors: Value of work done in 2012 by sizes and trades

Size of Firms (by number employed)	**Construction of Buildings** (billion £)	**Civil Engineering** (billion £)	**Specialised Construction Activities** (billion £)	**Total** (billion £)	**Percent**
Micro (0-13)	6.77	4.50	25.64	**36.90**	31.93%
Small (14-34)	2.94	2.75	10.90	**16.59**	14.35%
Medium (35-299)	9.66	6.61	11.77	**28.04**	24.26%
Large (300+)	13.20	12.43	8.43	**34.06**	29.46%
Total	**32.56**	**26.28**	**56.74**	**115.58**	100.00%
Percent	28.17%	22.74%	49.09%	100.00%	

Source: Author based on ONS (2014b)

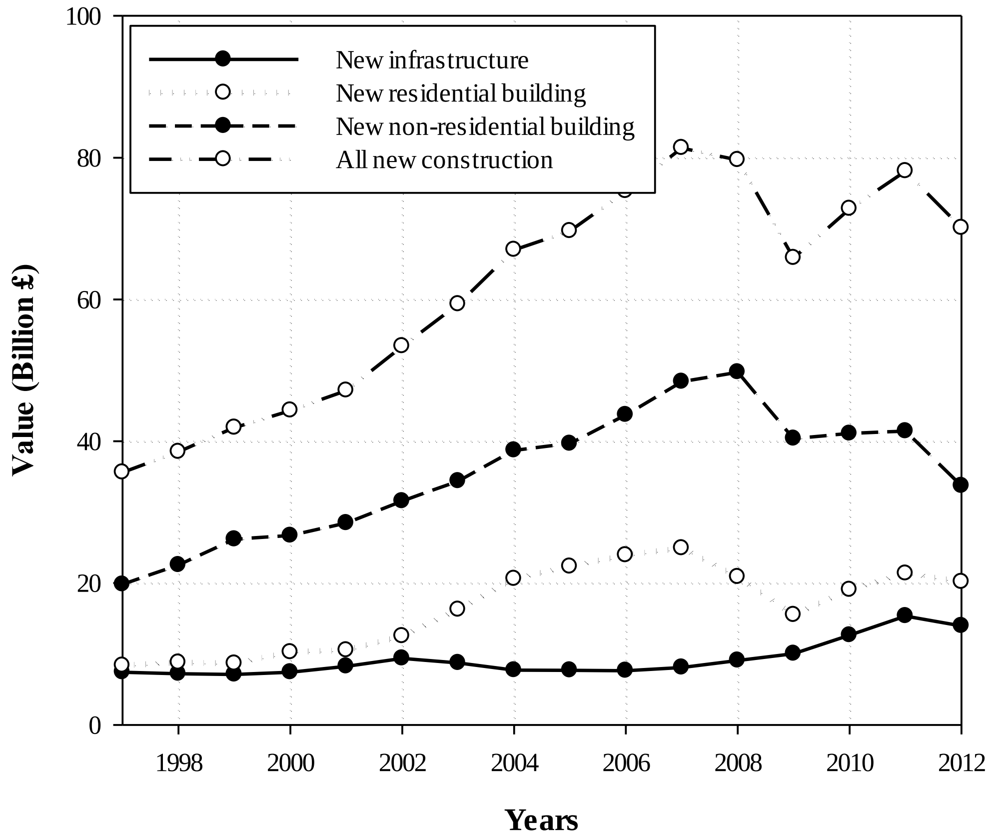


Figure 2-29 New construction in Great Britain
Source: Author based on ONS (2014b)

2.1.4.2 Construction Sectors in Great Britain

2.1.4.2.1 Residential Building

As stated by The Chartered Institute of Building (2013) about major refurbishment and building lifespan, half of all residential buildings in the UK have a lifespan more than 50 years and a fifth are more than 100 years old, and the proportion of dwellings built after 2000 in total stock of the UK is only 7%. Dwelling according to construction date confirms that the UK has the greatest numbers of old dwellings in the EU, followed closely by Belgium and Denmark (the ENTRANZE Project, 2008c). Throughout their life, buildings experience some refurbishments with a major refurbishment every 20-30 years. Due to weather reasons, masonry cavity wall is the dominant construction for UK residential building. Involving the external walls, a house has a double masonry layer separating by a cavity (Mortar Industry Association, 2013).

The UK produces 96% of bricks from clay depending on the locality of the brickworks, and these need mortar for binding (Mortar Industry Association, 2013). There are two types of residential building in Great Britain: private and public. The value of the new private residential building has been higher than new public residential building. In 2012, new private residential building had three times higher value than public (**Figure 2-30**). Comparing new construction and repair and maintenance activities, the annual value of refurbished activities (47-64%) in residential buildings has been generally higher than that of new construction (37-50%, **Figure 2-31**) and repair and maintenance value of residential building is mostly seen in private sectors in Great Britain (**Figure 2-32**).

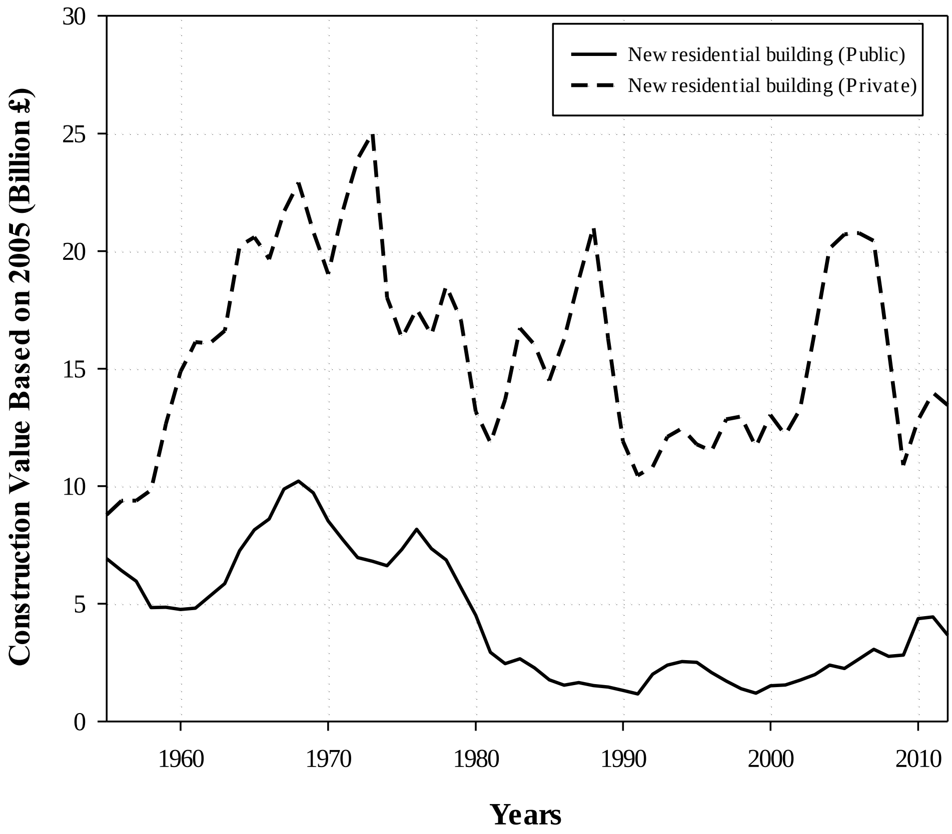


Figure 2-30 Value of new residential building in public and private sectors in Great Britain
Sources: Author based on ONS (2015a)

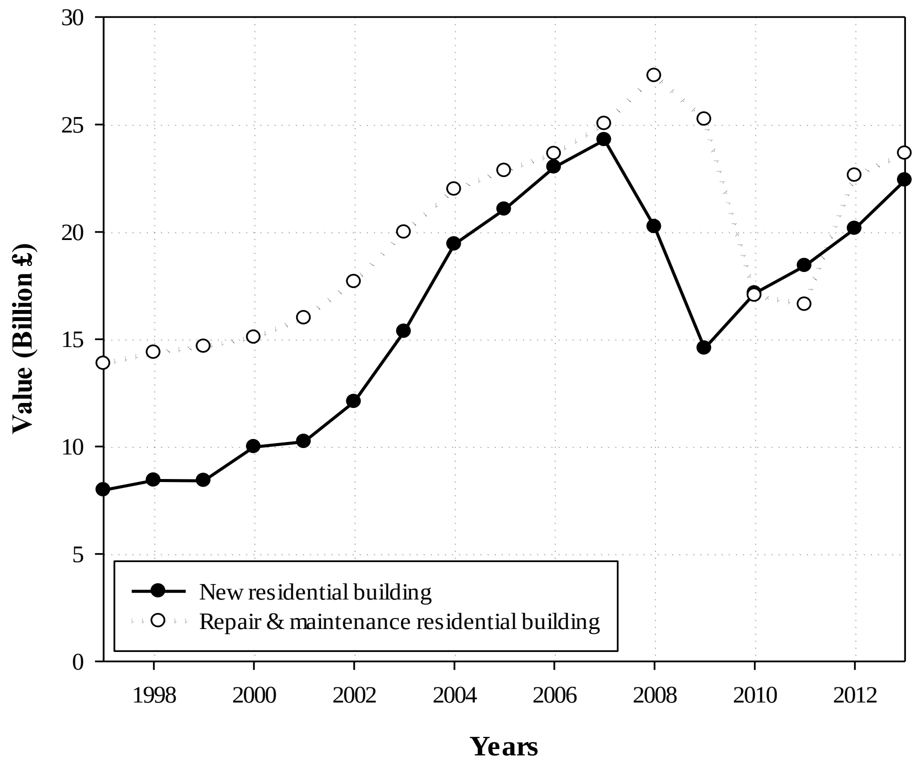


Figure 2-31 Value of new and repair & maintenance residential building
Sources: Author based on ONS (2008a), (2009a), (2010a), (2011c), (2012b), (2013b), (2014b)

Figure 2-32 Repair and maintenance value of residential building in public and private sectors in Great Britain
Source: Author based on ONS (2015a)

2.1.4.2.2 Non-Residential Building

The other group of buildings in Great Britain is non-residential. ONS (2014b) classified these buildings to be 12 groups as (1) factories, (2) warehouses, (3) oil, steel and coal facilities, (4) schools and colleges, (5) universities, (6) health, (7) offices, (8) entertainment, (9) garages, (10) shops, (11) agriculture and (12) miscellaneous. Schools and colleges was the main group built by the government in the public sector, followed by health and miscellaneous buildings. For the private sector, office, shop and entertainment buildings were dominant in construction (**Figure 2-33** and **Figure 2-34**). According to the above details, the public sector value of non-residential building in Great Britain is around half of the private sector value (**Figure 2-35**).

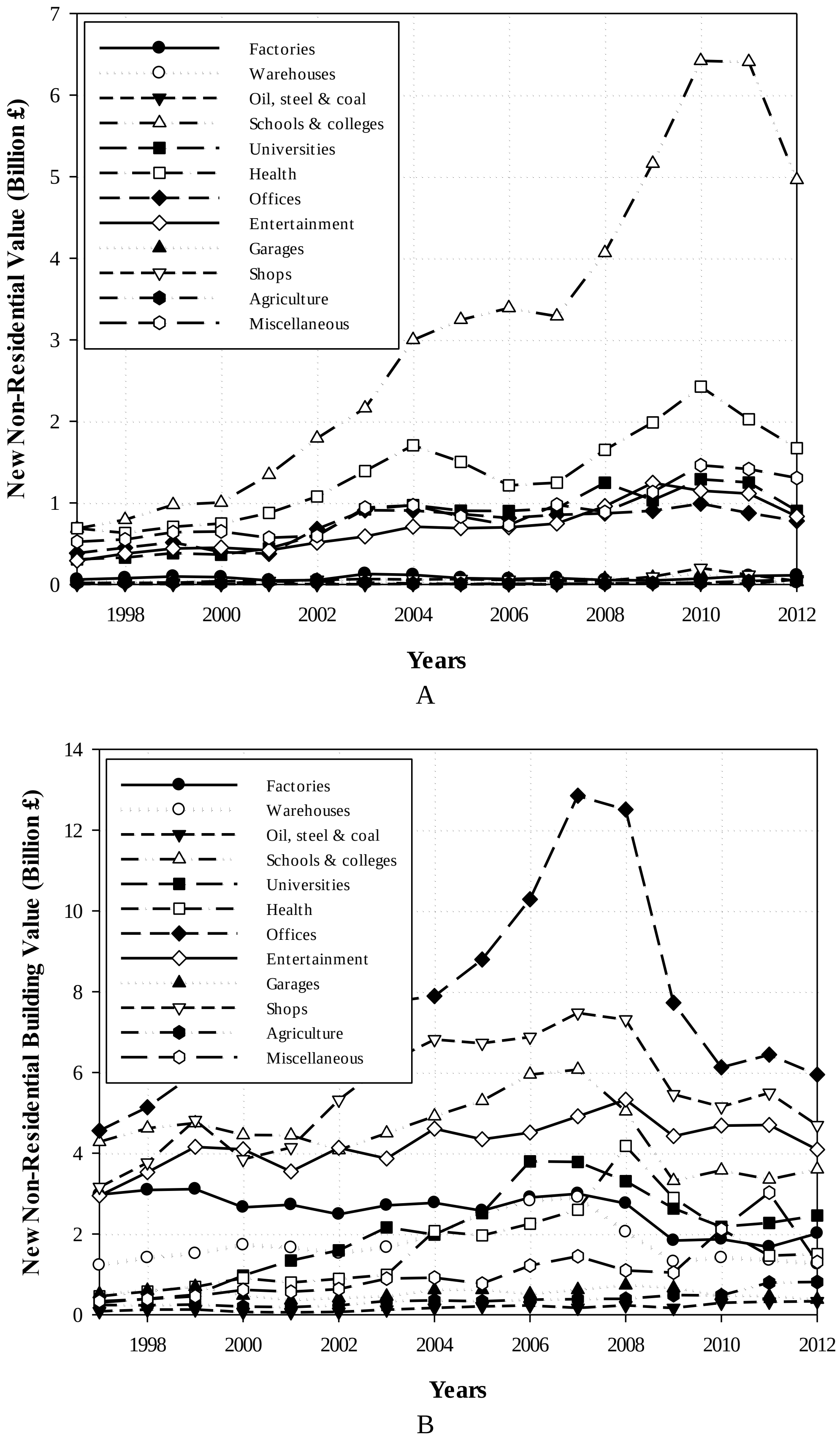


Figure 2-33 New non-residential building value in Great Britain public sector (A) private sector (B)
Source: Author based on ONS (2008a), (2009a), (2010a), (2011c), (2012b), (2013b), (2014b)

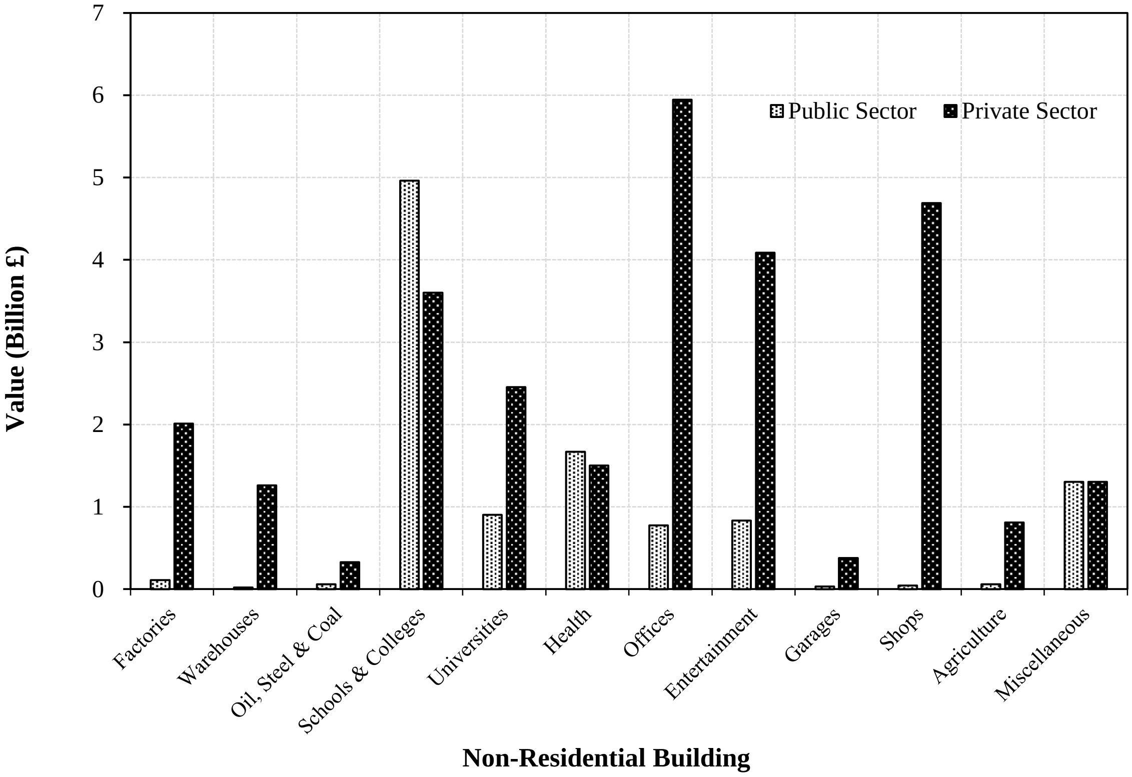


Figure 2-34 Types of new non-residential building in Great Britain in 2012
Source: Author based on ONS (2008a), (2009a), (2010a), (2011c), (2012b), (2013b), (2014b)

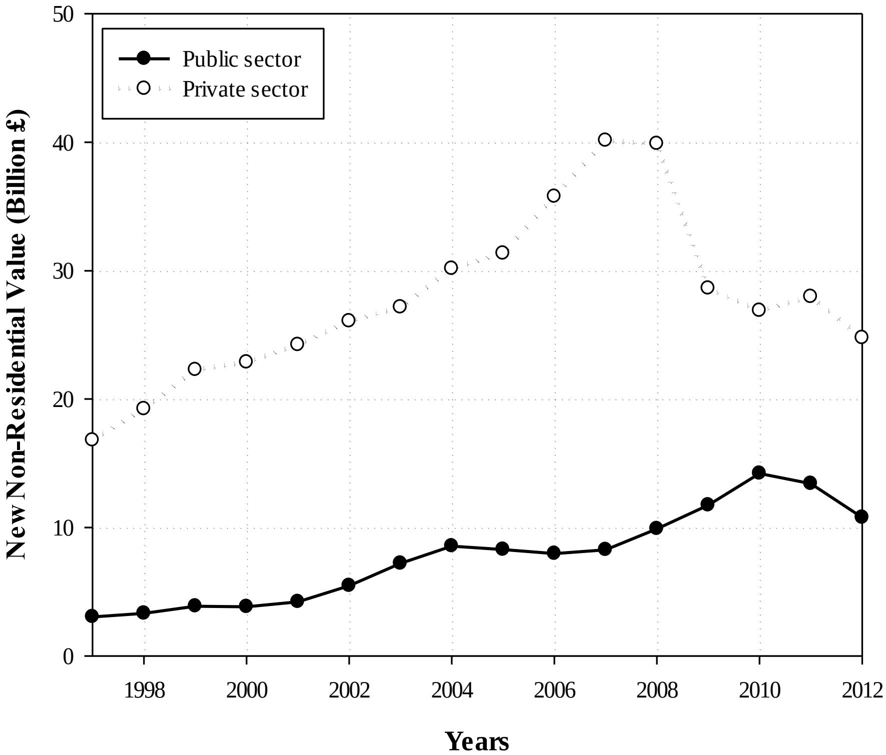


Figure 2-35 New now-residential building in Great Britain
Source: Author based on ONS (2008a), (2009a), (2010a), (2011c), (2012b), (2013b), (2014b)

2.1.4.2.3 Infrastructure

Like the residential building, infrastructure can be separated into two main types: public and private sectors. New private infrastructure in Great Britain increased to two times more expenditure than the public **(Figure 2-36**). Roads are the most important types of Great Britain infrastructure and now railway transportation tends to be important in Great Britain, increasing more in construction since 2008 (**Figure 2-37)**.

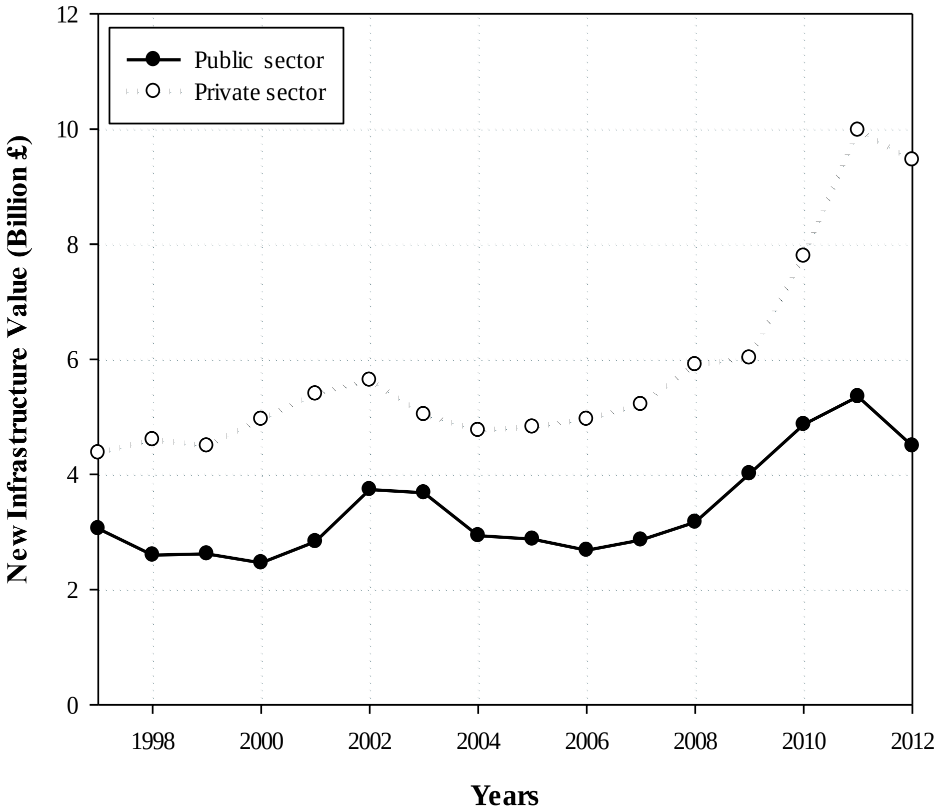


Figure 2-36 New infrastructure value for Great Britain public and private sectors
Source: Author based on ONS (2008a), (2009a), (2010a), (2011c), (2012b), (2013b), (2014b)

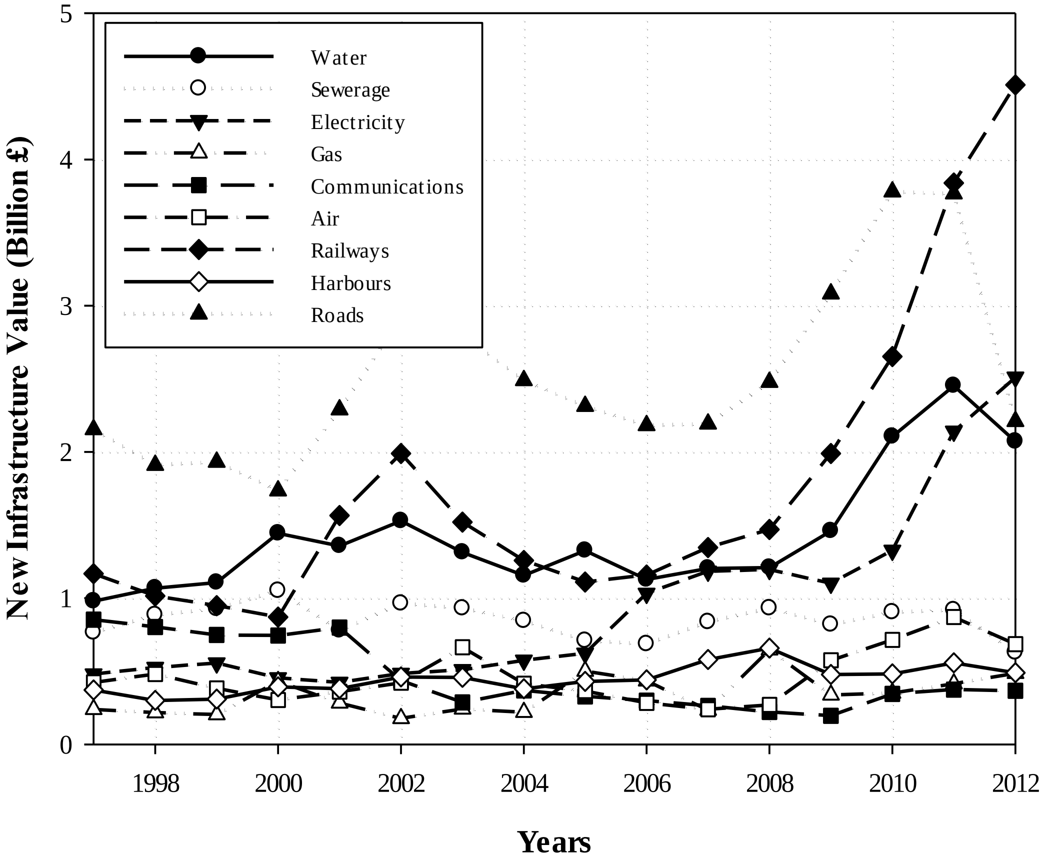


Figure 2-37 Types of new infrastructure
Source: Author based on ONS (2008a), (2009a), (2010a), (2011c), (2012b), (2013b), (2014b)

2.1.5 Waste Management

An increase in GDP and number of households relates directly to waste arising (ECOTEC Research and Consulting et al, 2001). In accordance with the economic and social perspectives of the EU region, the Houses of Parliament and the Parliamentary Information Technology Committee (PITCOM) in the UK have agreed to the EU strategy in waste management, and set up UK environmental policy commitments and Parliament's environmental performance to follow EU environmental targets based on environmental performance data in 2008/09. This baseline has been independently verified by external consultants using annual reported data. Its targets and performance relating to the management of all wastes and carbon emissions by 2020/2021 (Simmonds, 2010) are:

- To reduce absolute carbon emissions by 34%
- To decrease the weight of waste generated by 30%
- To recycle 75% of waste generated by weight

EU directives, regulations or decisions do address a range of environmental issues other than solid waste management but nevertheless may have a direct impact on industrial solid waste management systems. The EU has the overarching aim to decouple waste production from Gross Domestic Product (Council Decision 1600/2002/EC that introduced the 6th Environment Action Programme (EAP) in 2002). Earlier the European Communities (European Communities, 1999) agreed principles that support this later aim by stating that waste management should be based on the:

- prevention principle i.e. where possible to reduce and avoid the production of waste;
- producer or polluter pays principle i.e. waste producers or polluters of the environment should pay the full costs of their actions;
- precautionary principle i.e. potential problems should be anticipated; and
- proximity principle i.e. the disposal of waste should be as close as possible to where it is produced.

In the same publication the European Communities (1999) stressed the need for:

- reduced movement of waste and improved regulation of waste transport;
- improved waste management tools considering regulatory and economic instruments;
- provision of reliable and comparable statistics on waste;
- establishment of waste management strategies; and
- proper enforcement of legislation.

The Council of the European Communities introduced a number of directives, regulations and general guidance on waste management. It was found that there are some 197 EU legislative documents e.g. treaties, directives, regulations and decisions, with the word ‘waste’ in their title (Communitatis Europeae Lex, 2016). The EU divides its legislation into four categories i.e. the waste framework (Council Directive 75/442/EEC on Waste-Waste Framework Directive, updated in 2008), selected waste materials, processes and operations, and the transportation of waste.

UK (and where relevant England and Wales) legislation cannot as easily be divided between those parts that are relevant to industrial waste specifically or to the environment in general. Generally speaking UK legislation may be divided into two categories i.e. acts which provide legislative frameworks and selected regulations that address specific responsibilities. Both categories address parts of the classification, generation, transport, treatment, recovery and disposal of waste. **Table 2-6** lists the acts and regulations deemed most relevant across various waste management operations. The list is by no means exhaustive. It should be noted that not all legislation listed in the table are described here, as the application of many individual acts or regulations may depend on the actual waste stream or material that is disposed.

Table 2-6 Acts and regulations deemed most relevant across various waste management operations

Categories	Acts and Regulations
Acts	Control of Pollution Act 1974
	Environmental Protection Act 1990
	Environment Act 1995
	Pollution Prevention and Control Act 1999
Regulations	Environmental Protection (Duty of Care) Regulations 1991
	Landfill Tax Regulations 1996
	Pollution Prevention and Control Regulations 2000
	Landfill Regulations 2002
	Hazardous Waste Regulations 2005

Sources: Author

Based on the Control of Pollution Act 1974 (House of Commons, 1974) the general distinction, identification and controlling procedure for waste in general is following the source and properties of waste, differentiating between controlled and non-controlled waste streams (**Figure 2-38**).

There are some terms in use having no legal definition (e.g. difficult waste), and others are legally defined, often used in a broader context (e.g. hazardous waste). Although certain wastes are classified as ‘non-controlled waste’, it does not necessarily mean that there is no legislation governing their disposal. The management and disposal of waste mostly classified as controlled waste are principally regulated by the Environmental Protection Act 1990. However, larger waste disposal facilities are subject to the new permitting regimes introduced by the Pollution Prevention and Control (England and Wales) Regulations 2000, and the Pollution Prevention and Control (Scotland) Regulations 2000.

In detail, before sending waste for recycling and disposal in the UK, producers must describe any waste using the waste classification code, also referred to as List of Waste (LoW) or European Waste Catalogue (EWC) code, including consignment notes and transfer notes. According to a catalogue of all wastes divided into 20 chapters, the chapters must be used in the correct order of precedence. The waste classification code is used to decide how to handle waste and to complete the paperwork that waste owners must give waste contractors as part of their 'duty of care'(Environment Agency *et al.*, 2015).

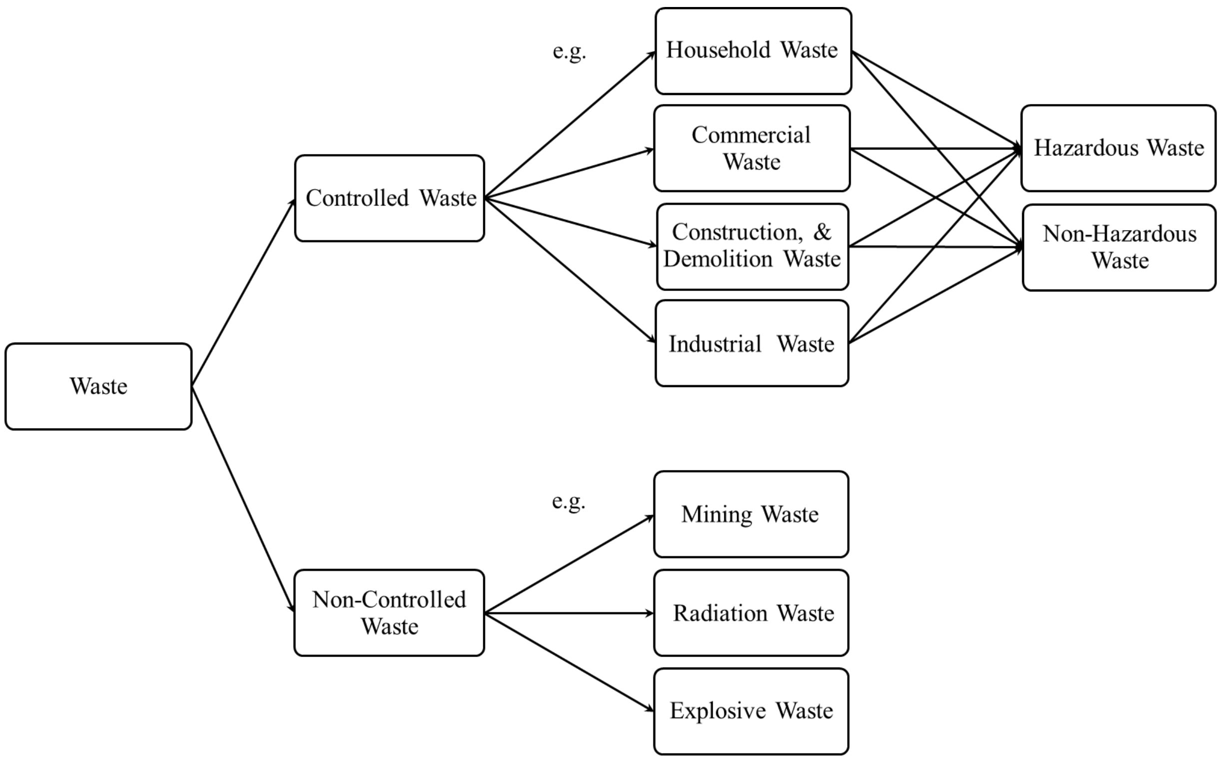


Figure 2-38 UK waste classification framework
Sources: Author

For construction and demolition waste (C&D waste) classified in Chapter 17 of EWC, it is estimated that the EU construction sector generated 821 Mt of waste (33% of total waste) in 2012 among EU-28 countries, 100 Mt of which was C&D waste arising in the UK (50% of UK total waste), or 1.57 tonnes C&D waste per UK capita (Defra, 2015b; Defra, 2015a; Eurostat, 2015c). To become a 'recycling society' before 2020, the EU intends to reuse, recycle and recover 70% by weight of non-hazardous waste from C&D waste (with the exclusion of non-contaminated soil and rocks from excavation) including use as fill (European Parliament, 2008; Fischer *et al.*, 2009).

From UK policy action following the EU expectation, the revised Waste Framework Directive (rWFD) also requires all UK member nations to recover a minimum of 70% waste generated from the construction industry by 2020 (Defra, 2012b). Moreover, the reuse of C&D waste on site in order to minimise additional disposal and raw material costs in the UK is reflected and impacted by the Landfill Tax and the Aggregates Levy (DCLG, 2006). From these supports, Defra (2015b) and Monier *et al.* (2011) reported that the UK is one of six EU countries (Denmark, Estonia, Germany, Ireland and the Netherlands), which had 86.5% recycling rate of non-hazardous C&D waste in 2012, higher than an EU target (at least 70 percent by 2020).

The landfill tax introduced in 1996 encourages people to separate the specific waste for reuse, recycling or recovery, becoming more financially attractive, and the tax varies depending on the waste types intended to landfill (Böhmer *et al.*, 2008). This tax is charged by weight with two main rates: standard rate (£84.40/tonne) for active wastes and lower rate (£2.60/tonne) for inert wastes. The rate of inert or inactive waste will be £2.65/tonne on 1 April 2016 (ECOTEC Research and Consulting et al, 2001; HM Revenue & Customs, 2016).

The other significant factor that enhanced the benefits from recycling/reusing C&D waste is the introduction of the Aggregates Levy in April 2002. This levy has imposed a £2 levy (since 1 April 2009) on primary sand, gravel and crushed rock production used for construction purposes. It increases by 30% the average prices in the UK of primary aggregates from 1) ground-dredged mines, 2) marine-dredged mines, and 3) import, with no effect on UK export products and recycled aggregate (ECOTEC Research and Consulting et al, 2001; Martin and Scott, 2003; Böhmer *et al.*, 2008).

The two main environmental taxes have reciprocal relationship and affect the use of construction materials and waste considered from extraction, use and disposal stages of construction materials. The Aggregate Levy has more influence in the extraction and use stages. The disposal stage is governed by the Landfill Tax and reinforces recycling and reuse activities that encourage users to reduce the use of primary extraction of raw materials.

2.2 Thailand

2.2.1 Cement Industry

2.2.1.1 Overview of Thai Cement Industry

Cement is an important material in the construction industry and plays a key role in modern Thai society. The first cement company in Thailand was Siam Cement, now SCG Cement Public Co. Ltd., which has operated since the First World War (1913) at Bangsue, Bangkok (SCG Cement Public Co. Ltd., 2014). This company, as intended by King Rama VI of Thailand, replaces imported cement from abroad with domestic production increasing as cement became an important material for Thai building.

Later, a new producer named Jalaprathan Cement Co.Ltd. was founded in 1956 to produce cement for dam, irrigation and canal construction. The other new cement producer, Siam City Cement Public Co.Ltd., was established in 1969. At that time, the Thai cement industry produced cement for only domestic consumption and involved three companies that formed a monopoly. This was because of previous government policy that influenced new cement company development through several limitations and conditions, such as a requirement for more than 70 percent of the shares to be hold by native Thai shareholders. As a result, no new producers appeared, but it contributed to capacity expansion by the original manufacturers (Department of Mineral Resources, 2008b).

After 1987, the Thai government changed to support and encourage old/new producers to establish new cement plant more easily and allowed joint ventures with foreign companies such as Holcim and Cemex. Consequently, another five new cement producers now operate. A great change in the Thai cement industry is the 1997 economic crisis. This crisis led the Thai government to assist and stimulate the cement industry by allowing free trade of clinker and cement products due to Thailand having high potential to compete in the cement business among the ASEAN countries (Supachalasai and Pangkanon, 1996; Department of Mineral Resources, 2008b).

At present, Thailand is an important cement manufacturer, consumer and exporter, ranked the third in ASEAN, following behind Vietnam and Indonesia (Saunders, 2015; TFCM, 2015). As concrete is the main construction material in all ASEAN countries, total cement production capacities in this region having active cement industries (excluding Brunei and Singapore) are around 265 million metric tonnes (Mt) from 139 cement plants in 2015 (Saunders, 2015).

Thai annual clinker manufacturing capacity is 46.92 Mt and 56.42 Mt for annual cement capacity. These products come from the 31 kilns (dry process) and 14 cement plants of eight cement companies, sporadically located in six provinces. The principal province near Bangkok as the main location of six cement factories is Saraburi Province. Plant location in the middle of the country facilitates transport of cement to construction sites around Thailand (**Table 2-7**, **Table 2-8** and and **Figure 2-39**). For Thai cement market share, the top three cement producers are 41% SCG Cement Public Co. Ltd. (from five plants), 26% Siam City Cement Public Co.Ltd. and 16% TPI Polene Public Co.Ltd. (**Figure 2-40**).

Table 2-7 Summary of Thai cement industry (2013)

Companies (units)	8
Plants (units)	14
Kilns (units)	31
Production Capacity for Clinker (tonnes)	46,916,000
Production Capacity for Cement (tonnes)	56,422,000
Cement Production (tonnes)	35,854,770
Domestic Sales (tonnes)	30,084,300

Source: Modified from TFCM (2015)
Note: Clinker capacity per year based on 320 days; clinker/ cement ratio 1:1.2

Table 2-8 Summary of each Thai cement company, plant and capacity

No.	Companies	Number of Kiln (Dry Process)	Productivity	
			Clinker (tonnes/day)	Cement (tonnes/year)
1.	**SCG Cement Public Co. Ltd.**	**14**	**60,500**	**23,232,000**
	The Siam Cement (Ta Luang) Co.Ltd. (Ta Luang Plant)	2	8,000	3,072,000
	The Siam Cement (Ta Luang) Co.Ltd. (Khao Wong Plant)	1	10,000	3,840,000
	The Siam Cement (Kaeng Khoi) Co.Ltd.	4	19,000	7,296,000
	The Siam Cement (Thung Song) Co.Ltd.	6	18,000	6,912,000
	The Siam Cement (Lampang) Co.Ltd.	1	5,500	2,112,000
2.	**Siam City Cement Public Co.Ltd.**	**6**	**38,500**	**14,784,000**
3.	**TPI Polene Public Co.Ltd.**	**3**	**23,500**	**9,074,000**
4.	**Asia Cement Public Co.Ltd.**	**2**	**13,000**	**4,992,000**
5.	**Jalaprathan Cement Public Co.Ltd.**	**3**	**6,100**	**2,342,400**
	Takli Plant	2	3,000	1,152,000
	Cha-am Plant	1	3,100	1,190,400
6.	**Thai Pride Cement Co.Ltd.**	**1**	**2,500**	**960,000**
7.	**Cemex (Thailand) Co.Ltd.**	**2**	**2,200**	**844,800**
8.	**Samukkee Cement Ltd.**	**No data**	**No data**	**No data**
	Total	**31**	**146,300**	**56,229,200**

Source: Modified from TFCM (2015)

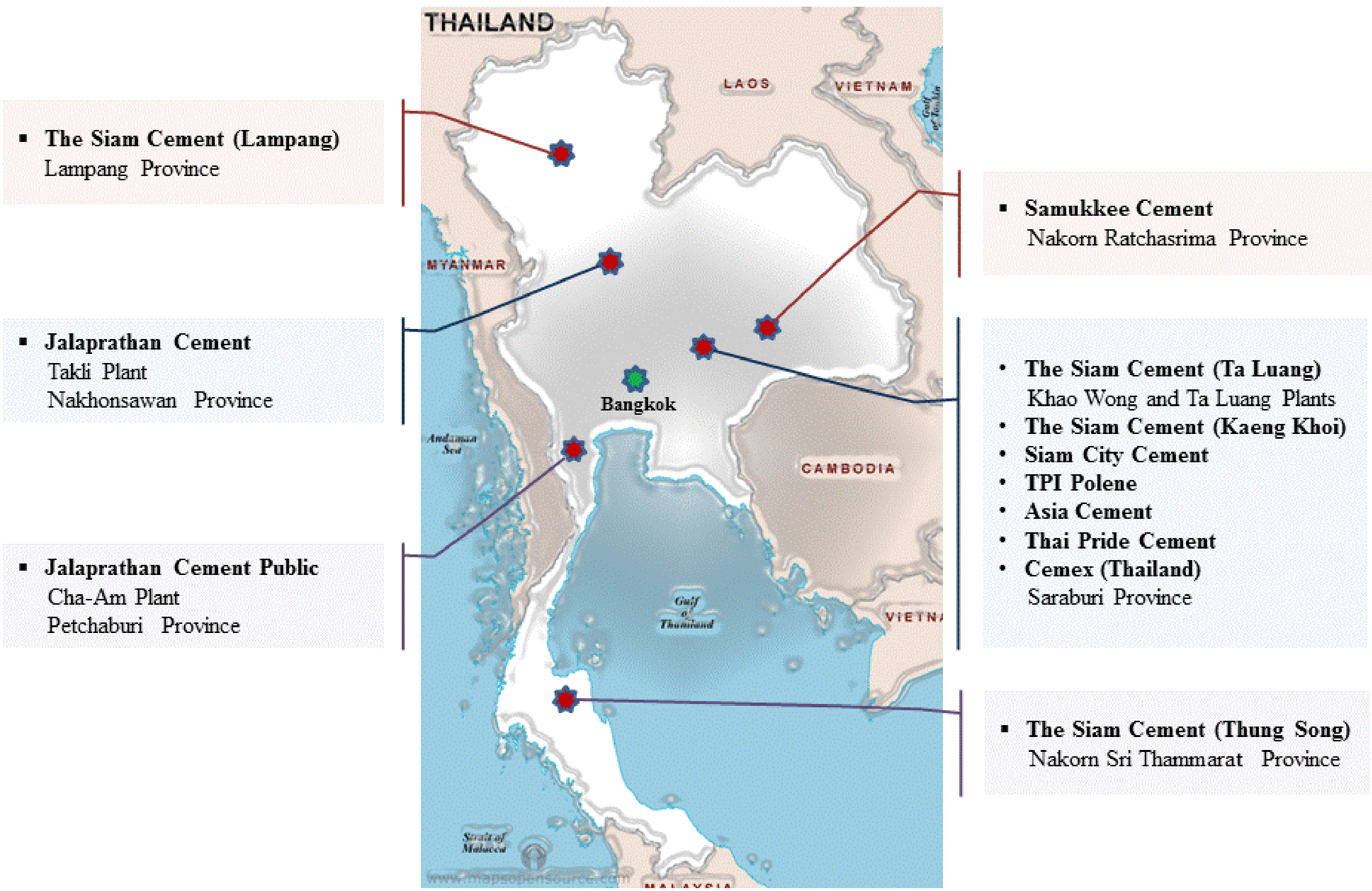


Figure 2-39 Thailand cement factories
Source: Author based on TFCM (2015)

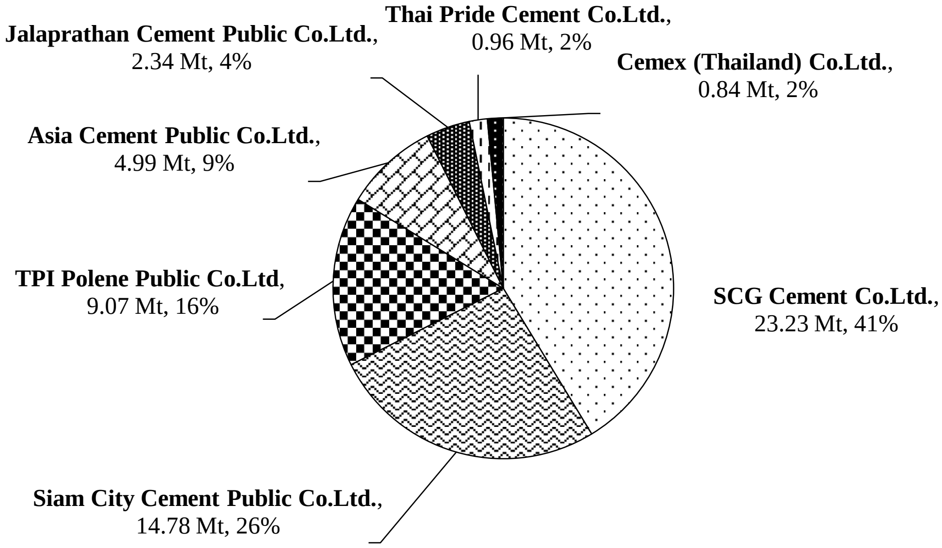


Figure 2-40 Thai cement productivity
Source: Author based on TFCM (2015)

2.2.1.2 Clinker Minerals

To produce clinker, Thailand also uses indigenous minerals, like Great Britain, and a similar ratio of raw materials as elsewhere in the global cement industry. Limestone production and consumption trends are important for clinker manufacturing due to the main raw materials formed by 75% limestone and 25% shale including other minor minerals (Manning, 1995; Conneely *et al.*, 2001; Worrell *et al.*, 2001). Relating to clinker production, about 60-70% of limestone consumption by volume, with increasing trend, is mainly used for the Thai cement industry (**Figure 2-41**).

As it is widely known, production cost is the main expenditure in cement manufacturing and distribution. In the Thai cement industry, Supachalasai and Pangkanon (1996) reported that 71% of total cost is production and the 29% remain is for distribution. Production cost includes 30% energy cost, 25% other costs, 8% packaging, 7% labour. Only 1% of the production cost pays for clinker minerals. Thai cement manufacturers currently pay a royalty for mineral resources at a lower rate than the value of lost natural resources (opportunity cost, Department of Mineral Resources (2008b)).

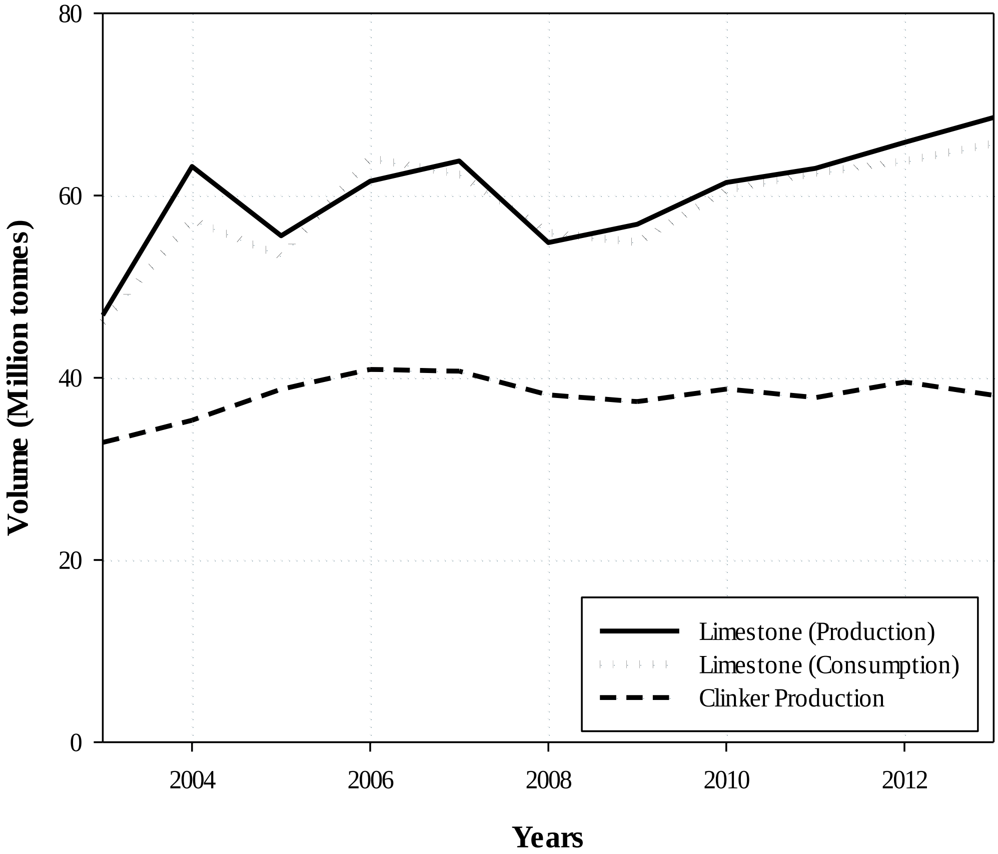


Figure 2-41 Production and consumption of limestone for Thai clinker manufacturing
Sources: Author based on Information Technology Centre (2006a); (2006b); (2009a); (2009b); (2012a); (2012b); (2014a) and (2014b)

2.2.1.3 Clinker Manufacturing

The volume of Thai clinker manufacturing tends to be stable with increases following higher cement requirements for domestic consumption and foreign trade demand. However, volume of export clinker has continuously reduced since 2007 (**Figure 2-42**), because of reduced clinker demand of foreign customers especially ASEAN countries (Office of Industrial Economics, 2013).

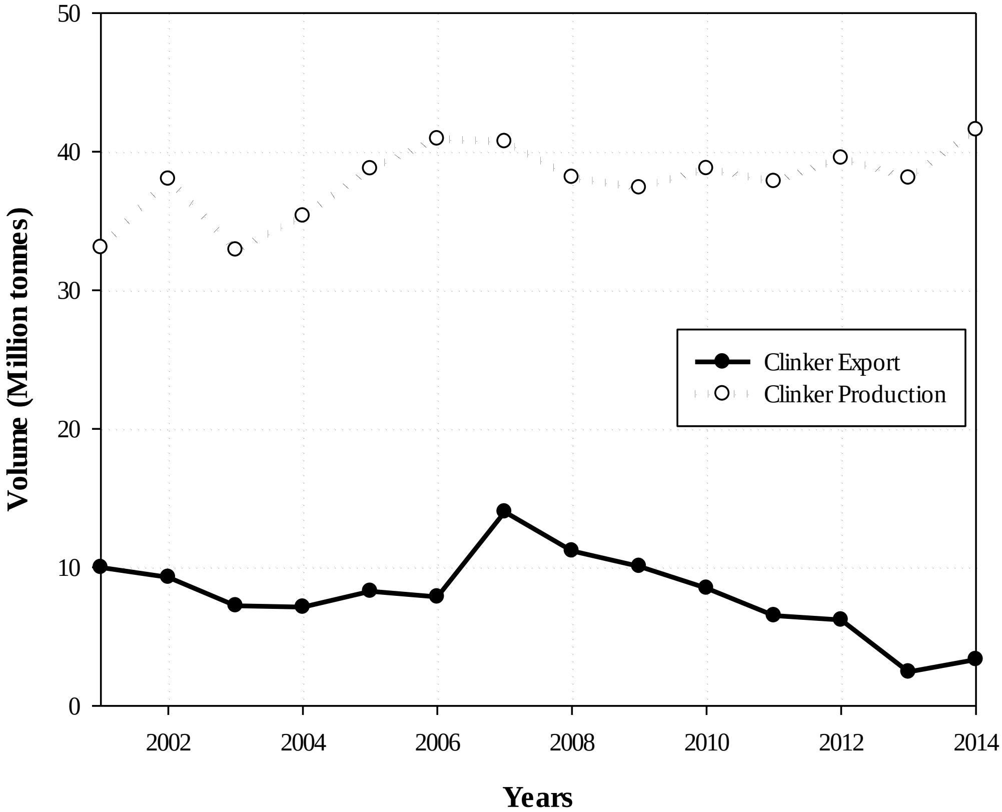


Figure 2-42 Volume of clinker production, domestic distribution and export
Sources: Author based on Office of Industrial Economics (2001); (2002); (2003); (2004); (2005); (2006); (2007); (2008); (2009); (2010); (2011); (2012); (2013); (2014)

2.2.1.4 Cement Manufacturing

The Thai Cement Manufacturers Association (TCMA) was established for coordination of all cement companies in Thailand and sets up policy and role assignment, including connection between cement industries and other agencies, both domestic and foreign. Furthermore, this organisation also collects some important data from all cement companies and presents them to the public. **Figure 2-43** and **Figure 2-44** show that volume of Thai cement consumption per capita is currently increasing, having a direct relationship with permitted construction areas (Bank of Thailand, 2015a; TFCM, 2015). For future Thai cement consumption, the Department of Mineral Resources (2008b) predicted that domestic cement requirement in the next 30 years will increase by around 0.27 Mt or 1% each year.

Higher demand in both Thailand and trading countries leads to increasing volume of Thai clinker and cement. As seen, the volume of cement export continuously rises, which seems to be the opposite trend for clinker export (**Figure 2-45**). This is because other trading countries, especially in the ASEAN region, tend to reduce clinker demand but still have higher demand for the cement finished product (Office of Industrial Economics, 2013).

Thailand has generally sent cement as an export product to other countries. The volume of domestic cement consumption is 70-85% and then the excess to requirement (around 15-30%) is exported to neighbouring countries. Besides, the cement price has also continuously increased, seen from the representative retail price of mixed cement (50 kilogrammes: Kg) in **Figure 2-46**. As cement is a monopoly product from only a few manufacturers in Thailand, cement price needs to be controlled by the Ministry of Commerce (Competitiveness Development Office, 2013).

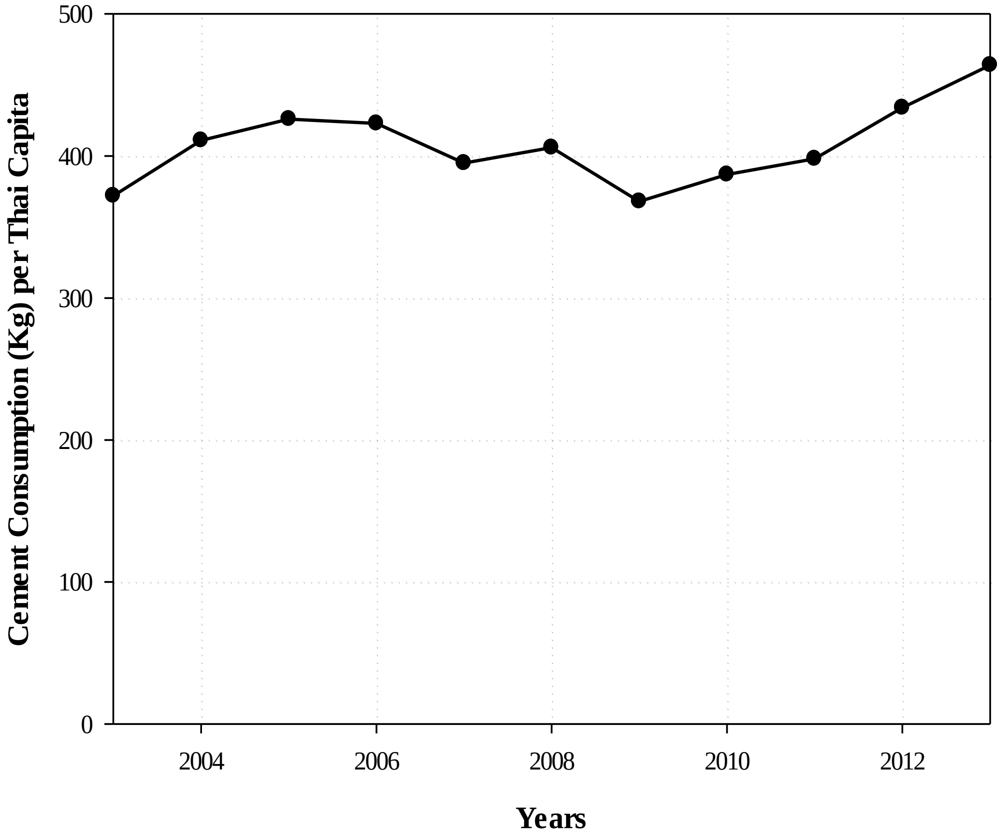


Figure 2-43 Cement consumption per Thai capita
Source: Author based on TFCM (2015)

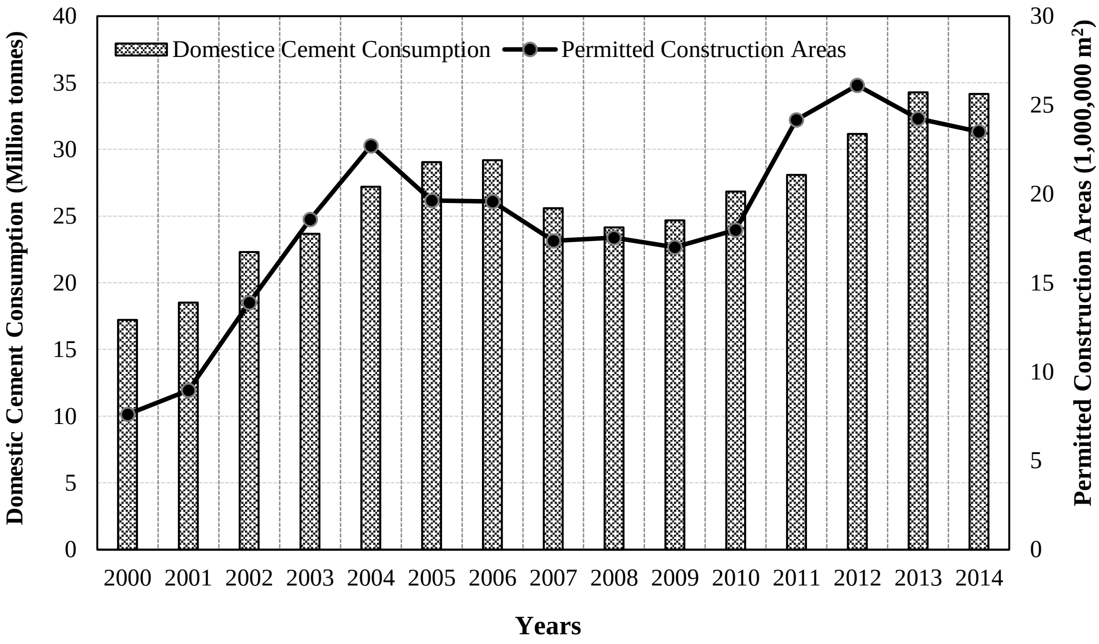


Figure 2-44 Relationship of domestic cement consumption and permitted construction area in municipality
Source: Author based on Bank of Thailand (2015a)

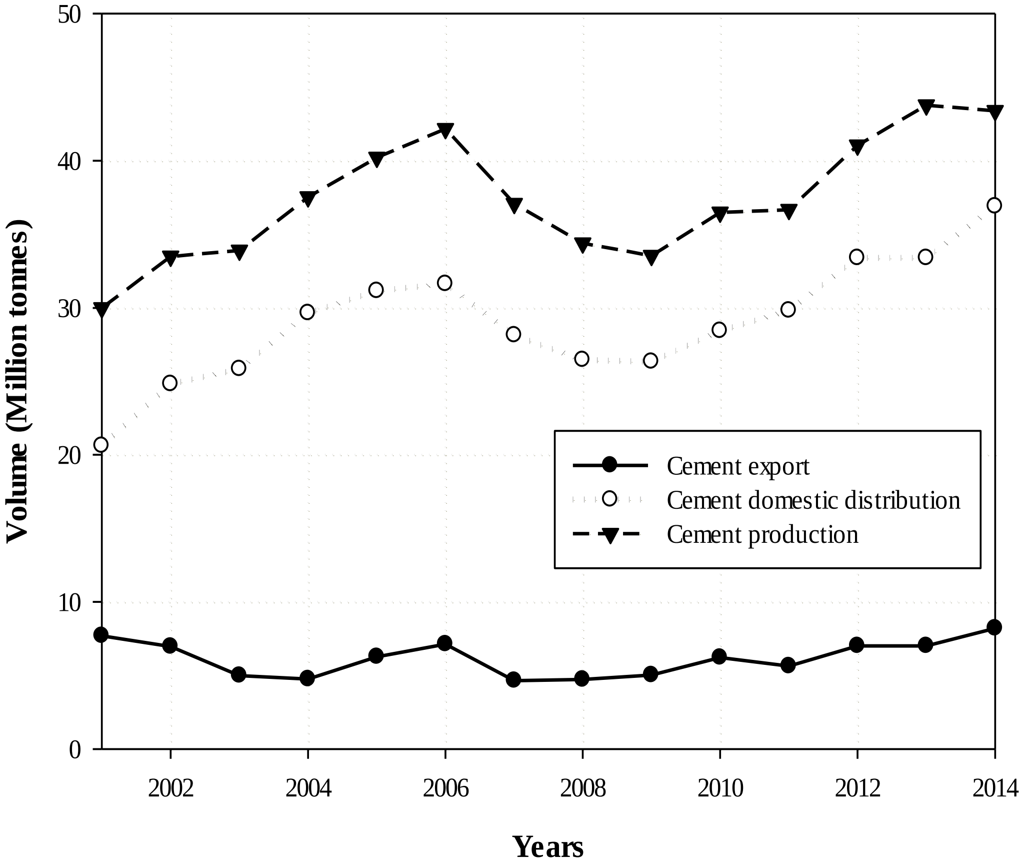


Figure 2-45 Volume of cement production, domestic distribution and export
Sources: Author based on Office of Industrial Economics (2001); (2002); (2003); (2004); (2005); (2006); (2007); (2008); (2009); (2010); (2011); (2012); (2013); (2014)

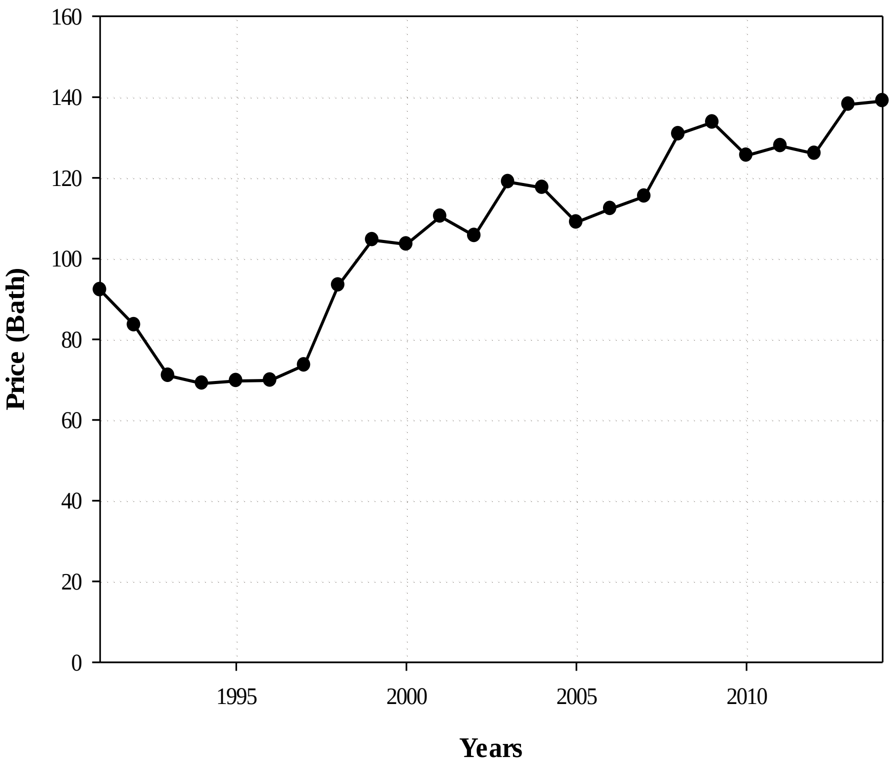


Figure 2-46 Mixed cement 50 Kg (retail price)
Source: Author based on Bank of Thailand (2015b)

2.2.1.5 Clinker and Cement for Foreign Trading

The Office of Industrial Economics (2013) reported that the production of Thai clinker and cement in 2012 increased from the previous year by 5.24% and 12.35% respectively. This increased trend came from (1) the restoration of infrastructure needed to cope with protection from flooding, severely experienced in 2011, and (2) economic expansion in Thailand and major markets in trading countries that are in ASEAN including some developing countries. Staying in the top 20 global cement exporters in 2012 (International Cement Review, 2013), Thailand exported clinker and cement corresponding to around 28% of its cementitious products in 2012, and the five most significant national markets are Myanmar, Cambodia, Bangladesh, Laos and Togo respectively (Office of Industrial Economics, 2013).

Nevertheless, the same organisation predicted that clinker export volumes will be likely to decline compared with previous years. This downward trend is because some Thai cement companies, aiming for leadership, have expanded their manufacturing operations to some ASEAN countries which are the main markets (**Figure 2-47**). Initially, there is expansion of investments and markets in Vietnam, Cambodia, Laos, Myanmar, Indonesia and the Philippines, including investment in distribution centres in Malaysia and Singapore (Office of Industrial Economics, 2013).

In the future, the Office of Industrial Economics (2013) estimated that export cement from Thailand will continuously increase because of rapid development in the ASEAN and South Asian countries (Bangladesh and Sri Lanka), including some developing countries, continuing to import cement from Thailand (such as Togo, Chile, and Kenya). However, the volume of clinker imported for Thai construction has been reduced and Thailand still needs to import a very small volume of a premium grade of cement from other countries, especially Japan, for some delicate construction works.

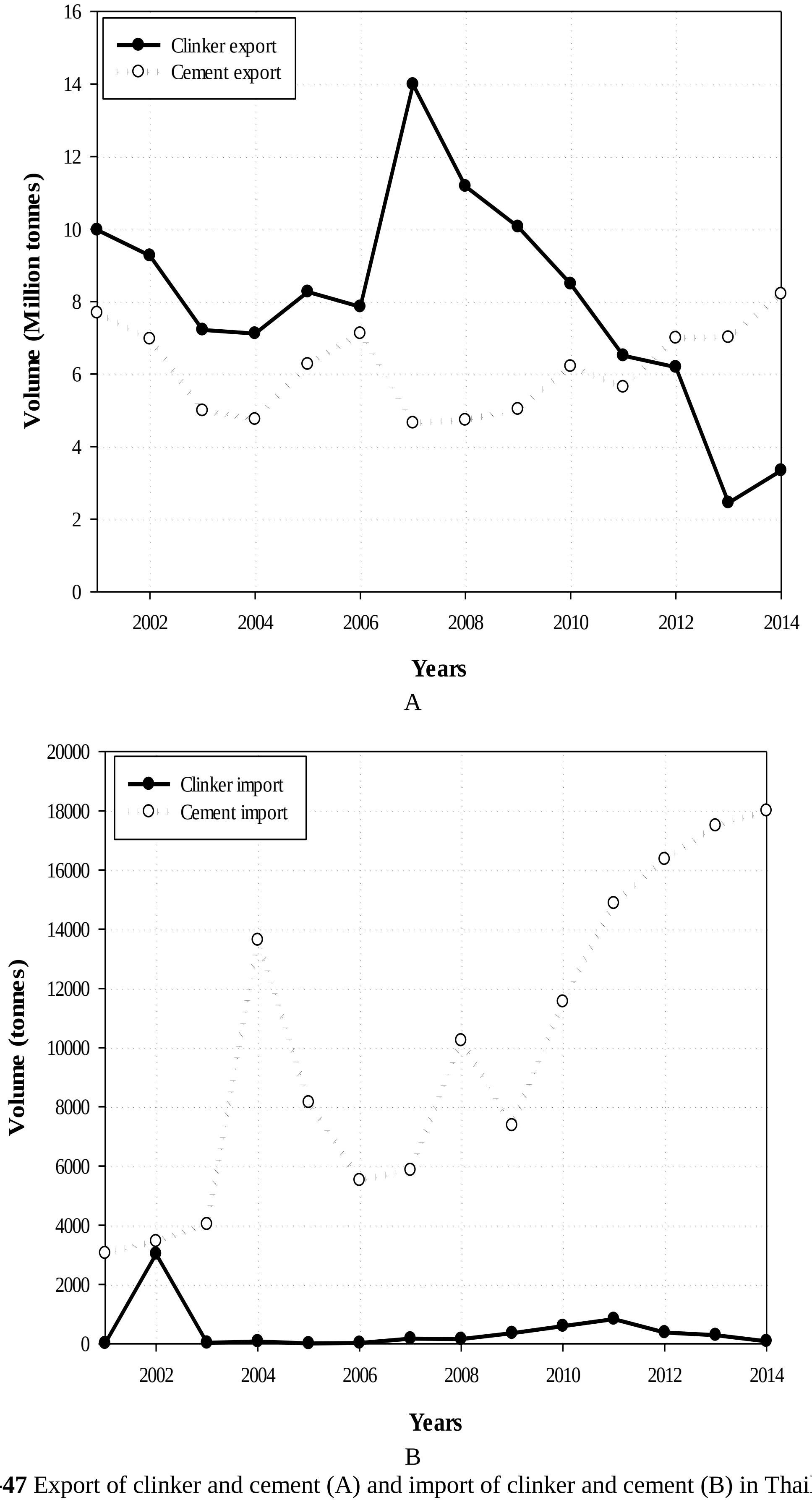


Figure 2-47 Export of clinker and cement (A) and import of clinker and cement (B) in Thailand
Sources: Author based on Office of Industrial Economics (2001); (2002); (2003); (2004); (2005); (2006); (2007); (2008); (2009); (2010); (2011); (2012); (2013); (2014)

2.2.2 Aggregate Market

Without identifying types of aggregates and data concerning recycled and secondary aggregates for concrete and construction uses like Great Britain, Thailand appears to use only indigenous aggregates and reports only limestone for construction. This has recently tended to increase in consumption (**Figure 2-48**).

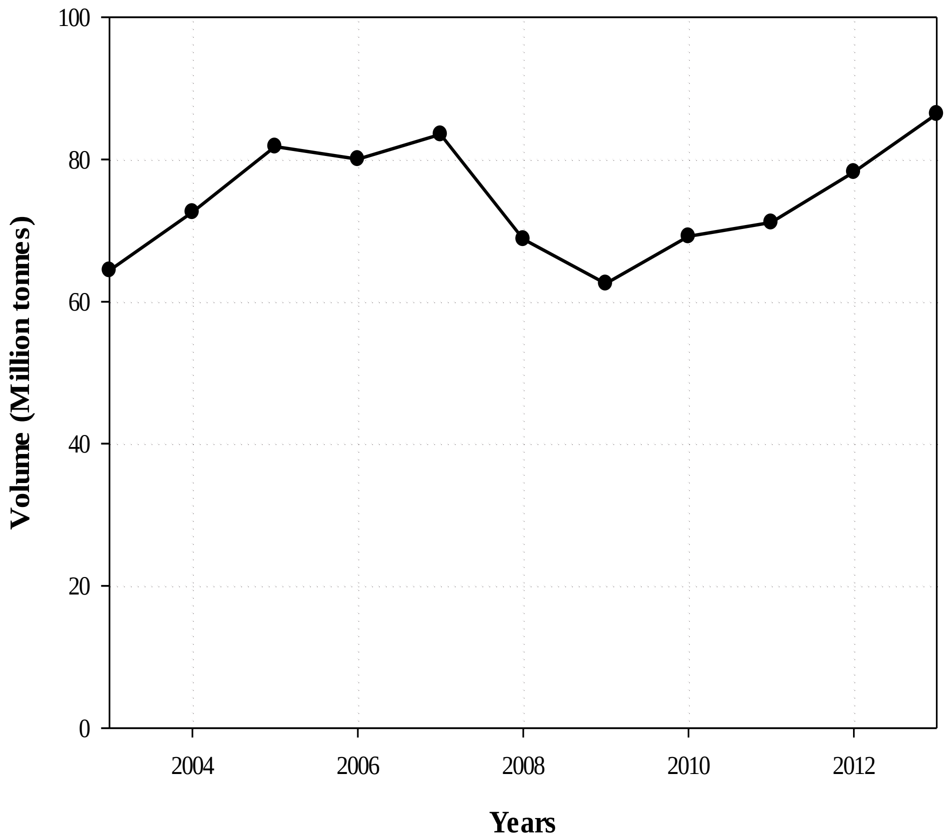


Figure 2-48 Limestone Consumption for Thai Construction
Sources: Author based on Information Technology Centre (2006a); (2009a); (2012a) and (2014a)

2.2.3 Concrete Industry

As the principal construction material, Thailand uses increasing amounts of concrete annually, but has no published strategy that encourages the use of recycled aggregates from concrete waste, no registered data, no integrated sustainability policy and no major government agency. Several categories of precast concrete are widely used in construction sites, described in a report by the Department of Primary Industries and Mines (2003). Cement block was the dominant finished concrete type (around 67%), followed by 26% of mixed finished concrete and 7% of prefabricated flooring, stake, finished pipe and finished fence (**Figure 2-49**). Like other developing countries, site-mixed concrete is more popular in Thailand, especially in rural areas (World Business Council for Sustainable Development, 2009).

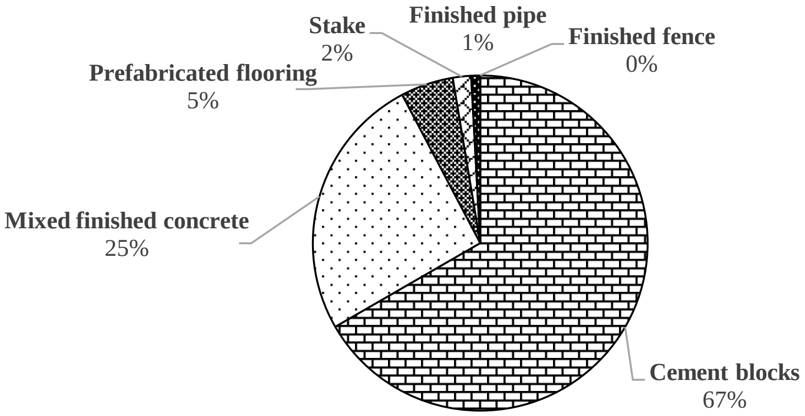


Figure 2-49 Types of Thai precast concrete
Source: Author based on Department of Primary Industries and Mines (2003)

2.2.4 Construction industry

2.2.4.1 Approval of Construction or Renovation

Following the Building Control Act 1979, new and renovated buildings need to obtain permissions from local governments. For Thai national data, the National Statistical Office, under the Ministry of Information and Communication Technology, has the responsibility to collect and report these permissions annually. In their reports, a number of new and renovated construction activities are separated into three main types as; (1) Building, (2) Non-building type 1 (fence/wall, road, bridge, dam/berm and drain) and (3) Non-building type 2 (pool, petrol station, port, stadium, parking and advertising sign; National Statistical Office (2012b)).

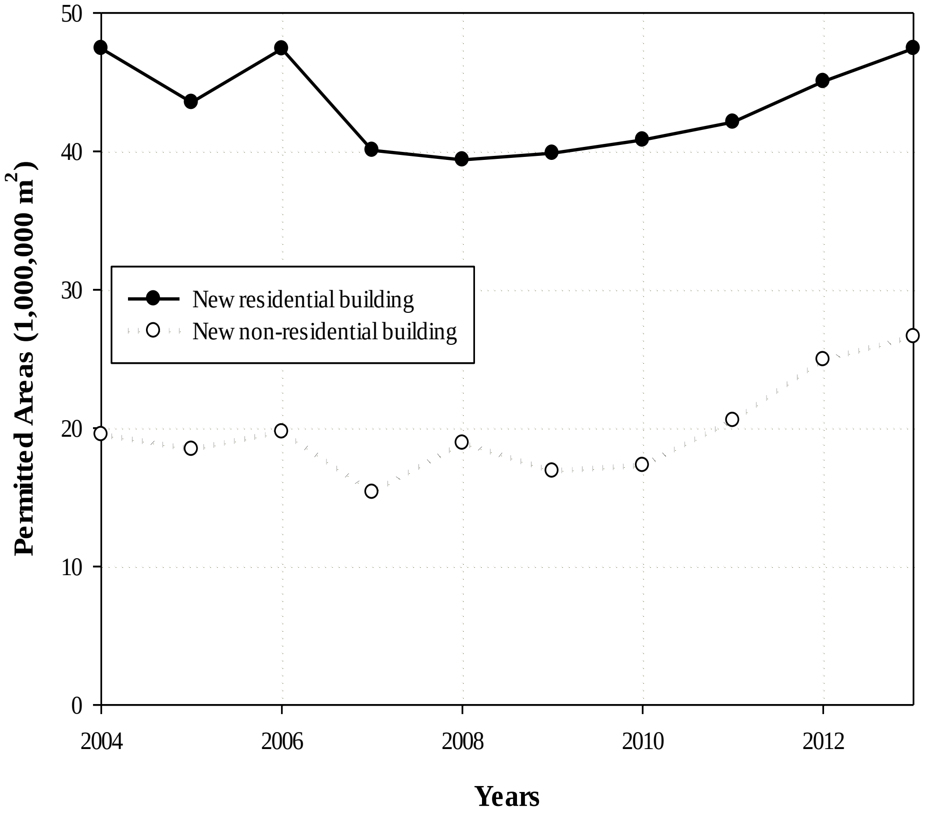
2.2.4.1.1 Building

For the following discussion about areas of permitted construction, it is noted that a future trend in the Thai construction industry in both new and renovated buildings is likely to involve more expansion (Bank of Thailand, 2015d). Until now, there have been more construction activities all over the country, particularly in Bangkok and five metropolitan provinces (Nakhon Pathom, Nonthaburi, Pathum Thani, Samut Prakan and Samut Sakhon provinces; National Statistical Office (2012b)).

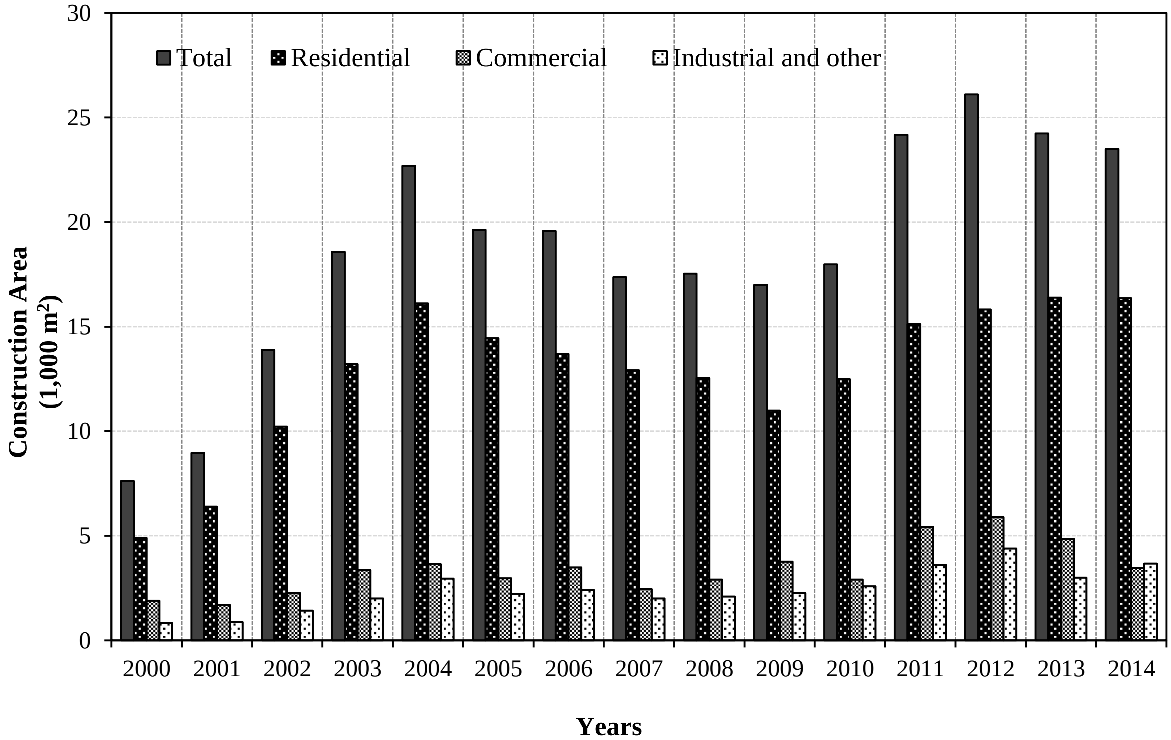
Separating building in Thailand into two sub-types (residential and non-residential building), new residential building is generally two times higher than non-residential building each year. This is consistent with the permitted area for different building types in municipalities (**Figure 2-50**), as residential building has more area to construct than other types of building or 89% of all buildings in Thailand (Tikul and Srichandr, 2011).

Figure 2-51 shows that in 2007-2008 Thailand had a drastic reduction of single residential building with an increase in multi residential building, which then slightly increased again from 2008. The popularity of multi residential building for Thai housing rapidly increased in 2007-2008 and then showed little change. Thailand has got more annual permitted areas for residents in new construction activities (>90%) than renovation activities (<10%; **Figure 2-52**; National Statistical Office (2013a)). Considering renovation activities since 2008, multi residential buildings have higher requirements for repairing than single residential buildings (**Figure 2-53**).

The lifetime of buildings in Thailand can be estimated from other Asian countries. Old residential buildings in China have a lifespan around 15-50 years (Hu *et al.*, 2010c) and 30 years for a multi-storied commercial building in Singapore (Kua and Wong, 2012). This turnover of stock encourages Thailand to consume more materials for construction especially for the residential sector. Until now, commercial and industrial buildings are still the major requirements in new non-residential building in Thailand (**Figure 2-54**). In addition, these tend to be renovated more than residential buildings (**Figure 2-55**).



A



B

Figure 2-50 New residential and non-residential building (A) and building types of permitted area in municipality (B)

Sources: A: Author based on National Statistical Office (2005), (2006), (2007), (2008), (2009a), (2010), (2011), (2012a), (2013a) and (2014)

B: Author based on Bank of Thailand (2015a)

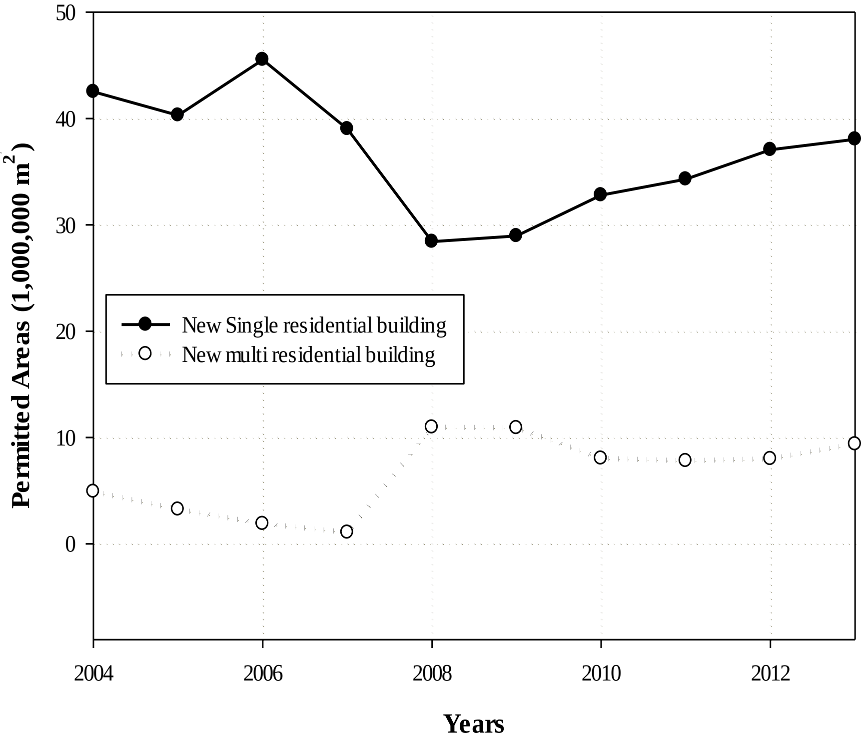


Figure 2-51 New residential building in Thailand
Sources: Author based on National Statistical Office (2005), (2006), (2007), (2008), (2009a), (2010), (2011), (2012a), (2013a) and (2014)

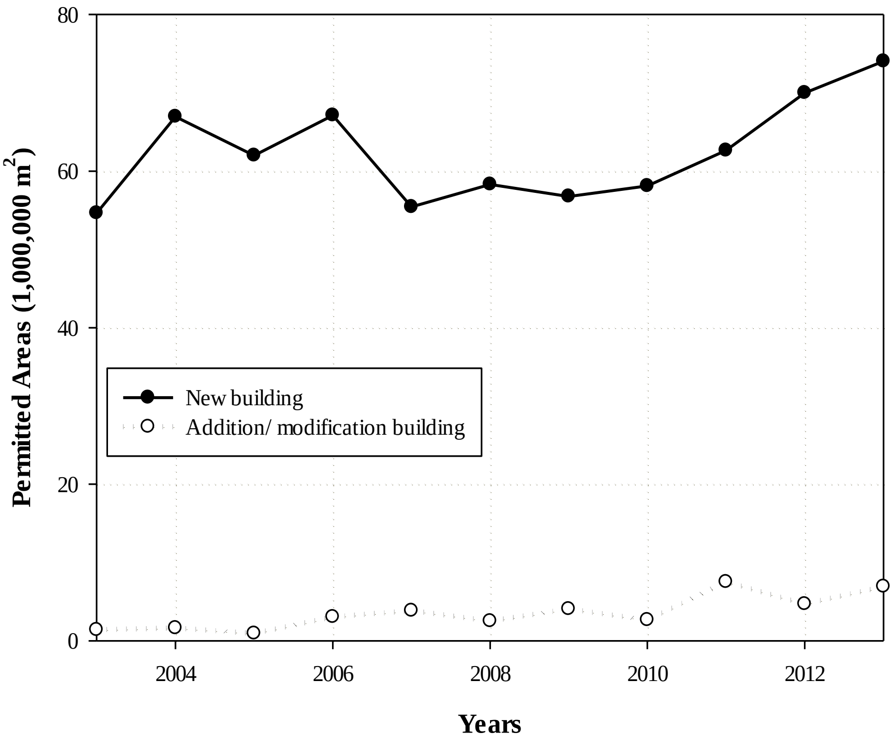


Figure 2-52 New and refurbished activities in Thai residential building
Sources: Author based on National Statistical Office (2005), (2006), (2007), (2008), (2009a), (2010), (2011), (2012a), (2013a) and (2014)

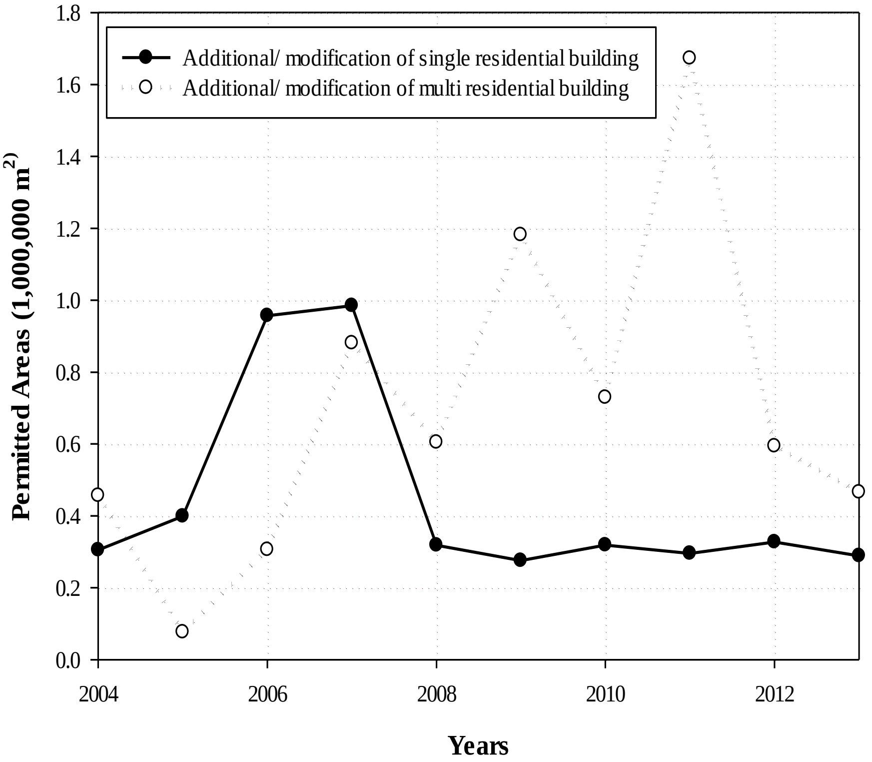


Figure 2-53 Addition/ modification of residential building
Sources: Author based on National Statistical Office (2005), (2006), (2007), (2008), (2009a), (2010), (2011), (2012a), (2013a) and (2014)

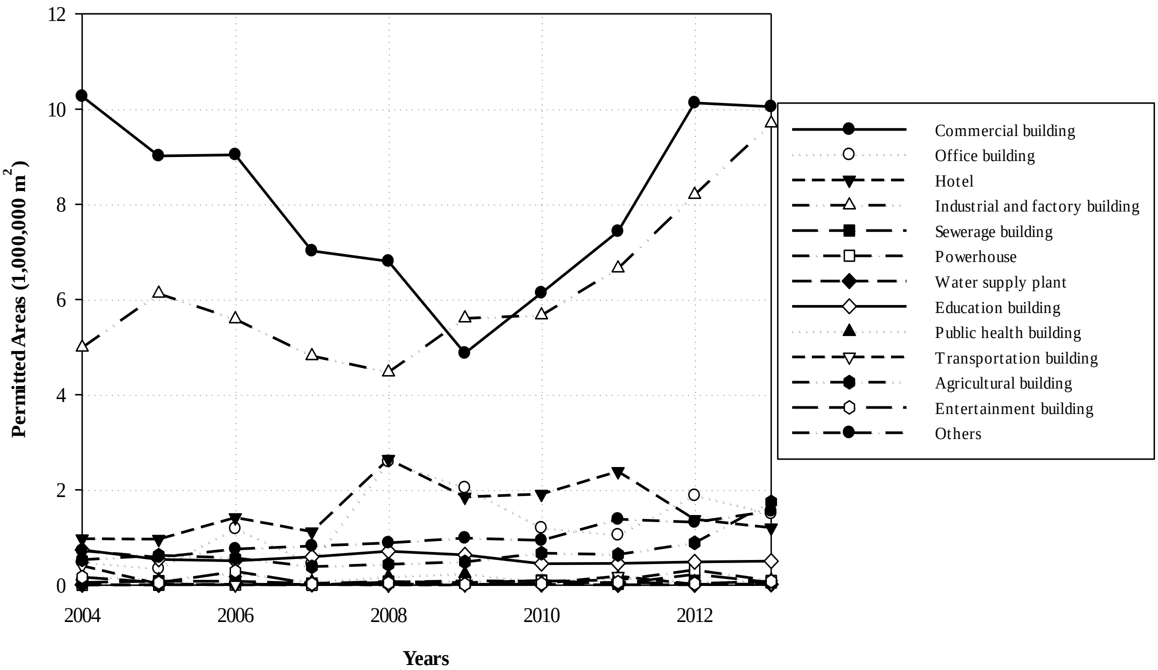


Figure 2-54 Types of new non-residential building
Sources: Author based on National Statistical Office (2005), (2006), (2007), (2008), (2009a), (2010), (2011), (2012a), (2013a) and (2014)

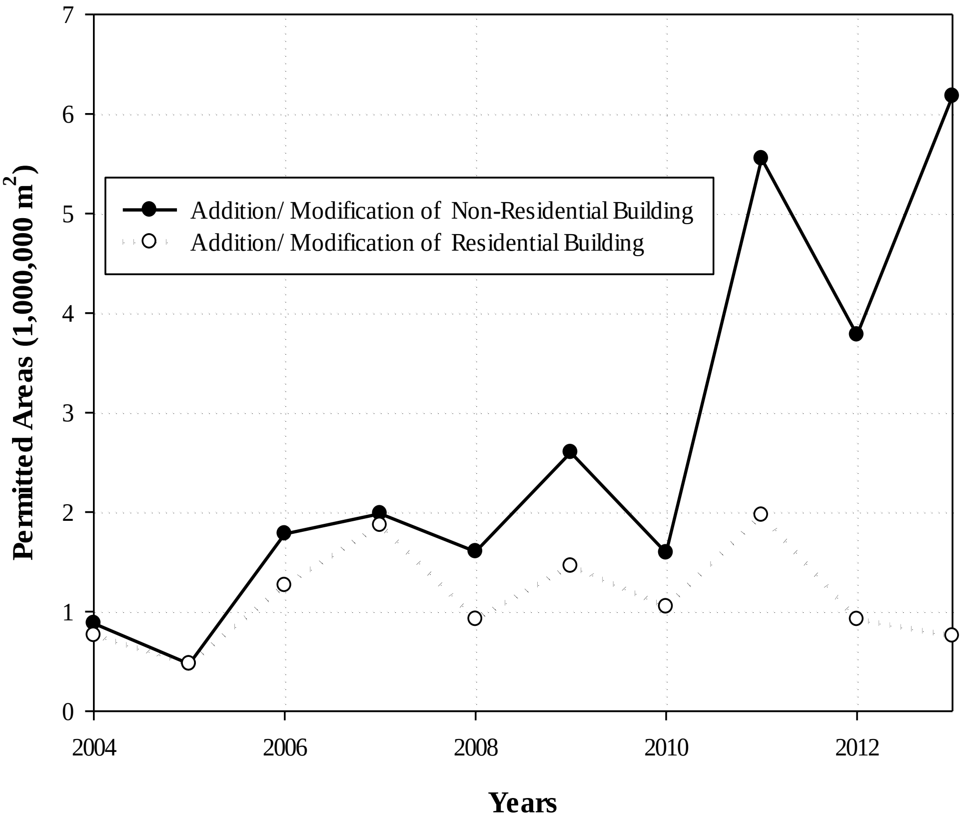
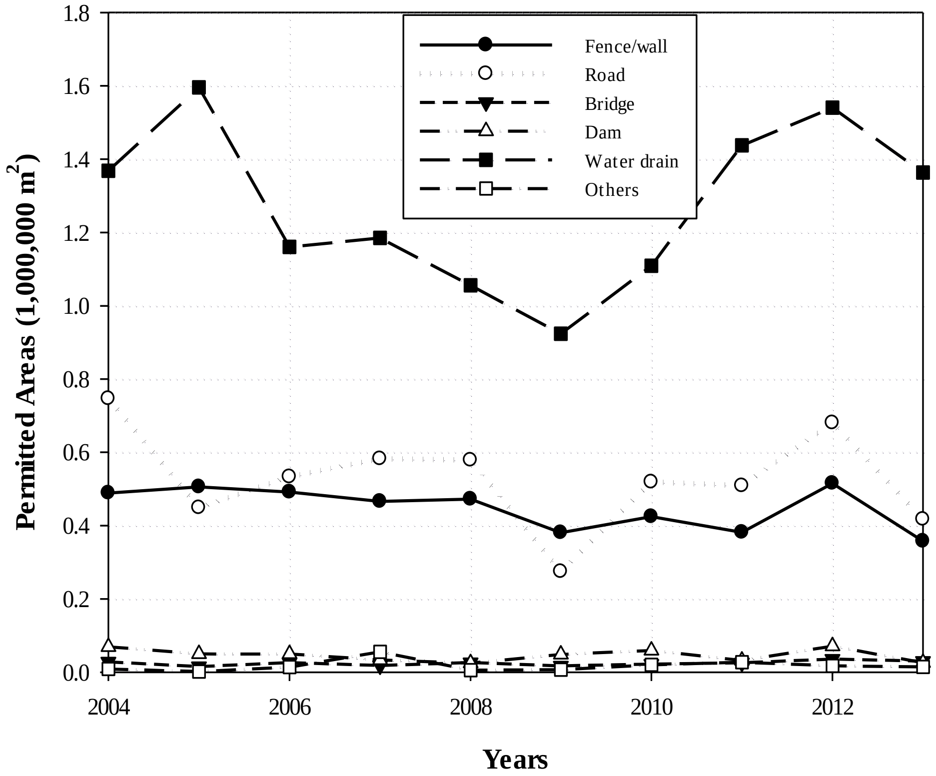


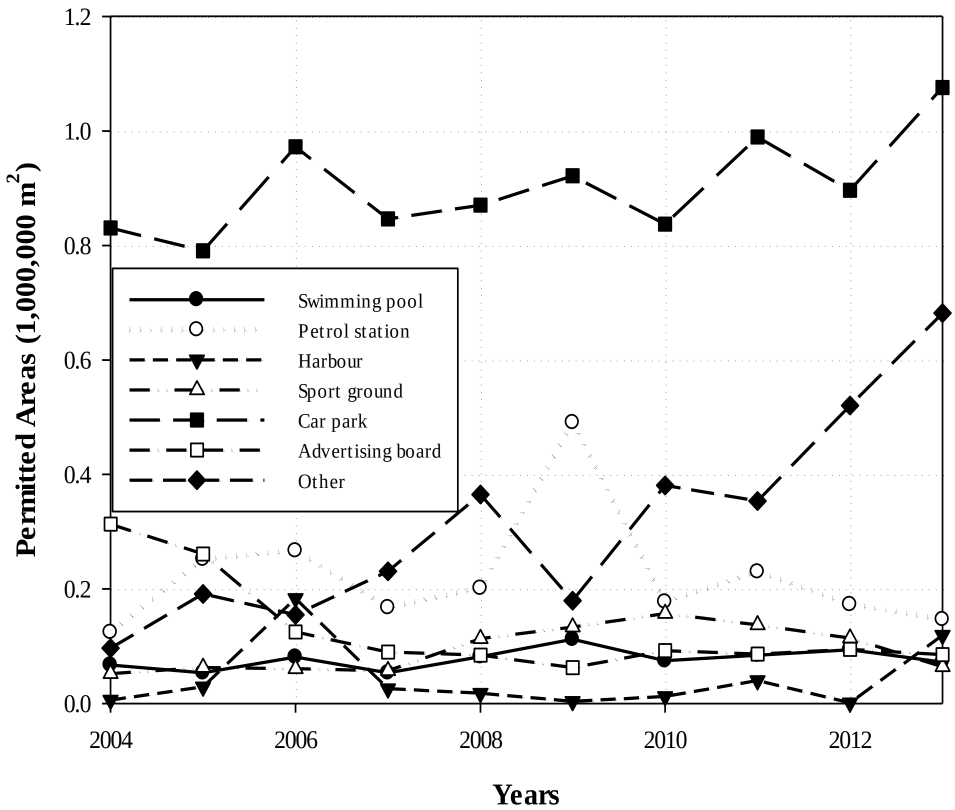
Figure 2-55 Addition/ modification of residential and non-residential building
Sources: Author based on National Statistical Office (2005), (2006), (2007), (2008), (2009a), (2010), (2011), (2012a), (2013a) and (2014)

2.2.4.1.2 Non-building Type 1 and 2

Thailand records new construction for non-building as (1) permitted length of fence/wall, road, bridge, dam/berm and drain as 'non-building type 1' and (2) permitted area of pool, petrol station, port, stadium, parking and advertising sign as 'non-building type 2'. The construction of non-building type 1 had a fluctuating trend, but there was a small increasing trend for non-building type 2. In addition, the major construction types of these new construction groups are water drain (non-building type 1) and car park (non-building type 2, **Figure 2-56**).



A



B

Figure 2-56 New non-building type 1 (A) and type 2 (B)
Sources: Author based on National Statistical Office (2005), (2006), (2007), (2008), (2009a), (2010), (2011), (2012a), (2013a) and (2014)

2.2.4.2 Construction Sectors in Thailand

Construction data in 2009 showed that Thailand had a number of construction establishments with 29,360 companies. These were mostly established in the Northeast (about 34%), followed by 18% North, 16% South, 13% Bangkok, 11% Central and 8% perimeters. Moreover, 57% of these companies had core competence for building construction. In addition, most construction firms in Thailand were small companies (around 18,000 firms) with only 1-5 workers and company value less than ฿1 million or £20,000. These firms have trade registration mostly in the name of an individual proprietor. The main area of construction in Thailand is the Central region, especially Bangkok (**Figure 2-57**).

To follow clear steps in Thai construction, it can be separated into four main stages as followed, (1) planning, (2) design, (3) structuring and supervision, and (4) use and maintenance. Moreover, according to Thai legislation, consulting companies and design consultants need to legally register with the Council of Engineers of Thailand (COE). Structure Engineering Consultation is one of responsibilities of the Consulting Engineer Association of Thailand (CEAT; Limsuwan (n.d.)).

To perform the Building Control Act 1979, a building owner who requires to build a new building or to carry out building renovation must receive a license from the local authority (The Royal Thai Government, 1979). In some controlled areas, the owner must obtain other permission from some government organisations such as highway, railroad and state land. In addition, the summary of all Thai legislations and several government organisations relating to construction materials and processes throughout waste management is showed as **Figure 2-58** and **Figure 2-59**.

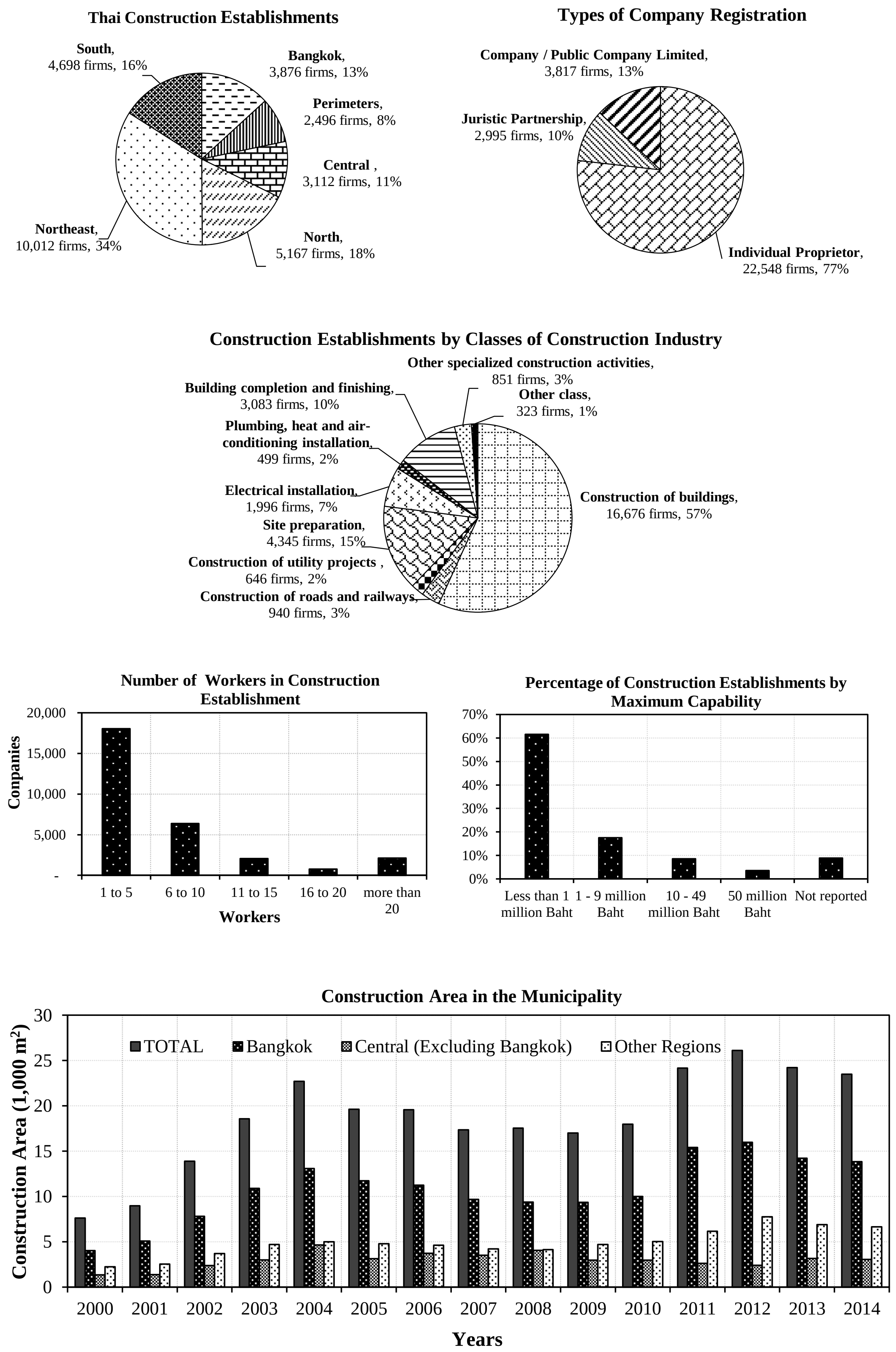


Figure 2-57 Information of Thai construction system
Sources: Author based on Bank of Thailand (2015a) and Economic and Social Statistics Bureau (2009)

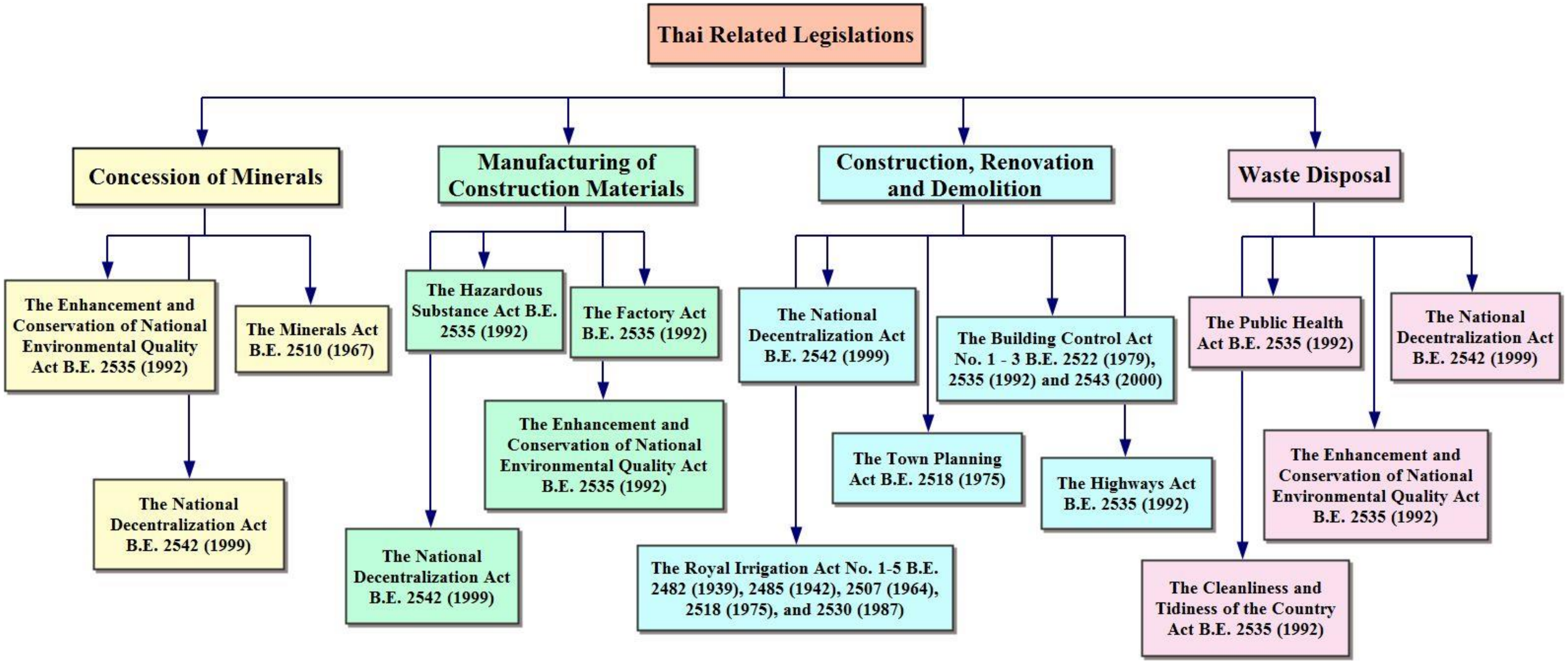


Figure 2-58 Thai related legislations for construction
Sources: Author
Note: B.E. means Buddhist Era

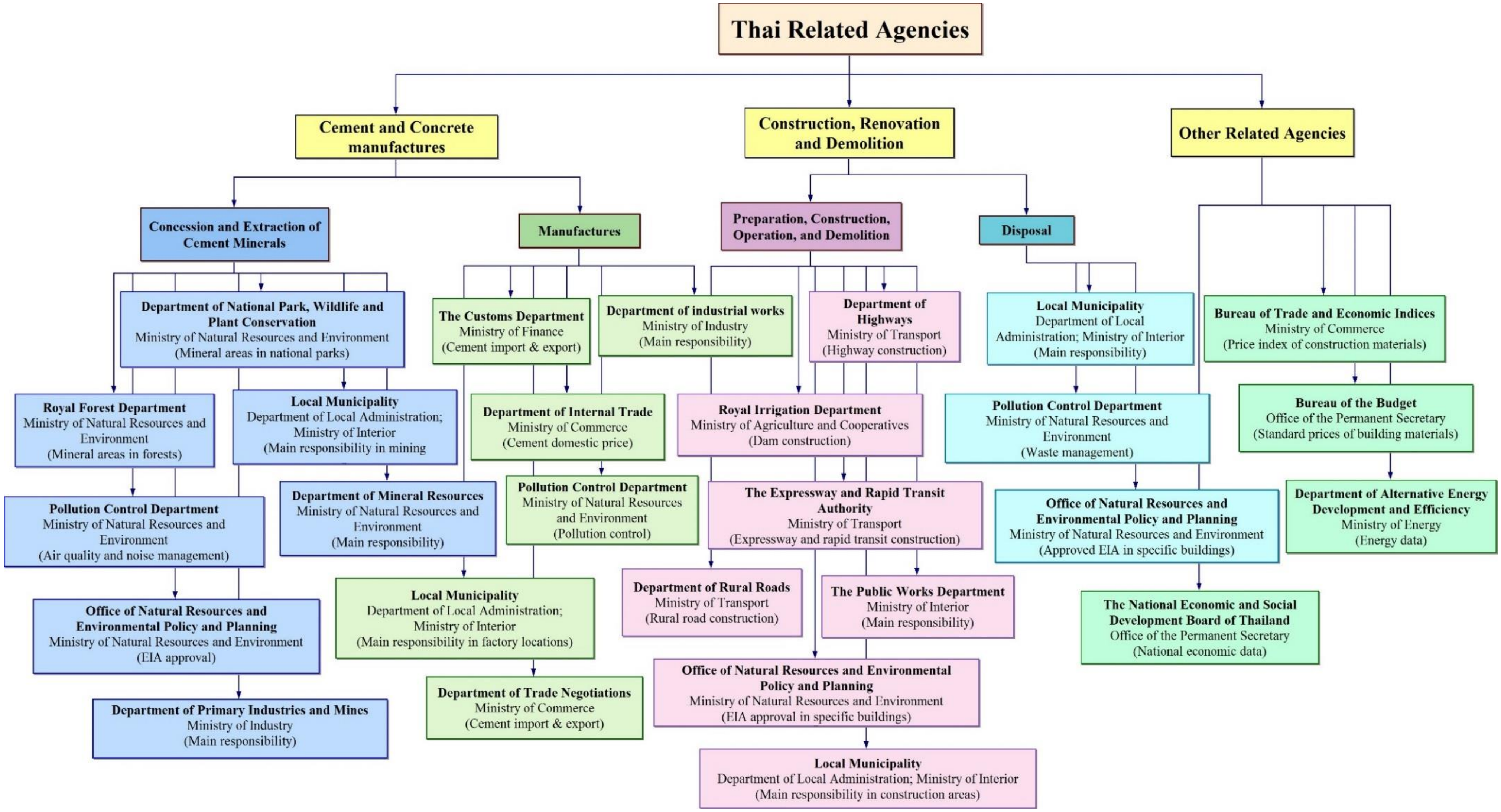


Figure 2-59 Thai related agencies for extraction, use and disposal of construction materials
Sources: Author

2.2.5 Waste Management

Several Asian countries including Thailand have no main organisation for handling C&D waste and have no specific regulations designed for C&D waste management (Nitivattananon and Borongan, 2007). Thus, this waste is disposed of unavoidably with household waste and controlled under the same regulations. Unlike Thailand, Japan has a specialized agency for C&D waste management under the Recycling Law, namely the Ministry of Land, Infrastructure, Transport and Tourism. This reason might make the system of waste management in Japan more successful than other Asian countries (Nitivattananon and Borongan, 2007).

2.2.5.1 C&D Waste Generation

With regard to building operation and maintenance, a service life span of buildings reported by several researchers is about 50 years (e.g. Kofoworola and Gheewala (2008);(2009b); Cuéllar-Franca and Azapagic (2012)) but some studies state that 70 years is the useful life of buildings (e.g. Li *et al.* (2013)). However, Chinese residential buildings have shorter lifespan being around 15-50 years (e.g.Hu *et al.* (2010c)). At the end of their lifespan, old buildings will be destroyed and become waste. In Thailand, demolished buildings are separated into two main parts by demolition companies. The first part includes reused and recycled materials, known as secondary materials such as lumber, glass, plastic and metals including alloys. The second is the remainder which must be handled outside and can be used as fill materials; including concrete debris and cut-off piles. In general, demolition activities involve confined spaces for separating demolition waste on site. Construction companies sometimes need to rent nearby areas for screening and storing secondary materials or these materials are transported to collect at company warehouses or yards (PCD *et al.*, 2007).

It is frequently seen that demolition waste is not managed properly and most C&D waste remaining after separation, consisting of concrete waste, is illegally dumped (PCD *et al.*, 2007; Kofoworola and Gheewala, 2009a). This is because most site managers disregard the benefits of waste separation and still believe that this method spends too much time and money. Thus, the attitude of site managers needs to be urgently improved and to find suitable areas identified for segregation (PCD *et al.*, 2007). One of most important reasons for illegal dumping in developing countries (Hora, 2007) is that the government pays no special attention to C&D waste because of having wide areas for informal dumping.

Estimates of C&D waste in the EU and the United States of America (USA) were about 180 and 136 million tonnes, respectively, and this waste is from new construction (8%), renovation (44%) and demolition phases (38%, Altuncu and Kasapseçkin (2011)). For Thailand, data for C&D waste are very hard to find, because of having no relationship for practical controls between construction and waste management systems. As stated by Kourmpanis *et al.* (2008a), it is hard to find recorded data on C&D waste in developing countries; these data are mostly available only in developed countries. Ordinarily, C&D waste in Thailand is under the control of local municipalities; management by the private sector with co-ordination of contractors is the most important key to success (Kofoworola and Gheewala, 2009a). With no awareness and poor understanding of Thai C&D waste, several researchers therefore can try to start only the first step of Thai C&D waste management that is the determination of waste generation rate.

Using the waste generation rate as 21.38 kg/m^2 habitat building and 18.99 kg/m^2 in non-habitat building from HQ Air Force Center for Environment Excellence (2006), Kofoworola and Gheewala (2009a) estimated that Thai construction waste from 2002 to 2005 was about 1.1 Mt per year or about 18 kilograms (Kg) per capita per year. In 2005, PCD *et al.* (2007) reported the volume of C&D waste only in Bangkok was greater than estimated by Kofoworola and Gheewala (2009a) for construction waste for the whole country. PCD *et al.* (2007) gave figures of 56.23 kg/m^2 for the generation rate of dwelling construction waste and 30.47 kg/m^2 for non-dwelling construction waste. In the case of demolition waste, Bangkok had waste from dwellings of 984.66 kg/ m^2 and 1,803.94 kg/m^2 from non-dwelling stocks, and so Bangkok had C&D waste around 498,584.12 tonnes per year or 73 Kg per capita per year.

The reasons behind increasing C&D waste generation according to Poon *et al.* (2004) come from two main causes. First, waste comes from unexpected sources, especially waste arising from inferior skill of workers. Second, damaged materials originate from poor design, including low quality as well as unguarded works during transportation, storage and other processes. In terms of the architects' perspective, C&D waste comes from the poor planning of contractors, misunderstanding designs and requirements of architects, and various activities of on-site operation. Moreover, other barriers that establish poor C&D waste management include incorrect understanding of waste, unknown main causes of waste, changing customer requirements, and low awareness of responsibilities, obsolete legislation, and no incentive (Osmani *et al.*, 2008). In addition, Yuan (2013) noted that fruitful factors for reducing C&D waste generation can be separated into several groups as follows; design change, scrupulous design, regulations, site space management, reduced construction waste technologies, financial impacts and a culture of waste management. Thus, the success of C&D waste management should be supervised from the beginning until the end of construction process (Lu and Yuan, 2011).

Generally, the increase of this waste comes from the increased growth rate of construction through various relevant factors such as stability of politics, tourism industry growth, and overseas investments (Ogunlana *et al.*, 1996). Therefore, to have effective C&D waste management, many researchers suggest that (1) the important indicators for construction and demolition businesses as economic, environmental and social performance including waste generation rate should be jointly controlled (Yuan, 2013), (2) quantity and qualification of C&D waste are absolutely necessary to evaluate for national information (Kofoworola and Gheewala, 2009a), and (3) construction stakeholders should be aware of generated waste problems (Manowong, 2012). To sum up, the main point of waste generation investigation is that it can be used for measurement and evaluation so as to drive policy for C&D waste management (Lu and Yuan, 2011).

2.2.5.2 C&D Waste Components

According to the report of C&D waste components in Bangkok, these are separated into 2 parts as waste from residential building and non-residential building. First, the residential building sector had an average rate of construction waste at 56.23 kg/m^2 and the main component was 74.9 – 79.4% concrete followed by 12.8 – 14.4% brick, 4.0 – 5.6% metal, 2.2 – 3.0% ceramic tile fragments and 1.3 – 1.7% rag fragments. For demolition waste from residential buildings, the generation rate was 984.66 kg/m^2 with 73% concrete, 19.6% brick, 3.2% metal, 2.1% ceramic tile fragments and 1.2% rag fragments (PCD *et al.*, 2007).

Second, the non-residential building sector in Bangkok had average construction waste around 30.47 kg/m^2 with 56.1 – 60.8% concrete, 19.7 – 23.8% metal, 10.0 – 13.9% autoclaved aerated concrete and 6.8 – 8.1% timber. As for demolition waste of non-residential building, Bangkok had an average around 1,803.94 kg/m^2, consisting of 88.6% concrete, 5.4% autoclaved aerated concrete, 4.9% metal and 0.8% granite (PCD *et al.*, 2007). Additionally, a study about C&D waste in Malaysia is similar due to the fact that Malaysia is a neighbouring country to Thailand and is also in the ASEAN community. In Malaysia, concrete is the largest group of C&D waste, like Thailand at about 68% followed by 27% soil and sand, 4% lumber, and less than 1% brick and blocks, metal products, roofing, plastic and packaging materials (Begum *et al.*, 2006).

In addition, supporting details from PCD *et al.* (2007) show that the random samplings of C&D waste in illegal dumping by the roadside are 88% concrete and minor elements such as clay and other waste including plastic, paper, dry grass, and fragments of lightweight block, tile and glass. Moreover, the research of Glauser (2007) about material flow of C&D waste in Bangkok found that the maximum component of demolition waste is concrete which is higher than 80% in some demolition sites as well as construction yards for second hand materials (PCD *et al.*, 2007). Thus, during construction and demolition periods, concrete waste is the main C&D waste in Thailand.

2.2.5.3 Concrete Waste Management

It is very difficult to find any recorded volume of only Thai C&D waste because this waste is classified as a part of municipal solid waste. **Figure 2-60** explains the Thai waste classification. It is really important to note that not only household waste but some construction and agricultural wastes are also sent to the same disposal site. Hence, municipal waste management has more difficulty because of several kinds of waste from several sources.

Presently, concrete is dominant in both C&D waste. This is because Thailand uses concrete as the main material for building (about 80%; Kofoworola and Gheewala (2008)). After separating building materials at the demolition stage, suitable materials are reused and recycled but the majority of the remaining valueless waste is also concrete, which needs proper disposal (PCD *et al.*, 2007).

As widely known, concrete waste is hard to handle and transport to disposal sites because of its bulky and heavy characteristics. This waste cannot be eradicated by techniques such as composting and incineration. Concrete waste can cause the reduction of operating areas in disposal sites and landfill liners may be destroyed by its heavy weight and angular nature. However, most concrete waste appears to be sent for disposal or reuse somewhere else, not in the proper landfill of local municipalities or the private sector.

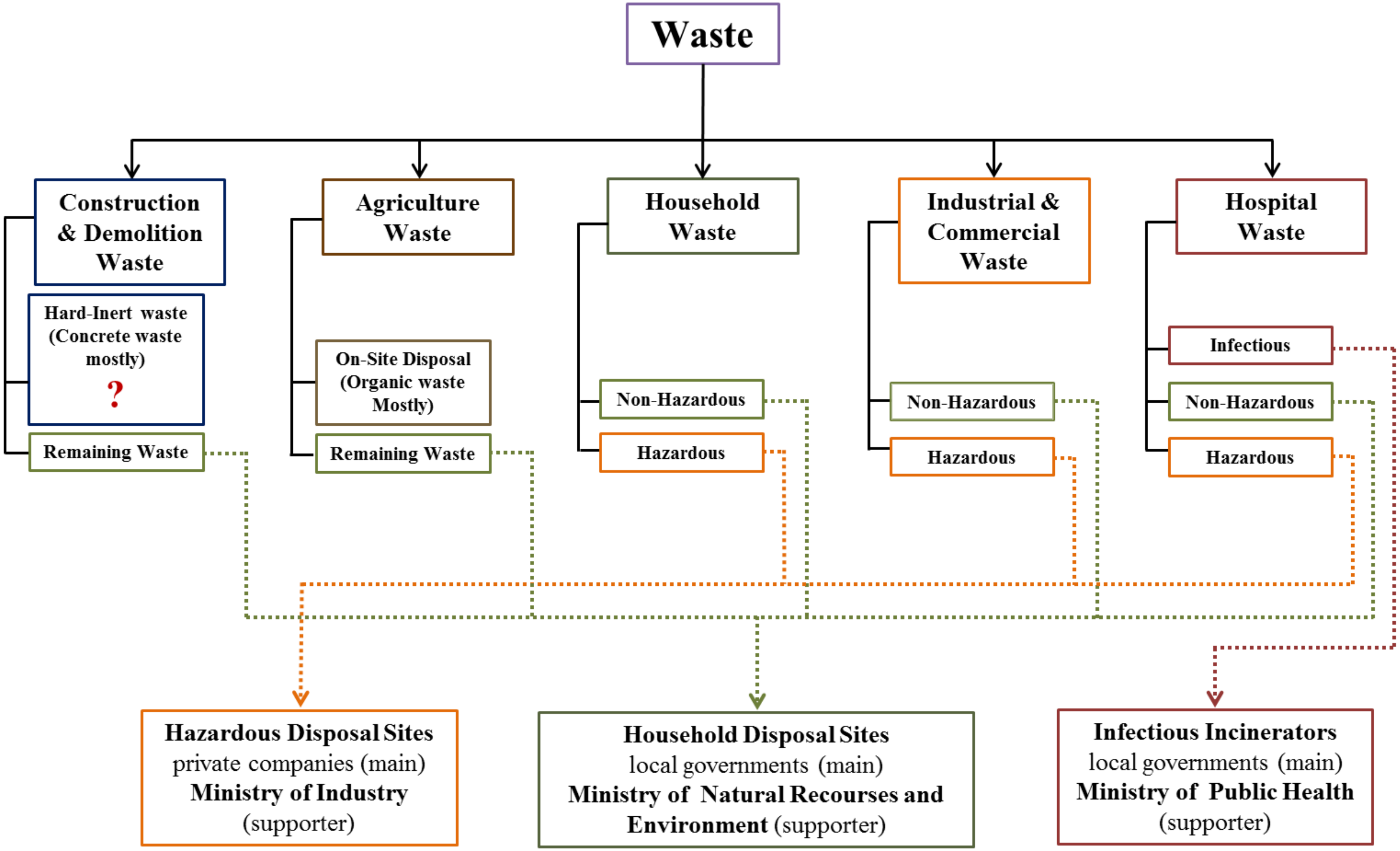


Figure 2-60 Thai waste classification in urban areas
Sources: Author

Thailand has no strategy for encouraging recycling of construction materials, no registered data, no integrated sustainability policy or no central private association like MPA, and many small quarries which are harder to control. All official organizations such as the Thai Cement Manufacturers Association (TCMA), the Thailand Concrete Association (TCA) and Mining Industry Council, are multi-specialized operations with independent and incoherent relationships. For example, the TCA has members only from universities, and the main purpose of this association is mostly related to concrete technologies and technical standards (Thailand Concrete Association, 2014). There are more than 300 small independent quarries for the Thai aggregates market (Department of Primary Industries and Mines, 2014).

Therefore, it is difficult for the Thai government to encourage the main policy associated with construction materials as cement, aggregates and concrete to perform in the same direction. In addition, Thailand has no equivalent to the Aggregate Levy to reduce the requirement of primary aggregates and to return benefit of the uses of recycled aggregates from C&D waste, with no system of recycling aggregates. There is no Landfill tax to discourage disposal of inert C&D waste to landfill as in the UK.

Using approved projects for Environmental Impact Assessment (EIA) relating to clinker mineral products from Environmental Impact Evaluation Bureau (2014), these projects indicate that the top three cement companies, SCG Cement Public Co. Ltd., Siam City Cement Public Co.Ltd. and TPI Polene Public Co.Ltd., own and operate their quarries. Moreover, the three leading cement companies with approximately 80% market share (TFCM, 2014) have their own downstream businesses including ready-mixed concrete and other construction materials such as tile, sanitary ware, ceilings, wall, insulation, and block paving. Thus, Thai construction materials are tightly controlled by only a few major cement companies.

A study by Henry and Kato (2012) that interviewed and investigated stakeholders in the concrete industry of Thailand and Korea, led to a better understanding of Thai barriers to sustainable concrete practice and materials, shown in **Table 2-9**. One similarity across Thailand and Korea is the strong role of academic institutions and professional associations, which have already begun sustainability activities such as technical committees and cooperative research work. However, continued researches in an ASEAN region will be necessary to build a stronger, more diverse knowledge based for building an Asian roadmap towards concrete sustainability.

Table 2-9 Barriers to sustainable concrete practice and materials in Thailand

Category	Barriers
Institutional	• Lack of performance-based design • Lack of standardized codes • Lack of institutional laws and regulations • Gap between research and implementation • Focus on initial cost
Socio-political	• No motivation to use sustainable materials • Political stability leads to inconsistent policies
Economic	• Investment in research does not increase market share • No market for sustainable products • Cost of new technologies is higher than labour or materials
Technological	• Low level of technology
Knowledge	• Lack of knowledge on sustainability • Lack of education among stakeholders • Lack of knowledge on additional value

Source: Taken from Henry and Kato (2012)

2.3 Summary

2.3.1 Great Britain

Great Britain nowadays almost entirely uses domestic raw materials for four main cement companies, and domestic aggregates for concrete with little export of cementitious materials and aggregates. This country uses half of production for ready-mixed concrete (the dominant cement use), followed by a quarter of production for precast concrete. Importantly, 36% of primary aggregates used for concrete is a main part of total primary aggregates required to be reduced and replaced by recycled aggregates. Thus, Great Britain uses the Aggregate Levy launched in 2002 as one main implementation to encourage the reduction of primary aggregate demand, and to increase the consumption of recycled and secondary aggregates.

Relating to construction activities, Great Britain has government buildings in the public sector as the biggest component with some 40% of the whole construction. Repair and maintenance activities were an outstanding sector with £44.64 billion in 2012 especially in the residential building due to the country having the longest lifespan of EU residential building, compared to the value of new construction (£70.95 billion). Although Great Britain has mostly small construction firms (95.40%), a few large firms (only 0.10% of total firms) can earn similar revenue to that of the combined number of micro companies. Importantly, non-residential building earned the most income and is the main type of new construction in Great Britain.

Importantly, the strong awareness and practice on sustainability from all stakeholders in construction materials and construction including natural resources and waste management can be clearly seen in Great Britain following the EU sustainable strategy and targets. As seen, the UK government gets quite effective supporting data from the main organisations for setting integrated policies of construction materials in natural resources and waste management such as Office for National Statistics (ONS), Department for Environment, Food & Rural Affairs (Defra), Waste & Resources Action Programme (Wrap) and the British Geological Survey (BGS). The Mineral Products Association (MPA) is also a key part of the cooperation working of private sector industry.

2.3.2 Thailand

The first cement company in Thailand has operated since the First World War (1913). Previously, cement was produced for only domestic consumption and involved few companies that formed a monopoly. Using domestic raw minerals, Thai cement manufacturers currently pay royalties for mineral resources, and clinker minerals are only 1% of the production cost. The 1997 economic crisis has changed the Thai cement industry by leading the Thai government to allow clinker and cement products to be free trade. Since then around 30% of cementitious products have annually been exported.

For domestic cement consumption, Thai cement per capita is currently increasing with a direct relationship to the number of permitted construction areas. Without identifying types of aggregates for construction uses like Great Britain, Thailand reports only limestone for whole construction and has no system of recycled aggregates including no use of recycled aggregate in the concrete industry, in contrast to Great Britain. Moreover, Thailand still uses old regulations and has more barriers, relating to construction materials and waste management.

A number of new and renovated construction activities are reported and separated into three main types as follows; (1) Building, (2) Non-building type 1 (fence/wall, road, bridge, dam/berm and drain) and (3) Non-building type 2 (pool, petrol station, port, stadium, parking and advertising sign). With fewer activities of renovation (<10%), Thailand tends to build more new building. Thai residential building, mostly private sector, has more permitted area to construct than other building types in the municipality.

The main area of construction in Thailand is the central region, especially Bangkok. In the Thai construction system, most construction firms are small, registered mostly in the name of an individual proprietor with only 1-5 workers and capability establishment less than ฿1 million or £20,000. Thailand uses concrete as the main material for building (about 80%). However, Thailand has no central organization for handling C&D waste, mostly concrete waste, and there are no specific regulations and taxations designed for C&D waste. Thus, unavoidably, this waste needs to be disposed of with household waste and uses the same regulations.

Chapter 3 Literature Review

This Chapter gives an overview of the global construction materials: cement, aggregates and concrete, including the global warming implications and factors affecting global construction activities and materials. Background details and reasons for selecting two national case studies, Great Britain and Thailand, are described, then clinker formation chemistry, which is used to calculate some important figures in the national cement industries.

For research methods, an overview of Material Flow Methodologies (MFMs) is given, consisting of six main methods and their historic details which are described and then presented with a summary of their important relevant time periods. Some methods (e.g. Life Cycle Assessment, Material Flow Cost Accounting and Carbon Footprint) involve the implementation of ISO 9000 and 14000 series for certifications in quality and environment management. This Chapter also provides reasons for choosing suitable methodologies used for this thesis.

Finally, sustainability and localism approaches in the construction sector of Great Britain and Thailand are concisely explained, together with the regulatory tools used in Great Britain as a package of integrated policy that pushes Great Britain to move forward under the EU implementation and strategy.

3.1 Overview of Global Construction Materials

The global construction sector is forecast to grow by over 70% by 2025 (Global Construction Perspectives and Oxford Economics, 2013), providing considerable growth opportunities in global markets for construction materials. These matters can be divided into two broad categories. Firstly, heavy materials consume two-thirds of cement production for infrastructure and building foundations (e.g. cement, aggregates, ready-mixed concrete and asphalt). Secondly, light materials are predominantly used above ground level in buildings (e.g. precast concrete, wallboard, insulation, bricks, tiles, pipe and glass).

Mostly using domestic raw materials in their manufacture, heavy materials face more barriers to entry and low import penetration and are subject to more disciplined pricing. Demand for these materials also relates directly to the national economy, with less fragmented business and low competitiveness (Andrews *et al.*, 2012). This research concerns and reviews the heavy material group in particular. All global governments are challenged for pushing forward coherent policies to influence demand of these materials, along with associated wastes during material manufacture and use, including building demolition and waste disposal.

3.1.1 Cement

3.1.1.1 Global Cement Industry

In the global cement industry, the rapid expansion of cement demand and supply is focused on developing countries as the largest proportion of the world's population. This movement is affected by variables of global economic and societal arrangements such as (1) expansion of domestic investment and manufacturing industries based on foreign companies, especially in some developing countries, having low-wages, (2) rapid urbanisation and (3) continuous increase in population. These situations require increased use of natural resources for construction materials. Thus, in the next decade, existing cement plants in developing countries are going to increase in capacity (Muller and Harnisch, 2008). Then, there are more incentives, from demand, to construct new cement plants near to available areas of raw materials (mainly limestone), where there are reserves for manufacturing for at least 50 years (Van Oss, 2005).

Muller and Harnisch (2008) explained cement production in developing countries (2006, Thailand is included) and a group of the Organisation of Economic Co-operation and Development (OECD) countries, including the United Kingdom (UK). Both national groups had similar volumes at around a quarter of global cement production (22% and 25% respectively). In 2050, developing countries will produce 42% of global cement; this is three times higher than the OECD group (13%), or a similar volume to the combined cement production from the world's largest cement producers (China and India, 45%, **Figure 3-1**). One reason for lower cement production (a part of the heavy construction materials) in developed countries or the OECD group is that cement market share has become less competitive compared to light construction materials (Andrews *et al.*, 2012).

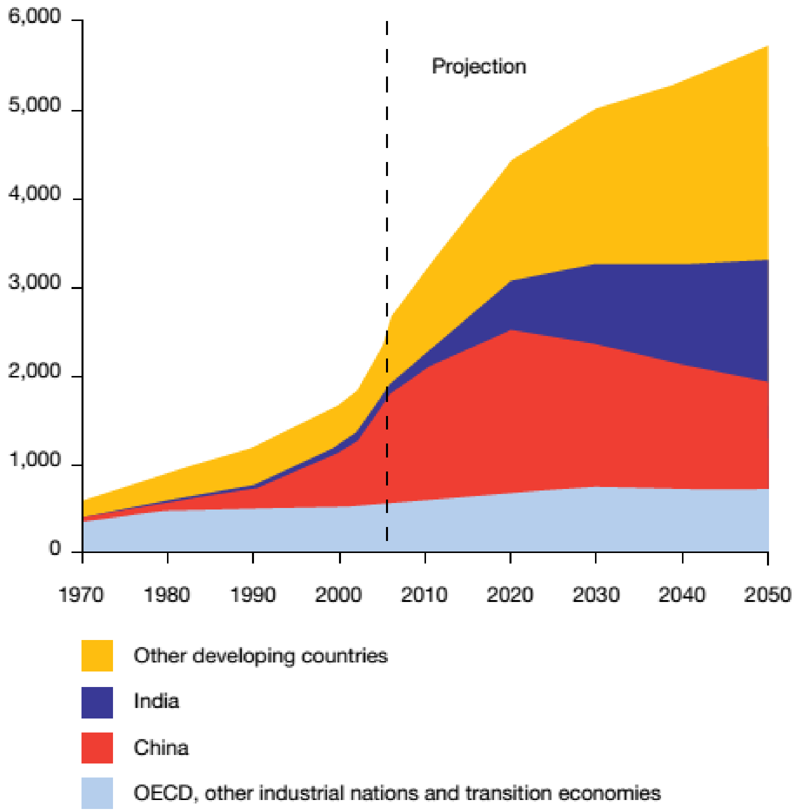


Figure 3-1 Past, present and forecasted cement production. (Mt/ year)
Source: Taken from Muller and Harnisch (2008)

3.1.1.2 National Cement Industry

In 2012, Great Britain and Thailand had 61.9 and 64.5 million inhabitants respectively (Department of Provincial Administration, 2015; ONS, 2015d). Although the population of both countries was almost equal, Great Britain has lower cement production than Thailand each year. As seen in **Figure 3-2**, the summary of annual cement production in Great Britain and Thailand from 2002-2012 is shown. This graph illustrates that Thailand had around 3-4 times greater annual cement production than Great Britain, with higher cement demand for construction but also a greater volume of cement for export, at around 12-25% of cement production (2001-2014, Office of Industrial Economics (2013)).

The evidence suggests that cement production in Great Britain slightly reduced from 2007. Then, this trend had a small increase from 2009 to 2011. Its growth probably comes from the rise in demand for stadium construction including buildings for the London 2012 Olympic and Paralympic Games, which started construction around 2009 (Defra, 2013). Then, after 2011, cement production showed a small downward trend again. Figures of export clinker and cement in Great Britain are low, due to the dominance of domestic consumption (BGS, 2014a).

In Thailand, the fluctuating trend decreased between 2006 and 2009; it is possible that this relates to consequent effects of the subprime mortgage crisis from the United States (US) which is one of the important trading countries of Thailand (Demyanyk and Van Hemert, 2011). It then combined with a protracted period of Thai economic, political and social tensions that impacted directly on the stagnant construction sector. Then, since 2009, Thai cement production has slightly increased. This probably is due to several reasons such as (1) higher domestic cement demand, driven by infrastructure investment of local governments and industries, especially concrete structures for flooding protection after the 2011 heavy inundation and (2) higher cement requirements from trading countries, particularly located in Southeast Asia (Office of Industrial Economics, 2013).

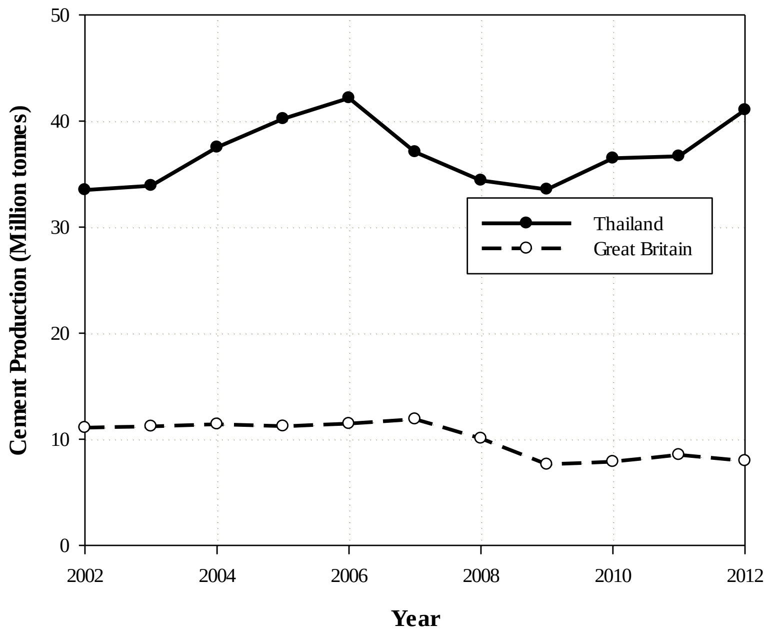


Figure 3-2 Quantity of cement produced in Great Britain and Thailand
Sources: Author based on BGS (2014c) and Office of Industrial Economics (2013)

3.1.2 Aggregates

3.1.2.1 Global Aggregate Market

The 2013 global market of construction aggregates was valued at US$ 99 billion. Asia-Pacific was the largest market, accounting for 42.5% to support higher construction demand that makes this regional market expand, and 26.9% of global construction aggregates was the European requirement. Market Research Reports (2013) predicted for the future market shares of global construction aggregates in 2017 that Asia-Pacific will remain the biggest region with increasing demand (47.6%). In contrast, the European requirement is expected to reduce to 22.7%.

3.1.2.2 National Aggregate Market

A wide range of construction aggregates in the UK comes from several sources such as crushed rock acquired from quarries, sand and gravel extracted from pits, marine dredged aggregates, blast furnace and steel slags, by-products of the iron and steel industry and other metal processes, and recycled aggregates. In 2012, BGS (2013) and ONS (2014d) reported that Great Britain consumed 50.04 million metric tonnes (Mt) of primary sand and gravel, and 82.89 Mt of primary crushed rock. These consumption figures of primary aggregates continuously declined (**Figure 3-2**) over previous years. In addition, the volume of recycled and secondary aggregates, mostly originating from concrete waste, was 54 Mt or 29% of total aggregates, consumed for Great Britain construction in 2012 (DCLG, 2007; MPA, 2013c).

The quantities of recycled aggregates produced and used in the UK have progressively increased over the last 30 years for construction such as concrete manufacture, concrete products and pavement construction, in both private and public sectors of industrial and housing projects (MPA, 2011). The main reason of the increasing uses of recycled aggregate derives from two main environmental taxes: the Landfill Tax and the Aggregates Levy that were introduced in 1996 and 2002 respectively. Additionally, other supporting use of recycled aggregates includes developing recycling techniques for C&D waste, where European countries have been the lead since the Second World War (DePauw and Vyncke, 1996). Additionally, there are European Standards for Aggregates in the National Guidance Documents, produced by British Standards Institution (BSI) for primary and secondary aggregates for concrete and other construction e.g. BS EN 12620:2013 (BSI, 2013b) and the PD 6682-1:2009+A1:2013 (BSI, 2013c).

In Thailand, there is no clear identification of types and volume of construction aggregates, together with no data for imports and exports. The Information Technology Centre (2014a) reported only primary limestone consumption for Thai construction in 2012, at 78.23 Mt expected an increasing future trend. Thailand usually uses concrete waste for filling material as the proper disposal, or leaves it behind as waste piles. Unlike Great Britain, Thailand seems lesser concerned about recycled and secondary aggregates for concrete and construction uses because of no supporting technologies, standards and applicable regulations.

3.1.3 Concrete and Global Warming Implications

As previously noted, concrete, as an essential material to construct worldwide buildings and infrastructures, requires cement as a principal binder to mix with coarse and fine aggregates including other minor components. In 2012, global cement produced for construction was around 3.6 billion tonnes, 3% more than in 2011 (Boston Consulting Group, 2013). In addition, carbon dioxide (CO_2), the principal cause of the greenhouse effect, is produced with 5-7% of global man-made CO_2, releasing from cement plants. Producing one tonne of cement provides 0.9-1 tonnes of CO_2 emitted into the atmosphere (Davidovits, 1994; Benhelal *et al.*, 2013).

Cement, mostly distributed for blending into concrete, is around 12-16% of concrete weight and aggregates are about 85% by weight for the concrete components (Boston Consulting Group, 2013; Berndt, 2015). Aggregate manufacturing is also one of the causes of global CO_2 emissions. Evidence from the UK market of construction aggregates indicated that 2.45 million tonnes of CO_2 were emitted by the UK aggregate sector in 2008, or 0.46% of the total UK carbon emissions (Mitchell, 2012). In addition, concrete is the main contributor to present construction and 36% of its embodied carbon is mostly associated with building materials, excluding waste, transport and energy (Monahan and Powell, 2011). Thus, using concrete provides both benefits and drawbacks for human beings and the globe.

Presently, a proportion of recycled aggregates has been encouraged for use in the concrete and construction industries, especially in the EU member countries (The European Environment Agency, 2008). In the UK, improving the quality standards by the BSI encourages more confidence for contractors and consumers to consume these reused aggregates increasingly. For Asian countries, reusing aggregates for new concrete receives interest from academic researchers in particular and some private companies such as SCG Cement Public Co. Ltd. The government sector performs a slow implementation with this issue. In Thailand, only Bangkok Metropolitan Administration (BMA) operates a pilot study for C&D waste sorting plant.

3.1.4 Factors Affecting Global Construction Activities and Materials

National economy and demand for housing construction can be measured and represented by GDP per capita and floor area in use (FAU). Concrete in use (CU) is steadily growing as a principle material for global construction presently and has a minimum lifetime of 60 years (Scottish Building Standards Agency, 2007).

Several supporting criteria affecting housing construction activities (construction, renovation and demolition) and concrete demand, together with future concrete waste mostly generated in a demolition phase, derive from rapid growth in national population and economy including rapid urbanisation. Moreover, like Great Britain experiences, longer building lifespan, more effective national policy and regulation following the EU strategies including other factors, such as higher quality of building and more renovation activities, can reduce the amount of concrete required and future concrete waste. These links can be illustrated in **Figure 3-3**.

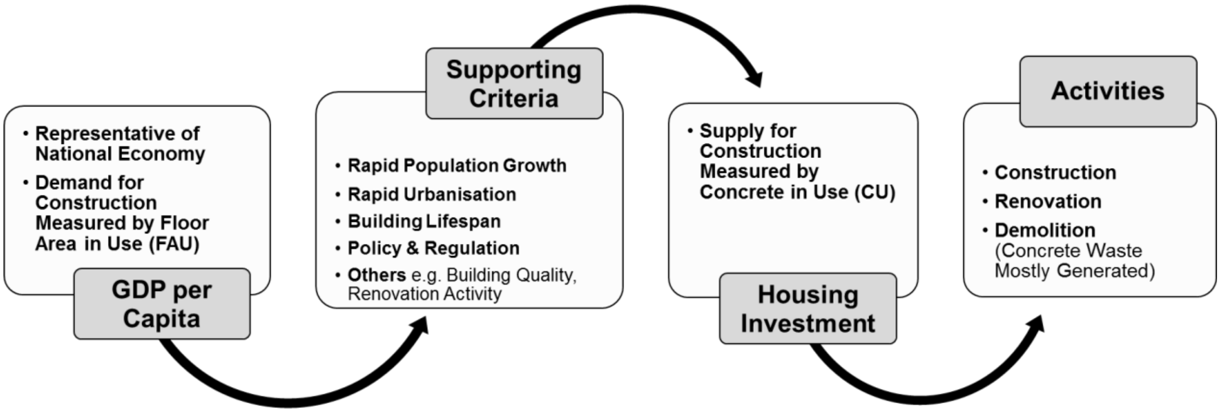


Figure 3-3 National construction demand in a housing sector
Sources: Author

3.2 Generic Overview of Countries

Great Britain (as the mainland area of the UK) and Thailand have similar populations, and Thailand has a territorial area more than twice that of Great Britain. The economy of the two countries is obviously different. As UN (2014) classified global countries, there are three main groups: developed, transition and developing economies. The UK is assigned into a group with a major developed economy, while developing economies with upper middle income is the defined group of Thailand. As seen in **Figure 3-4**, the UK plots in the same group of other leading countries in the world because of its high-income economy, since the UK has high GDP price level index and high GDP per capita as well as a medium size of GDP expenditures. Some Asian countries excluding Thailand can be presented in the small and middle-income economies categories, mostly grouped at a lower position than the UK.

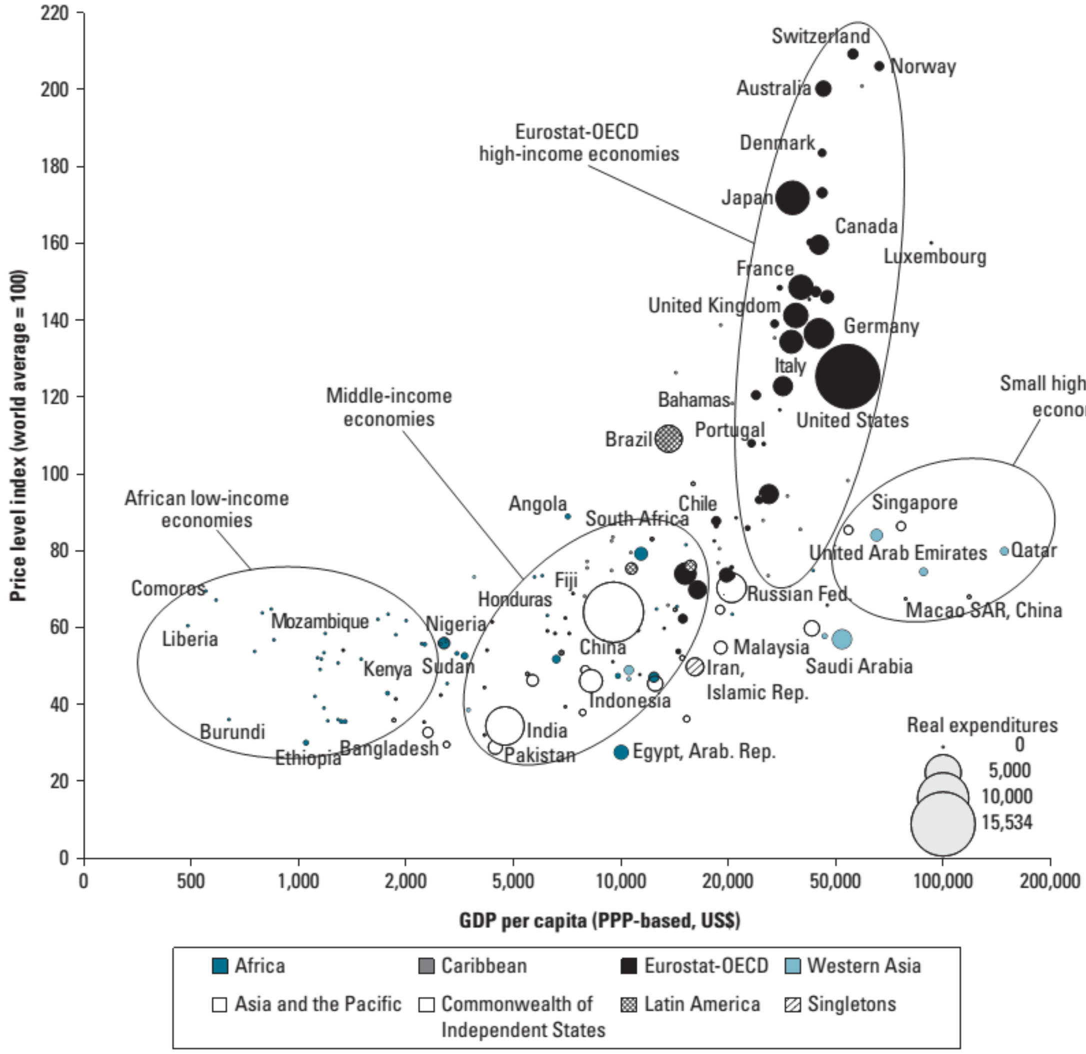


Figure 3-4 GDP price level index versus GDP per capita and size of GDP expenditures
Source: Taken from World Bank (2015c)

This thesis uses Great Britain and Thailand as case studies. Great Britain, consisting of England, Wales and Scotland, forms a good case study as it:

- produces cement for the domestic market and does not export much,
- provides sustainable policies and environmental taxes (Aggregates Levy and Landfill Tax) under the EU strategies,
- achieved the 70% target of reuse and recycling rate for the specific stream of C&D waste in the EU (Monier *et al.*, 2011; Defra, 2015a),
- achieved the highest rate of use of recycled and secondary aggregates in the EU, accounting for 29% of total aggregates in the 2012 aggregate market or three times higher than the average aggregate consumption in the EU (The European Environment Agency, 2008; The Concrete Centre, 2009; MPA, 2013c).

Thailand is a good case study of the cement, aggregates and concrete industries as it:

(1) has a similar government form, constitutional monarchy, as Great Britain,
(2) is a major manufacturer, consumer and exporter of cement in the ASEAN,
(3) uses concrete as the main construction material,
(4) represents similar problems among ten ASEAN countries such as management of natural resources and environment, policies and taxations with broadly similar economic and social conditions.

A more detailed account of the national overview of Great Britain and Thailand as (1) geographical and administrative, (2) demographic and social and (3) economic summary is described in **Appendix A**.

3.3 Clinker Formation Chemistry

Clinker consists of three main chemical components, lime (CaO), silica (SiO_2) and alumina (Al_2O_3). Limestone provides CaO as the principal oxide making up approximately 75–80% of the raw materials used for manufacture of cement clinker (Bye, 1999) and shale contains SiO_2 and Al_2O_3 (Manning, 1995). During clinker manufacturing, the clinker minerals alite (45%) and belite (27%) are formed, according to the chemical reactions occurring when heated in long rotary kilns (**Table 3-1**). There are two distinct clinker processes: dry and wet processes. For the wet process, a slurry of fine raw materials is pumped into a longer rotating kiln with a substantial quantity of water, typically 30–35% of the raw material mass. In the dry process, raw materials are finely ground as powders and are preheated by hot gases before entering a shorter rotary kiln (Taylor, 1997). Thus, this dry process requires less energy than the wet process (Manning, 1995).

Table 3-1 Clinker mineral components

Minerals	Abbreviated Formula	Full Chemical Formula	Typical Proportion in Cement (wt %)
Tricalcium Silicate (Alite)	C_3S	Ca_3SiO_5	45
Dicalcium Silicate (Belite)	C_2S	Ca_2SiO_4	27
Tricalcium Aluminate	C_3A	$Ca_3Al_2O_6$	11
Tetracalcium Aluminoferrite	C_4AF	$Ca_4Al_2Fe_2O_{10}$	8

Source: Taken from Manning (1995)

2C		S		C_2S	
$2CaO$	+	SiO_2	=	Ca_2SiO_4	(1)
lime		silica from shale		belite	

3C		A		C_3A	
$3CaO$	+	Al_2O_3	=	$Ca_3Al_2O_6$	(2)
lime		alumina from shale		tricalcium aluminate	

4C		A		F		C_4AF	
$4CaO$	+	Al_2O_3	+	Fe_2O_3	=	$Ca_4Al_2Fe_2O_{10}$	(3)
lime		alumina		ferric oxide		tetracalcium aluminoferrite	

C		C_2S		C_3S	
CaO	+	Ca_2SiO_4	=	Ca_3SiO_5	(4)
lime		belite		alite	

Within the cement triangle (**Figure 3-5**), clinker is a mixture of the three components known to cement chemists by the abbreviation C, S and A respectively, following above four equations, and with minor Fe_2O_3.

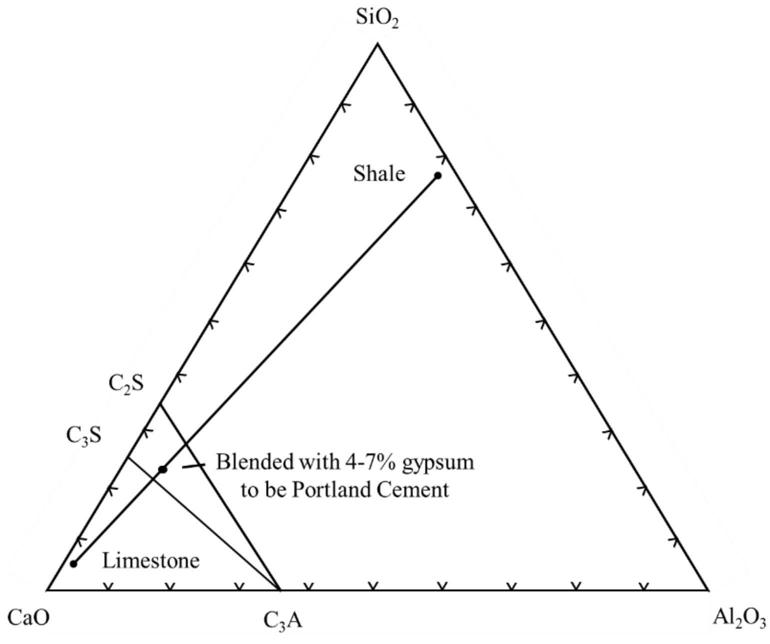


Figure 3-5 Proportions of 75% limestone and 25% shale required to make Portland cement
Source: Amended from Manning (1995)

Taylor (1997) explained the reactions in clinker formation from finely ground raw clinker minerals (typically 75% limestone and 25% shale). He separated these major reactions into three groups.

(1) Reactions below about 1300°C, including (a) the decomposition of calcite (calcining), (b) the decomposition of clay minerals and (c) reaction of calcite or lime formed from it with quartz and clay mineral decomposition products to produce belite, lime, aluminate and ferrite.

(2) Reactions between 1300 and 1450°C (clinkering), in which much of the belite and nearly all the lime react in the presence of the melt to give alite. Then, the heated raw material nodulizes to become clinker.

(3) Reactions during cooling include crystallization of the liquid to form aluminate and ferrite mainly, and polymorphic transitions of the alite and belite occurring during the reduction of temperature in a kiln chamber.

Then, to make Portland cement, the clinker is finely ground and blended with 4-7% gypsum depending on its purity. Gypsum is added to inhibit cement setting while mixing and applying (Manning, 1995; Bye, 1999). Once put in place, a mixed Portland cement paste consisting of di- and tri-calcium silicates develops strength primarily by hydration (Bye, 1999).

3.4 Research Methods

3.4.1 Overview of Methodologies

The static and dynamic dimensions of the appropriate computational data can be augmented for spatial regions with geographic dimensions (global, regional and national). Moreover, adequate and sufficient data in the different time series (historic, present and future) can also assist policymakers to obtain a proper model for natural resources and waste management (**Figure 3-6**). As Material Flow Methodologies (MFMs), analytical methods to quantify flows and stocks of materials, substances, or products across different industrial sectors or within ecosystems as a well-defined system, can be used to support three balanced constituent pillars of ‘Sustainable Development’: the economy, environment and socio-politics.

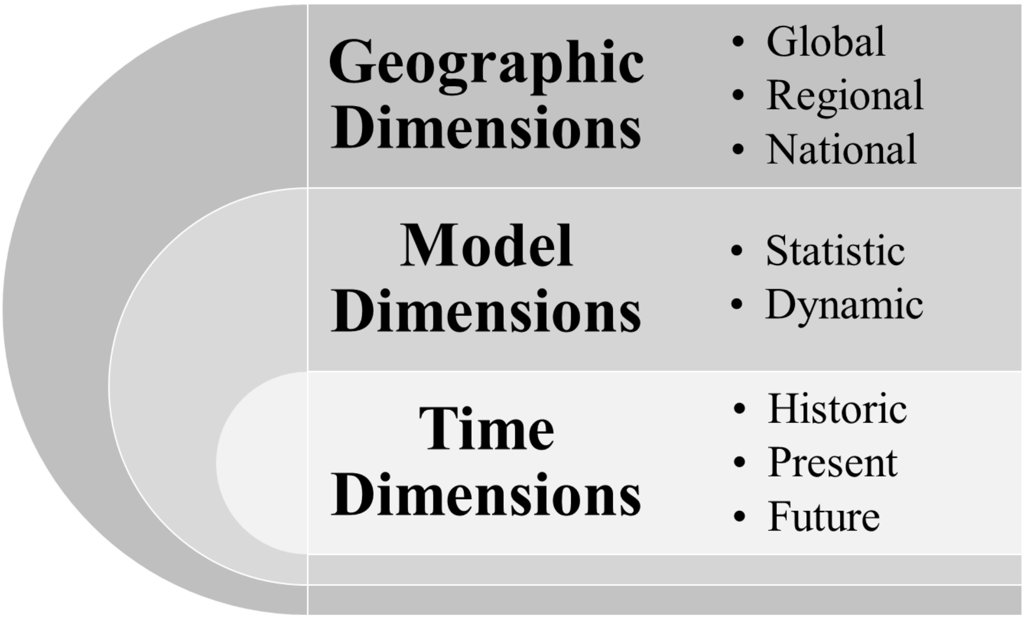


Figure 3-6 Methodological dimensions
Sources: Author

An essential aspect of national sustainable development starts with the government vision, partly backed up by decision making tools, and one of the important supporting devices is the MFMs. For policy-relevant applications, these methodologies, based on the system approach and mass balance, can determine material flows using indicators for different societies. They also allow assessment of strategies for improving the system by material flow management, so creating a more national efficient economy with fewer pollutants and other unwanted by-products (Yuan *et al.*, 2006). Due to their methodological results, policymakers can become better informed about quantifying national flows and stocks of special materials. Then, sound technology and allowance for technological changes can be used to support regulation as effectively as possible (Frosch and Gallopoulos, 1989). Therefore, MFMs have more benefits for the global economy, ecosystem, and society, especially for adjusting proper policy in developing countries.

The most significant environmental concern in the construction materials sector is natural resources and waste. Presently, all countries still extensively use and transform several natural resources such as cement minerals and aggregates as essential elements for making concrete. As known, these resources cannot be re-established (they are finite), so they must be used to achieve their maximum benefits. For this reason, MFMs can be used to achieve a national decision making tool for national policy by analysing, investigating and evaluating in physical and monetary units the complete activities of construction materials.

There are three fundamental reasons for published studies to describe the objectives for the environmental policymakers (Bouman *et al.*, 2000): (1) to reduce the use of virgin materials (2) to abate atmospheric emissions and (3) to reduce waste disposal sites. Moreover, the key factors to reduce errors in these analyses making final results reliable are trustworthy information, clear allocation of burdens in each activity and specialisation of researchers (Azapagica and Cliftb, 1999; González *et al.*, 2003; Cencic and Rechberger, 2008b).

This section, therefore, attempts to provide background and necessary information as well as to compare their methodological advantages and limitations. There are six main MFMs: Input-Output Analysis (IOA), Life Cycle Assessment (LCA), Material Flow Analysis (MFA), Material Flow Cost Accounting (MFCA), Carbon Footprint (CF) and Stock Dynamic Analysis (SDA).

3.4.1.1 Input-Output Analysis

'Input-Output Analysis: IOA' is a mathematical environmental tool for direct and indirect environmental impacts which is used for tracking physical (Physical Input-Output Tables in physical units: PIOTs) and monetary flows (Monetary Input-Output Tables in money terms: MIOTs) in products and services. This analysis can describe, analyse and predict the structure of an economic system (Christ, 1955; Garfield, 1986; Eurostat, 2008b; Ewing *et al.*, 2010; Wiedmann, 2010a; Mattoon, 2013).

In a case of the national economy, IOA is a tool for connecting both the supply and consumption of products and services including capital creation, revenue and labour (Finnveden *et al.*, 2009). IOA can represent the national economic account, and can be used to calculate annual accounts of GDP (Ewing *et al.*, 2010; Wiedmann, 2010a).

One of the most important objectives of IOA defined by Eurostat (2008b) is to calculate unknown activities in each sector (internal variables) for specified final requirements (external variables) due to a complicated relationship to the aspects of changes. IOA is especially well suited to scenario analysis as a particular configuration that is specified through the quantification of the relevant inputs and outputs (Suh, 2009).

Basically, IOA uses a set of linear equations and input-output tables providing purchases and consumption flows of products and transactions in business, national or global economy in a defined year (Moll *et al.*, 2006; Halpern-Givens, 2010a). This method assumes that waste and emissions correspond to each other in a one-to-one way (Nakamura and Kondo, 2009), and it can define and quantify the economic and environmental consequences (Suh, 2009).

3.4.1.2 Life Cycle Assessment

Life Cycle Assessment: LCA, known as a 'cradle-to-grave' analysis, is a systematic assessment in a complete life cycle context from raw materials acquisition to final waste disposal for a business or service (McLaughlin, 1998; Roy *et al.*, 2009; Björklund, 2012). Moreover, LCA has two benefits. The first is the reported holistic environmental impacts of its material and energy inputs and outputs of products or activities. The second is that LCA can also identify the severity levels of environmental impacts in each activity (Assies, 1998; Berlin, 2002).

LCA can focus on environmental impacts with or without costs. An effective LCA allows analysts (1) to provide information defining environmental impacts in each activity, (2) to identify opportunities for environmental improvements, and (3) to provide a full systems perspective, a comprehensive assessment, an understandable systematic framework and a possible design process for interactions in all environmental activities (Institute of Management Accountants, 1996; Finnveden *et al.*, 2009; Roy *et al.*, 2009; Williams, 2009).

In its processes, LCA can be narrowed down to four main inter-related activities: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life-cycle impact assessment (LCIA) and (4) interpretation (Rebitzer *et al.*, 2004; World Steel Association, 2011). Its results can be used by decision makers at all levels: government or multinational organization or company. Examples of benefits from LCA include (1) decisions on legislative and economic policy instruments, such as requirements, bans, environmental taxes and fees, (2) strategic planning of infrastructure, (3) selection of indicators and requirements for eco-labelling schemes, and (4) procurement decisions (World Bank, 2012).

3.4.1.3 Material Flow Analysis

A simple meaning of Material Flow Analysis (MFA) used by several groups of researchers (e.g. Müller (2006); Wiedenhofer *et al.* (2015); Bergsdal *et al.* (2007b)) is a systematic evaluating technique identifying a pattern of material stocks and flows by setting boundaries of space and time. It uses the balance principle of input, stock and output of processes or materials to other economies or back to nature, in physical units (e.g. tonnes). Moreover, there are five major steps: (1) goal and scope definition, (2) targeting material prediction, (3) determination of lifetime distribution, (4) dependent time calculation and (5) quantified material flow analysis (OECD, 2000; Eurostat, 2001; Eurostat, 2009; Park *et al.*, 2011).

MFA can quantify aggregated resource inputs and outputs of economic systems. Its primary data can be taken from available national or international statistics depending to a large extent on quality and completeness. Most of the material categories concerning domestic material inputs (e.g. fossil fuels, metal ores, industrial and construction minerals and biomass) are covered by official statistics. In general, data coverage is lower due to physical trade flows and outflows of waste and emissions (Suh, 2009).

There are three main MFA types based on a law of material conservation, namely substance flow assessment (SFA), process-based MFA and industry-based MFA (Streicher-Porte *et al.*, 2007). The objectives of this technique are (1) to understand precisely in terms of physical metabolism about a combination of economic and environmental statistics for all indicators of resource usage, and (2) to estimate material flows induced by imports and exports using PIOTs which can describe material flows between the economic system and the natural environment. Furthermore, PIOTs have two main uses for (1) the balance of consistent investigation and estimation, and (2) a basis for modelling and analysis (Eurostat, 2001).

MFA can have five major steps (1) goal and scope definition, (2) targeting material prediction, (3) determination of lifetime distribution, (4) dependent time calculation and (5) quantified material flow analysis (OECD, 2000; Eurostat, 2001; Eurostat, 2009; Park *et al.*, 2011). In addition, several researchers provide the MFA advantages as:

- MFA boundary can be defined (1) the extraction of primary materials from the national environment and discharge of materials to domestic environment and (2) political (administrative) borders that determine material flows to or from other countries by import and export (Eurostat, 2001).
- MFA is used (1) to support systematic information and indicators for the assessment of sustainable development, (2) to analyse critical pathway links and key substances in the environment and (3) to provide the relationship between material flows and processes of sustainable development (Huang *et al.*, 2012).
- MFA can be used for active policies of sustainability, regarding natural resources and waste management (Woodward and Duffy, 2011).

However, MFA still has problems with corresponding uncertainties and error trends due to converting into a graph and handling of uncertain, inconsistent and contradicted data (Sygulla *et al.*, 2011).

3.4.1.4 Material Flow Cost Accounting

Material Flow Cost Accounting (MFCA) is a managed information tool, combining two main concepts of physical flows/ stocks and environmental accounting. Its results can be presented in both physical units (mass: kilogrammes, tonnes, liquid-litres, or energy: MJ, kWh) and monetary units throughout all production activities including finished products and waste management. Moreover, this method gives more advantages for small and medium-scaled businesses in a whole system of processes using calculations from a simple spreadsheet (The Ministry of Economy Trade and Industry (Japan), 2007; Jasch, 2009; Kokubu *et al.*, 2009; Viere *et al.*, 2011).

This methodology is based on the principle of material balance and special association from material losses with product costs. It is useful for reducing environmental impact, raw material use and waste volume, improving efficient material consumptions (The Ministry of Economy Trade and Industry (Japan), 2007; Kokubu *et al.*, 2009; Kokubu and Kitada, 2010). This method is utilised to improve the efficiency of material and energy use in an individual manufacturing step and whole processes, and to evaluate process configurations and technologies of resources, with cost efficiency for a company's economic and environmental performance (Sygulla *et al.*, 2011).

One of the particular MFCA operations is the definition of finished products and waste as positive and negative products respectively. Production costs in MFCA are based on two main concepts: (1) dividing costs into positive and negative costs, (2) calculating costs throughout all processes such as material, system, energy and waste treatment. Waste in all operations can be recognized as non-marketable products consumed in manufacturing activities, and the emissions are known as one product (The Ministry of Economy Trade and Industry (Japan), 2007; Kokubu *et al.*, 2009; Kokubu and Kitada, 2012).

3.4.1.5 Carbon Footprint

Footprint Analysis (FA) or Footprint Family is known as an appropriate quantitative measurement for natural biological resources, carbon dioxide (CO_2) uptake and greenhouse gas (GHG) emissions. It is based on a consumption-based perspective in three significant ecosystem compartments; biosphere, atmosphere, and hydrosphere through the Ecological, Carbon, and Water Footprint (Hoekstra, 2008; Galli *et al.*, 2011). This thesis discusses only the Carbon Footprint, a member of environmental footprint groups, which relates to material flows.

Wiedmann and Minx (2008) suggested the definition of Carbon Footprint (CF) as a specially measured tool for the total amount of CO_2 and GHGs. These gases are emitted over the entire lifecycle of products or services. Emissions can be quantified in tonnes of CO_2 equivalents for direct and indirect causes in several sectors in some particular activities, inhabitants, enterprises, institutes and countries. However, CF is widely utilised for driving brand and image as a marketing tool in companies (Ercin and Hoekstra, 2012a).

Moreover, CF can be separated into three main directions; bottom-up based on Process Analysis (PA), top-down based on IOA, or a hybrid methodology between IOA and LCA (Wiedmann and Minx, 2008; Ercin and Hoekstra, 2012b). It depends on the objectives of investigating with available data and resources including intensive time (Čuček *et al.*, 2012). GHG emissions can be reduced by practical solutions. There are three main steps: (1) to understand carbon footprint of each product or service, (2) to separate necessary emissions that could be reduced or eliminated, and (3) to set zero on measures that provide the greatest benefits for involved cost (Grenon *et al.,* 2008; Ercin and Hoekstra, 2012a).

3.4.1.6 Stock Dynamic Analysis

Müller (2006) first applied Stock Dynamic Analysis (SDA) based on historical data of populace, housing and construction materials to investigate in-use national housing stocks and flows, together with the subsequent diffusion of concrete demand and waste in the Dutch housing sector between 1900-2100. His study depends on a mass balance principle from historical construction activities and a lifetime probability function. As the traditional SDA approaches are widely used in modern industrial ecology, several researchers interrogate the stock of construction materials and waste for national policy, resource implications and waste management, in particular for the housing sector, such as:

(1) Norway: Bergsdal *et al.* (2007b) applied SDA to the Norwegian housing stock and then this method was enhanced by including renovation, as this seems to be the main activity of future housing construction in Norway (Sartori *et al.,* 2008). To examine future renovation in Norwegian dwelling stock more, Sandberg *et al.* (2014b) used a dynamic segmented model developed from SDA. They found that although renovation

activities are increasing continuously in Norway, these activities seem unrealistic from the oversight of European roadmaps and action plans. Moreover, they also investigated the uncertainty of other input parameters to describe energy consumption or greenhouse gas emissions in the Norwegian housing stock (Sandberg *et al.*, 2010; Sandberg and Brattebø, 2012; Sandberg *et al.*, 2014a).

(2) China: Hu *et al.* (2010c) also used SDA for strategic construction and demolition waste using Beijing housing. They modified this method to compare urban and rural housing stock in China, as the main challenge of Chinese housing presently is a rapid growth in urban and quick shrinkage in its rural areas (Hu *et al.*, 2010a).

Their studies also include an iron and steel study in Chinese residential buildings (Hu *et al.*, 2010b). Their model indicates that a short lifetime of the building causes obvious costs of higher CO_2 emissions and natural resources. Then, Wang *et al.* (2015) added indirect energy intensity in steel and direct energy intensity for building construction using applied SDA to explain steel use for Chinese building more clearly. They found that lifetime extension of building and application of high-strength steel might save nearly 40% of future primary iron ores.

(3) Japan and the US: Fishman *et al.* (2014) applied SDA to focus on the relationship between material stocks and flows of national materials: timber, minerals, iron and other metals in both national economies. Its results become useful in an economic context and can extend the services delivered by higher quality buildings and infrastructure as a broader perspective of stocks.

In addition, SDA concepts can also support other studies such as energy, building waste, building material flow and environmental impacts, domestic mass flow, reserves for resources, predicting building demand, empty buildings and brownfield sites (Kohler and Hassler, 2002). Other examples of specific topics as particular investigations using applicable SDA are:

(1) Estimation of lost material stock of building and roads by Tanikawa *et al.* (2014) from the Great East Japan Earthquake and Tsunami. This research includes the use of geographical information system (GIS) databases and statistics. Its results can assist urban planners and can probably convey more appropriate disposal information based on the works of municipalities in disaster-afflicted areas.

(2) Forecast of demand for pipeline construction and cement consumption for improving water quality by wastewater treatment infrastructure due to the presently increased volume of discharged wastewater in Chinese urban areas (Hou *et al.*, 2015).

(3) A promising alternative method for characterising urban buildings to investigate materials stocked in Philadelphia using GIS, design codes, and building models (Marcellus-Zamora *et al.*, 2015).

3.4.2 Methodological History

3.4.2.1 International Cooperation and Conceptual Foundation

The major conceptual foundation of MFMs is sustainability, which specialists from many fields and countries widely use as the main principle of industrial activities and environmental management. The formal beginning of global sustainable development was a significant outcome of the United Nations Conference on Environment and Development (UNCED), known as the ‘Earth Summit’, held in Rio de Janeiro, Brazil in June 1992.

This was an international meeting of high officials from all over the world such as heads of states, chiefs of governments, senior diplomats and government officials including delegates from United Nations agencies, officials of international organizations, some non-governmental organization (NGO) delegates and journalists. The conference led to the Rio Declaration on Environment and Development, on which was based future national decisions and policies for environmental implications and socio-economic development. It also set international agreements which respect and protect the integrity of the global environmental and developmental system (UN, 1992).

After the 20th anniversary of the previous conference, the UN Conference on Sustainable Development took place in Brazil on 20-22 June 2012 with a significant objective of renewed political commitment for sustainable development (Chee, 2012). Several researchers suggested that the meaning of sustainable development is an attempt to carefully use and keep natural resources for future generations. Thus, governments need to set flexible policy for balancing commercial management systems of economic efficiency, environmental protection and social development (OECD, 2001; Quazi *et al.*, 2001).

3.4.2.2 Research Collaboration

The scientific field of ‘Industrial Ecology’ was created at the end of the 1980s from North America. Its studies combine essential aspects of engineering, economics, sociology and toxicology together with natural sciences. The overall concept including its MFM tools is a multidisciplinary aspect of material and energy flows through sustainable industrial systems, influenced by the natural ecosystem principle (Glöser *et al.*, 2013). A network of industrial processes extracts natural resources from the Earth and then transforms those resources into commodities (supplies), sustaining humanity’s demands.

This approach aims (1) to quantify the material flows and document processes or services from natural resources and capital investments through becoming waste (open loop systems), forming a modern industrial, national, regional or global function, and (2) to use waste streams from new industrial process as input materials for other processes or a closed loop system for minimizing materials lost to the environment (Frosch and Gallopoulos, 1989).

MFMs concern impacts of industrial activities on the environment, natural resources and waste management. Thus, these research tools are rapidly growing in studies, together with a community of researchers and policy analysts in North America and Europe. Its distribution also includes Japan, one of the Asian countries, that pays more attention to the studies of MFMs and has set up an Industrial Ecology Working Group since the early 1970s (Suh, 2009). Presently, China is widely featured on this research field due to increasing environmental and economic concerns.

3.4.2.3 History of Each Methodology

Over the past 80 years, more information has become available on MFMs; Wassily Leontief developed IOA in 1936, applied to economic impact analyses, and published some articles both in German and English using monetary units (Giljum and Hubacek, 2004; Aroche, 2009). In 1973, he was judged to receive the Nobel Prize in Economic Sciences (Halpern-Givens, 2010b). Moreover, since the 1960s, IOA has been used for analysis in an environmental-economic relationship (Giljum and Hubacek, 2004) and then this application has popularly been used for energy analysis from the early 1970s (Wiedmann, 2010a).

Subsequently, after IOA had been used for around 50 years, the International Organization for Standardization (ISO) published the first vision of ISO 9000 series in 1987. This can be adopted as standards of quality management systems all over the world (Delmas, 2002; Corbett *et al.*, 2004). Until now, there are many standards in the ISO 9000 family and the newest version was published in September 2015 called ISO 9001: 2015 (Croft, 2012). After the consistent acceptance of ISO 9000 series, ISO launched the outstanding supporting standards for global commerce in 1996 called ISO 14000 series. These standards provide complete consistency with sustainable development, environmental management systems, pollution prevention, and compliance assurance (Maltitz, 2000; Delmas, 2002).

During the 1990s, many publications of environmental accounting had originated from major organizations in North American such as the Canadian Institute of Chartered Accountants, the Society of Management Accountants of Canada, the Certified General Accountants Association of Canada, the U.S. Institute of Management Accountants, and the International Federation of Accountants. This situation came from the origin of social accounting reporting at the beginning of the 1970s with acceptable skilful practices five years later (Gale and Stokoe, 2001).

As widely studied in businesses, environmental accounting became popularly used for nations. This is because the UN Statistical Commission (UNSC) formed the United Nations Committee of Experts on Environmental-Economic Accounting (UNCEEA) to elevate and implement the System of Integrated Environmental and Economic Accounting (SEEA) in 2005, including the creation of an international statistical standard which can provide strategic planning and policy analysis data for sustainable development (Eurostat, 2008a; Gagne, 2011).

At the same time, the Statistical Programme Committee (SPC) established a high-level task in 2003 to develop the European Strategy for Environmental Accounting (ESEA) which was reviewed and revised by the Working Group in 2007 and finished in 2008. Then, ESEA has been implemented by Eurostat, involving cooperation with researchers and international bodies such as the Organisation for Economic Co-operation and Development (OECD) and UNCEEA (Eurostat, 2008a).

For LCA, its concept and study have evolved since the 1960s (Miettinen and Hämäläinen, 1997; Roy *et al.*, 2009), and the start of current approach to LCA was for the Coca-Cola Company (the US, 1969, Guinée *et al.* (2010)). Since the 1970s, numerous studies have attempted to develop LCA from just an energy analysis to a wider environmental analysis (Roy *et al.*, 2009; Guinée *et al.*, 2010). Between the 1970s and 1980s, LCA became less favoured due to the lack of standardization (Williams, 2009). However, during the 1980s and 1990s (Guinée *et al.*, 2010), the full life cycle impact assessment and life cycle costing models were popularly introduced, including applying LCA for solid waste concerning natural resources and environmental emissions which was first done in 1988. Noticeably, the most significant event of LCA development is in 1997, when ISO first published the ISO 14040 standard in LCA (Rebitzer *et al.*, 2004). Afterwards, ISO 14040 LCA: 2006 version was released by the cooperation between ISO and the Society of Environmental Toxicology and Chemistry (SETAC,Cleary (2009)). Now, there are many published ISO standards of LCA series.

The third methodology, MFA, was applied to the average metabolism in a city as shown by Wolman in 1965 (OECD, 2000). Then, in 1969, Robert Ayres, a physicist, and Allen Kneese, an economist, launched the first version of MFA (Fischer-Kowalski *et al.*, 2011). In the early 1970s (Suh, 2005), the system definition and calculation changed because of the contributions of different researchers. Moreover, the first study of MFA in Europe was in 1980 and performed a study of hazardous chemicals at the end of the 1980s (Hinterberger *et al.*, 2003; Haes *et al.*, n.d.). From the 1990s, MFA has become a national economic tool (Fischer-Kowalski *et al.*, 2011) and the first achieved and published as a methodological guidebook by the European Statistical Office was in 2001 (Eurostat, 2001).

MFCA was first developed in the late 1990s by Professor Bernd Wagner and colleagues at Institute für Management und Umwelt (IMU) in Augsburg, Germany and first introduced in Japan in 2000 (Kokubu *et al.*, 2009). Furthermore, the Ministry of Economy, Trade and Industry (METI) published the Environmental Management Accounting Workbook in 2002 and explained MFCA case studies for Japanese companies (Kokubu and Nakajima, 2004). Afterwards, the Japanese Industrial Standards Committee (JISC) submitted a MFCA proposal to ISO to create a new working group called Working Group 8 (WG 8) in March 2008 and then ISO 14051 for MFCA was formally published in 2011 (Kokubu *et al.*, 2009; Kokubu and Kitada, 2012). In Japan, a number of companies have continuously used MFCA and strongly supporting the METI approach (Kokubu and Kitada, 2012).

The other methodology is CF, and the beginning of the 'Footprint Family' is the 'Ecological Footprint', developed by the mathematicians Wackernagel and Rees in 1997 (Ewing *et al.*, 2010). Then it was developed into CF in 2005 (Borucke *et al.*, 2013). ISO has launched CF as an environmental standard called ISO 14067 in 2013 (Radunsky, 2012).

Most recently, SDA is a new model for defining national or regional demand of materials and waste generation using estimations of the population and lifestyle, generally used GDP to investigate these (Müller, 2006). The method is based on national physical accounting instead of using direct prices or GDP as main drivers. Its results illustrate the variation of scenarios and parameters in a long-term period. The higher demand for construction materials from the population and its changing lifestyle makes the requirement of national resource and waste generation higher, represented by the increased floor area in use (FAC), and requiring more concrete in use (CU) for construction. Müller (2006) applied this method to the Dutch housing and concrete stock. Flows of C&D waste leaving from the stocks in use and moving into the waste management system can be projected by activities of construction, renovation and demolition (Bergsdal *et al.*, 2007a). Then, other researchers have also applied his model for other countries such as the Chinese and Norwegian stocks (Bergsdal *et al.*, 2007b; Hu *et al.*, 2010c).

All in all, from the 1930s, the most global consideration in MFMs had started only on the quality management system, environmental management and economic analysis in businesses or organisations. Then, these methodologies have been accepted and improved to represent national perspective by several recognized organizations and some research groups such as United Nations, Eurostat, Organisation for Economic Co-operation and Development (OECD), and national governments including the Industrial Ecology group.

In addition, some MFMs have been improved so that they can be implemented as ISO 9000 and 14000 series for certifications. Standards of environmental management systems in ISO 14000 series were widely suggested following successful operation of the ISO 9000 series (standards of quality management system). These standards are accepted for use in international trade for sustainable development, pollution prevention, and compliance assurance (Delmas, 2002) and require the need to document in depth details of each item and step within an environmental management system (Wilcox, 2007). Lastly, a comparison of advantages and limitations of each material flow methodology is provided in **Appendix B**, and a summary of crucial starting moments and periods described above is shown in **Figure 3-7**.

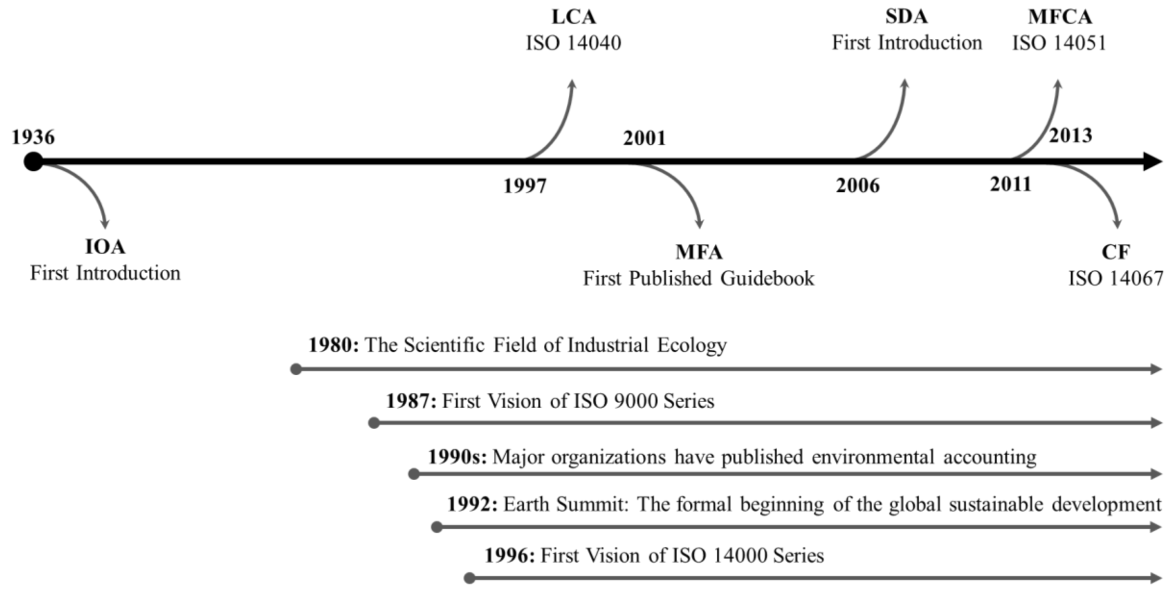


Figure 3-7 Summary of particularly relevant periods
Sources: Author
Note:

IOA = Input-Output Analysis   MFA = Material Flow Analysis   CF = Carbon Footprint

LCA = Life Cycle Assessment   MFCA = Material Flow Cost Accounting   SDA = Stock Dynamic Analysis

ISO 9000 series = standards of quality management system

ISO 14000 series = standards of environmental management systems

3.5 Approaches Driving Sustainability in Construction

3.5.1 Sustainability Approaches

3.5.1.1 Manufacturing of Construction Materials

Following its invention in the UK in 1824, cement manufacture has been growing continuously in Europe. The UK is now sixth for cememnt production and seventh for cement consumption in 25 EU-countries (The European Cement Association, 2007; Schorcht *et al.*, 2013).

Thailand is one of the leading countries that form the ASEAN. The use of economic cooperation to improve the welfare of people in this region was first promoted with the Bangkok Declaration on 8th August 1967 (Khoman, 1992). ASEAN and its ten member countries desire to reduce poverty and socioeconomic disparities. To achieve a stable, prosperous, competitive region and equitable economic development in Southeast Asia, the ASEAN Economic Community (AEC) will be established in the very near future (The ASEAN Secretariat, 2008; KPMG Asia Pacific Tax Centre, 2014).

Like the EU, the AEC envisages to be a single market and production base, fully integrated into the global economy. It means more concern with the regional economy, and probably disturbs the three pillars of sustainability, as ASEAN countries in general pay less attention than EU countries to the sustainable use of their natural resources and environment. Following a review of Wilson *et al.* (2012), business generally is concerned more with the production cost as a key motivator and often focuses on avoiding environmental costs.

As noted, the first cement company in Thailand was Siam Cement, now SCG Cement Public Co. Ltd., which has operated since the First World War (1913) at Bangsue, Bangkok (SCG Cement Public Co. Ltd., 2014). This company based on the intention of the King Rama VI of Thailand replaces imported cement from abroad, as cement is an important building material in Thailand (Department of Mineral Resources, 2008a). Thailand is an important cement manufacturer; consumer and exporter ranked the third in ASEAN following Vietnam and Indonesia, with 56.42 Mt of production capacity in 2013 (Saunders, 2015; TFCM, 2015).

Presently, the three leading cement companies, SCG Cement Public Co. Ltd., Siam City Cement Public Co.Ltd. and TPI Polene Public Co.Ltd., have approximately 80% market share. They also have their own downstream businesses including ready-mixed concrete and other construction materials such as tiles, sanitary ware, ceilings, walls, insulation, and block paving (TFCM, 2014). Thus, Thai construction materials are tightly controlled by only a few major cement companies as a monopolistic competition.

Thailand has higher annual concrete production, as it is used as the principal construction material, but has no published strategy that encourages the use of recycled aggregates for concrete and construction industries including ineffective control of emissions. Thailand has a short lifespan of building like other Asian countries such as China, and uses site-mixed concrete mostly. The quality of concrete for Thai buildings, therefore, relies directly on the operations of contractors. In contrast, concrete applications in Great Britain depend largely on the concrete industry that supplies ready-mixed and precast concrete, controlled by manufacturing standards.

Together, all ASEAN countries that have active cement industries have combined cement production capacities around 265 Mt from 139 cement plants in 2015 excluding Brunei and Singapore (Saunders, 2015). From earlier discussion about Thailand, ASEAN countries may experience similar Thai obstacles such as rapid depletion of natural resources through rapid urbanisation, ineffective management of emissions, wastes from manufacturing processes and C&D waste, and inferior quality of construction.

3.5.1.2 Construction

In Great Britain, although the number of other private contractor firms (small, medium and large firms) are significantly less than the micro-group, there are more employees in these bigger firms and a few large firms (only 0.1%) can earn similar revenue to the combined micro companies (ONS, 2014b). Therefore, as above discussed, Great Britain has more potential to host a sustainable construction business.

In contrast, most Thai construction firms are very small companies with only 1-5 workers and company value less than ฿1 million or £20,000. These firms have trade registration mostly in the name of an individual proprietor (Economic and Social Statistics Bureau, 2009; Bank of Thailand, 2015a). Thus, to improve practices in the construction sector in Thailand like Great Britain, the Thai government needs a well-organized strategy within the small group of Thai construction firms as the first priority.

3.5.1.3 Demolition

At the end of their lifespan, buildings and infrastructures are changed to be waste requiring suitable methods, such as recycling and landfill, for disposal and to reduce environmental impacts. Renforth *et al.* (2011) estimated global C&D waste, using 2010 world population data, to be 1.4-5.9 Gt/ year. In addition, 79% of C&D waste comes from demolition and 21% construction owing to increases in population and standards of living that encourage more growth of waste generated from decommissioning to build new buildings (Lawson *et al.*, 2001; Bergsdal *et al.*, 2007a). In developing countries, it is hard to find recorded data on C&D waste generation, most of them are available only in developed countries (Kourmpanis *et al.*, 2008a).

For C&D waste in the whole EU, concrete waste is the main component (60-70%, Monier *et al.* (2011)). Likewise, PCD *et al.* (2007) reported that Thai C&D waste consists mostly of 70-80% concrete waste. Therefore, this waste acquires more concerns. It estimated that the EU construction sector generated 821 Mt (33% of total waste) in 2012 among EU-28 countries. 100 Mt of which was C&D waste arising in the UK (50% of UK total waste), or 1.57 tonnes of C&D waste per capita (Defra, 2015b; Defra, 2015a; Eurostat, 2015c). Following Chapter 17 of the European Waste Catalogue (EWC) classifications, quantities and types of C&D waste in Great Britain are reported by this recording system. Morever, it can be found that GDP and the increase in households relate directly to waste arising in the UK (ECOTEC Research and Consulting et al, 2001).

To become a ‘recycling society’ before 2020, the EU has intended to reuse, recycle and recover 70% by weight of non-hazardous waste from C&D waste, including filling operations. It excludes non-contaminated soil and rocks from excavation (European Parliament, 2008; Fischer *et al.*, 2009). The UK is one of six countries (Denmark, Estonia, Germany, Ireland and the Netherlands) where it was reported that the recycling rates of non-hazardous C&D waste in 2012 was higher than the 70% EU target (Monier *et al.*, 2011; Defra, 2015b).

Thailand has less evolved C&D waste management with no registered data, no integrated sustainable policy and no major government agency. Kofoworola and Gheewala (2009a) estimated that an average of 1.1 million tonnes of only construction waste was generated per year (between 2002 and 2005) in Thailand. Moreover, C&D wastes remaining after separation and consisting of concrete waste mostly are disposed of by illegal dumping (PCD *et al.*, 2007; Kofoworola and Gheewala, 2009a).

3.5.1.4 Recycled Aggregates Activities

In the interests of the concepts of sustainability, primary aggregates can be used in combination with recycled aggregates in concrete manufacturing and construction industry. There are two main recycled aggregate sources: through on-site and off-site activities. The benefits of reuse of old concrete on-site can save natural resources and can reduce dust and transportation cost (Di Maio *et al.*, 2012). For off-site operations, the main manufacturing processes involve removal of metal and reducing the size of concrete waste to produce coarse and fine recycled aggregates. Then, the remaining inert waste can be sent for disposal at landfill.

Recycling activities are general operations for concrete waste in urban areas of Great Britain such as the operation of Thompsons of Prudhoe at Springwell Quarry, Gateshead, Newcastle upon Tyne. MPA (2013c) reported that 54 Mt of recycled and secondary aggregates, 85% of which was coarse recycled aggregates, were used for concrete and construction industries in 2012 and 5 Mt were used for the concrete industry (DCLG, 2007; MPA, 2013b). Fine recycled aggregates have some potential to be reused in the cement industry as alternative mortar; for example, it is reported that the 20% replacement ratio can perform better than a reference mortar (except for adhesive strength and dimensional stability; Neno *et al.* (2013)).

Using Great Britain’s experiences as described above, a sustainable life cycle of construction materials is summarised in **Figure 3-8**.

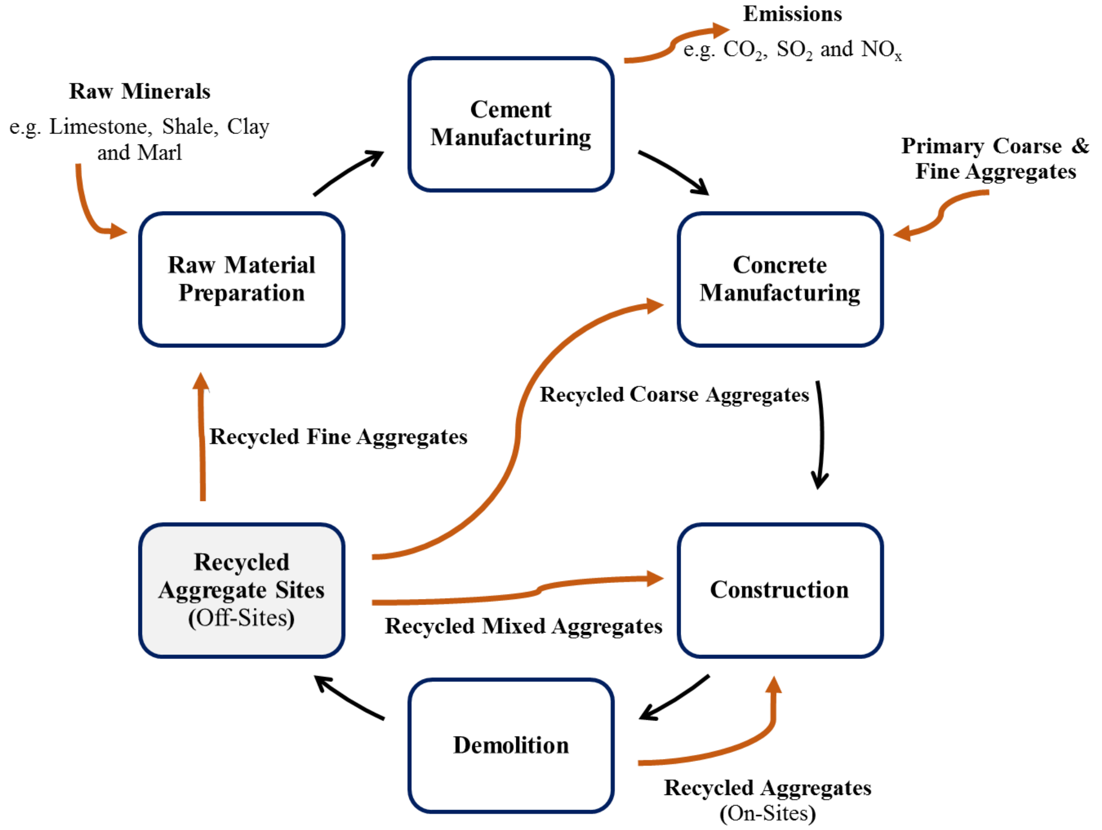


Figure 3-8 A sustainable life cycle of construction materials
Sources: Author

3.5.2 Localism Approach

3.5.2.1 Great Britain and European Union

To make the growth of the EU economy as the ‘Single Market’ stable, the EU established the Europe 2020 strategy. A sustainable growth in promoting more resource efficient, greener and more competitive economy is an important part of this strategy (European Commission, 2010). The UK is one of the 28-EU members, controlled by a politico-economic union, established since the 1940s. UK Government and Devolved Administrations for Scotland, Wales and Northern Ireland have agreed and adopted sustainable development as a primary target of the governmental policy framework for plan-making and decision-making following the EU sustainability strategy, but there are also industrial commitments relating to the uses of natural resources such as in the construction material industries (Defra, 2011; DCLG, 2012).

(1) Cement Industry

24 leading cement producers operate in more than 100 countries with 30% of global cement production and have a global effort called the Cement Sustainability Initiative (CSI). All members consider sustainability within their business strategies and operations following the initiative of the World Business Council for Sustainable Development (WBCSD, 2014). The worldwide cement producers are striving to lower the clinker content in their cement because of cost reduction and CO_2 emission with limits imposed by the regional and global availability of appropriate materials (Schneider *et al.*, 2011). For UK performance, MPA (2014c) stated that the cement industry can compete globally and maintain a sustainable domestic economy. The sustainable local production of cement is not just for the benefit of MPA member producers to maintain the cement industry's competitiveness, but for the whole of the UK.

(2) Aggregate Market

Great Britain has enough primary aggregate reserves to last a very long time at current rates of extraction. The aggregate market characteristically uses domestic resources, although there is some international trade. Used, recycled and secondary aggregates are encouraged and these materials can extend Great Britain's non-renewable resources (BGS, 2008a). The utilisation of recycled and secondary aggregates in Great Britain can alleviate pressure on finite primary aggregate resources, achieving the highest proportion of the aggregrate stock (29%) in the aggregates market or three times higher than the EU average in 2012 (The European Environment Agency, 2008; MPA, 2013c). However, Great Britain still uses less recycled and secondary aggregates than its potential, especially in the concrete industry.

(3) Concrete Industry

'The UK concrete industry will be recognised as a leader in sustainable construction, by taking a dynamic role in delivering a sustainable, zero-carbon built environment in a socially, environmentally and economically responsible manner', announced by The Concrete Centre (2012). This means a sustainable solution can be designed and built in both precast and ready-mixed concrete because of its inherent benefits as shown in **Table 3-2**.

Table 3-2 Concrete credentials: sustainability for precast and ready-mixed concrete

	Precast Concrete	Ready-Mixed Concrete
CO_2	A commitment to use additional additives where performance requirements permit exists throughout the industry. Transport distances for the average delivery of precast concrete products are just over 150 kilometres (km).	Additional additives e.g. slag, flyash, boittom ash and admixtures are used by most concrete manufacturers to optimise cement content and can reduce the embodied CO_2 of the concrete. Transportation CO_2 is minimal with the average delivery distance of ready-mixed concrete being 8 km and 50% of ready-mixed plants are located at the aggregate extraction site.
Recycling	Recycling systems capture virtually all process water, slurry, aggregates or cement and these are re-used in the production process. 85% of the waste produced by the precast sector is recycled or re-used.	At the end of the life of a structure, all cured concrete waste can be recycled to create new construction materials.
Resource depletion	23% of aggregates used in the precast sector are recycled or from secondary sources. The sector has set a target to increase the use of additional cementitious materials to 25%. Precast products can often be re-used in their entirety.	Every tonne of ground-granulated blast-furnace slag (GGBS) or fly ash used in concrete mixes saves about 1.4 tonnes of raw materials and fossil fuels. Aggregates are abundant the world over and the UK has enough aggregate reserves to last for hundreds of thousands of years at current rates of usage.
Waste	The precast concrete sector uses more waste than it produces. A tonne of precast product uses 218 kg of secondary materials and by-products and produces only 6 kg of waste that goes to landfill. Concrete buildings can be designed with less finishes reducing the associated material waste.	Modern formwork systems and efficient site management minimise ready-mixed wastage which is estimated at less than 2%. Systems are available to re-use 'returned ready-mixed concrete' and this does not go to landfill. Concrete buildings can be designed with less finishes reducing the associated material waste.
Water	Dependency on mains water supplies is being drastically reduced across the industry as companies adopt recycling systems and alternative water sources such as rainwater harvesting. 180 litres of water are used per tonne of precast concrete product; 38% of which is from licensed non-mains sources. Water-reducing admixtures also minimise water use.	A cubic metre of fresh concrete contains 140 to 190 litres of water. The use of admixtures can reduce the water content by up to 30 litres per cubic metre. 90% of ready-mixed concrete already includes water reducing admixtures.
Emissions	The precast concrete sector is closely regulated by the Environment Agency. In 2008 the sector achieved an increase in the percentage of sites with Environmental Management Schemes (EMS) to 80%. A target has been set to increase this to 85%.	All ready-mixed plants have dust suppression systems in place.

Source: Taken from The Concrete Centre (2010a)

The Concrete Centre, a part of the MPA, aims to (1) commit to its role in achieving a sustainable built environment and contribute to the construction industry and government initiatives, (2) engage with the broader supply chain to inform good practice and explore new ways of improving its sustainable production performance continually, and (3) communicate with clients to provide knowledge of concrete solutions, enabling the design and construction of a sustainable built environment.

The performance indicators for the industry to ensure the relevance of new targets for performance improvement are set as:

- 90% reduction in waste to landfill by 2020 (2008 baseline),
- 30% reduction in CO_2 emissions from concrete production by 2020 (based on 1990),

- 95% of production certified to responsible sourcing standard BES 6001 (Framework Standard for the Responsible Sourcing of Construction Materials) by 2020.
- 100% of relevant production sites with action plans for site stewardship and biodiversity.

BES 6001 launched in 2010 is one of the BRE Environmental & Sustainability Standards, which is the property of BRE Global Ltd. This standard and certification scheme will help organisations manage and reduce impacts throughout the supply chain, and is made publicly available for information purposes only.

(4) Construction Industry

To improve the quality and efficiency of UK construction, a report by the Construction Task Force stated that sustainability is equally important with whole life costs including costs of energy consumption and maintenance costs from the design stage (Department of Trade and Industry, 1998). The Chartered Institute of Building (CIOB) is a member of the Society for the Environment and awards the Chartered Environmentalist (CEnv) qualification. It has more than 340 CEnv members, and this number is steadily growing.

Moreover, the CIOB wholly supports sustainable construction, through best practice and innovation in the design, construction, operation, maintenance, retrofit and refurbishment, as well as in skills and leadership of carbon reduction. The CIOB commitment uses the Carbon Action 2050 initiative to support the built environment sector in achieving the CO_2 reduction target as set out in the Climate Change Act 2008 with 80% reduction in emissions by 2050, based on 1990 levels (The Chartered Institute of Building, 2013).

In addition, the new Sustainability Action Plan 2012-2015 by the Sustainable Construction Task Group and CIOB also regards Sustainable Construction and Building Information Modelling (BIM). Its fullest sense enables environmental simulation and assessment of individual projects and also scales urban developments across cities. BIM provides a platform to design, construct and manage environmental performance at a level of accuracy previously unattainable. Both the action plan and CIOB expect to use BIM as a significant impact of being able to achieve more sustainable projects and communities (The Sustainable Construction Task Group, 2012; The Chartered Institute of Building, 2013).

3.5.2.2 Thailand and ASEAN countries

(1) Influence upon ASEAN Development

A key founder of ASEAN, the Thai approach to sustainable development is distinctive. Since a general concern in business is the production cost as a key motivator, it often focuses on avoiding the environmental costs (Wilson *et al.*, 2012). Thus, a mainly economic concern and less attention to the management of their natural resources and environment, including slow cooperation in the region, might create instability of the three main sustainable pillars of the ASEAN region in the future.

(2) Profound Influence upon Thai National Policy

His Majesty King Bhumibol Adulyadej gained international recognition as the 'Developer King' and is the soul of Thailand. His philosophy, called 'Sufficiency Economy', firstly introduced since 1974, lies in the Thai people's hearts (UN, 2000; Curry and Sura, 2007). This localism philosophy has been a balanced approach to develop Thailand as the blueprint for development and administration.

To modernise with the forces of globalisation, this philosophy stresses the middle path, consisting of moderation, reasonableness, and self-immunity with knowledge and integrity conditions to external shocks, as an overriding principle for appropriate conduct by the populace at all levels: family, community and nation (United Nations Development Programme, 2007; National Economic and Social Development Board, 2011). As seen in **Figure 3-9**, balancing of economy, society, environment and culture is appended to this localism philosophy of the Thai king.

The Thai government has officially adopted and applied this philosophy, strengthened through the depth of economic, social, and administrative aspects including resource and environment issues in the National Economic and Social Development Plan since the ninth issue, and the eleventh (2012-2016) issue is the most recent plan (National Economic and Social Development Board, 2011).

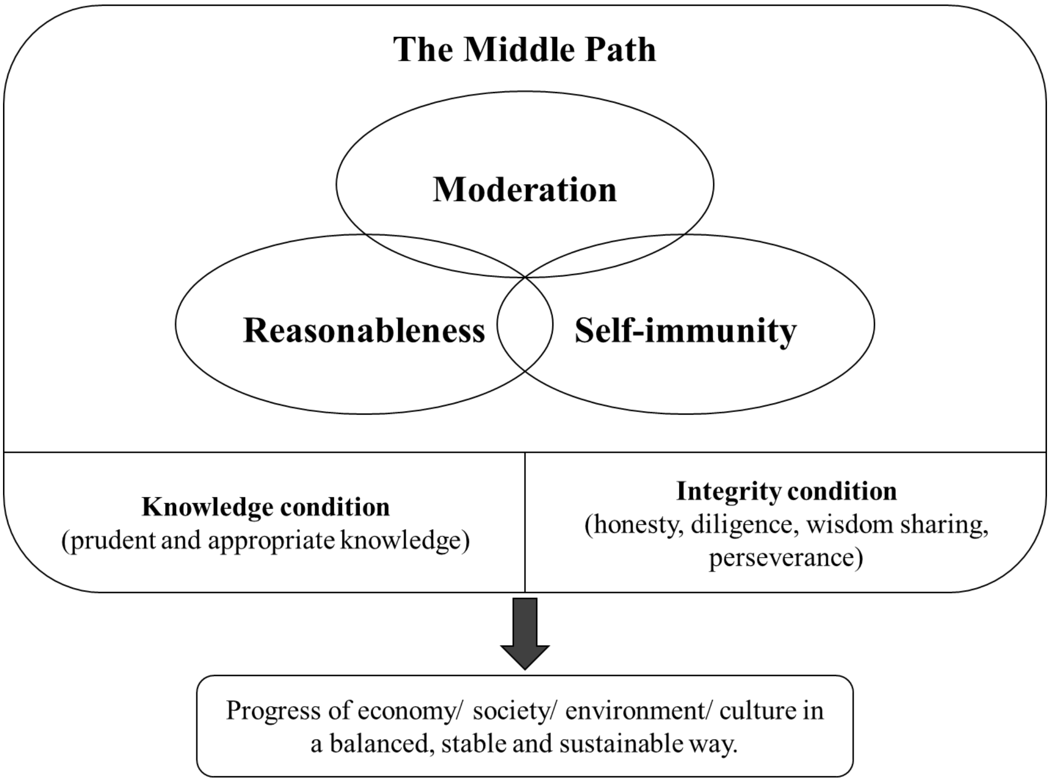


Figure 3-9 Conceptual framework of Philosophy of Sufficiency Economy
Source: Taken from Office of the National Economic and Social Development Board (2007)

(3) Sustainability Concept in Thai Present Plan and Implementation

Following the eleventh (2012-2016) plan which indicated the urgency to handle the natural resources and environment, Thailand still has no better performance and no particular plan for natural resources relating to construction materials and C&D waste management. Thus, C&D waste needs to be disposed of alongside household waste, and uses the same national laws and regulations. As seen, environmental agencies focus mainly on air pollution, waste water and a waste system consisting of municipal solid waste, infectious waste, industrial waste and household hazardous waste by presently forming the National Waste Management Plan, (National Economic and Social Development Board, 2011; PCD., 2015).

The natural resources and environment in Thailand have only two channels of the central government budgets for policy operation, with no environmental taxes like the ones in Great Britain. The first budget is the Environmental Fund established by the Ministry of Finance under the Enhancement and Conservation of National Environmental Quality Act 1992 (Office of Environmental Fund, 2011). The second is the budget established by the Environmental Quality Management Plan at the provincial level. For the above reason, the Thai government can allocate only the central budget to operate prescribed plans and policies of the natural resources and environment.

Like other developing countries, business leads the national economy and appropriate policy is clearly seen in Thailand. With less concern for natural resources and environmental management in the wealth of construction materials, Thai natural resources and environment have continuously been depleted and have deteriorated. Thus, it is necessary to utilise the existing resilience of Thai society and economy toward well-balanced development to generate genuinely pragmatic solutions under the real purposes of the Philosophy of Sufficiency Economy.

3.6 Regulatory Tools Used in Great Britain

To improve natural resource productivity through sustainable materials and waste management, there are (1) coherent framework conditions using shared targets, principles, policies, standards and guidelines to increase efficiency, (2) enhanced partnerships considering incentives for productive contributions and behaviour change, (3) information and material flows to understand economy, material patterns of national and inter-national, productivity relations, environmental risks and wastes generated, (4) a possibility based on existing infrastructure, (5) an appropriate legislative framework for the competent authorities, (6) taxation of non-recyclable items and wastes, and (7) international perspectives with common visions and differentiated solutions from countries with similar demand and background (Kourmpanis *et al.*, 2008b; Don't Incinerate Steering Committee (DISC), 2010; OECD, 2011).

A number of obstacles have to be overcome to achieve sustainable material uses and waste management, including the excessive compartmentalisation of policies, financial obstacles, mismatched time horizons among stakeholders, lack of awareness of economic and environmental benefits, modification of old consumption patterns, regulations neglected and a lack of knowledge about natural resource scarcity and waste management (OECD, 2011; Yuan *et al.*, 2012). In the context of EU regulation, factors that encourage Great Britain to achieve the targets of natural resource and waste management are (1) systematic recorded data, (2) integrated sustainable policies and regulations, (3) environmental taxes and (4) environmental funds, as summarised in **Figure 3-10**.

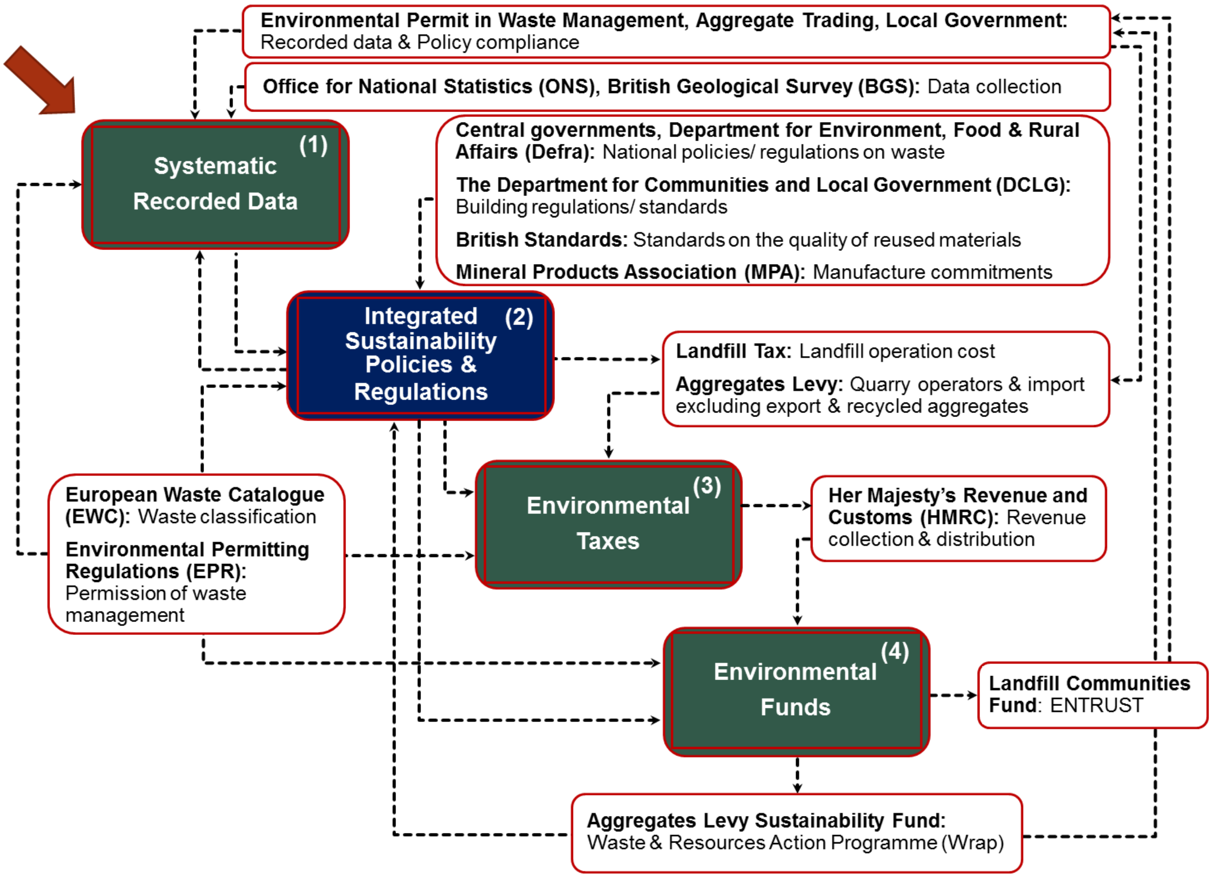


Figure 3-10 Regulatory tools used in Great Britain
Sources: Author

3.6.1 Systematic Recorded Data

Successful waste management depends on the systematic collection of data and statistics for waste planners at all levels (local, national and regional) to obtain accurate aims and plans (Symonds Group Ltd. et al (1999). The categories in the European Waste Catalogue (EWC; Commission Decision 2000/532/EC) have been used by EU members since 2004 and provide a common terminology throughout the community to improve the efficiency of waste management activities. This catalogue is separated into twenty main chapters, most of which are industry-based but some of which are based on materials and processes. Additionally, data collection in this way can reflect the potential for reuse and/or recycling of the materials concerned, and identify the requirements for treatment or disposal as accurately as possible (European Parliament, 2008). The EWC underpins all steps of national regulation in Great Britain as the same EU underlying reference.

In the EU, waste management is carried out under the Environmental Permitting Regulations (EPR). A waste operator, carrier, broker or dealer in Great Britain seeks permission from the competent environmental authority in England, Wales and Scotland for one of two types: (1) a bespoke permit for a specific site or a mobile plant activity and (2) a standard rules permit with a set of generic rules applicable to all activities of a certain type (Environment Agency, 2011). For landfill, operators may be large private companies, local authority-owned companies, local authorities or sole traders. The operators must monitor and report their operations and emissions once they get an environmental permit continuously or periodically to the competent environmental authority, including to Her Majesty's Revenue and Customs (HMRC).

For aggregates, anyone responsible for commercially exploiting or importing virgin aggregates into the UK needs to register for the Aggregates Levy, account for production and pay the levy to HMRC, allowing the activities to be measured and valued (The House of Commons, 2002). Therefore, the amount and charges of primary aggregates used annually can be recorded from a levy operation of the aggregate trading. The British Geological Survey (BGS) records aggregate consumption annually for different activities and regions, and the Office of National Statistics (ONS) and the competent authorities in England, Wales and Scotland report related national statistics that reflect the clear movements of these natural resources including waste management.

3.6.2 Integrated Sustainability Policies and Regulations

Integrated policies and regulations in Great Britain come from two main governmental organisations. The Department for Environment, Food & Rural Affairs (Defra) aims to achieve sustainable development across the UK with other international negotiations, through effective protection of the environment and prudent use of natural resources while maintaining high and stable levels of economic growth and employment (House of Commons, 2002). The Department for Communities and Local Government (DCLG) administers building regulations and national building standards (DCLG, 2015a).

By the EU definition, C&D waste is further specified referring to EWC in Chapter 17. In addition, the 70% target for the reuse and recycling rate of the C&D waste stream by 2020 is driven by the Waste Framework Directive 2006/12/EC, revised by Directive 2008/98/EC, which sets general principles and requirements for proper C&D waste management in the EU (European Parliament, 2008; Fischer *et al.*, 2009; Monier *et al.*, 2011). The report of Monier *et al.* (2011) indicates that the UK has had an operating rate higher than the 70% target since 2009.

The economic development in the EU from local to regional sources has been supported by self-sufficient production in construction minerals especially aggregates. Reducing EU's consumption of the primary raw materials and relative import dependence by resource efficiency recycling and renewable raw materials is assisted by the European Raw Material Initiative (The European Parliament and the Council, 2008). The EU has also developed new criteria to distinguish secondary raw materials from waste to create greater legal certainty and operating criteria for the recycling sector (OECD, 2011). These initiatives are important to enable the aggregate market to use recycled and secondary aggregates appropriately in Great Britain.

Although Great Britain achieves the highest rate of recycled aggregates (29%) in the EU aggregate market, the use of recycled aggregates is still below capacity with more potential to increase (MPA, 2013b; MPA, 2013c; The Concrete Centre, 2013). The increased use of recycled and secondary aggregates does depend mostly on the identification of additional sources of supply and certainty of users (The European Environment Agency, 2008; MPA, 2013c). These limitations led some researchers to argue that secondary and recycled aggregate use cannot increase further (Thompson *et al.,* 2008; Mankelow *et al.,* 2010; Brown *et al.,* 2011).

Growth in use of recycled aggregates has been reinforced by several actions such as the revision of the British Standard on recycled coarse aggregates for concrete (BS EN 12620:2013) and various projects relating to a sustainable resource-efficient economy carried out by the Waste Resource Action Programme (WRAP; The British Standards Institution (2013); WRAP (2015b)). The existence of an industry trade association, the Mineral Products Association (MPA) also stimulates development in the private sector. The MPA was formed by the merger in 2009 of three related industry organizations, the Quarry Products Association, the British Cement Association and the Concrete Centre (MPA, 2009).

3.6.3 Environmental Taxes

Environmental taxes were first introduced in Europe in Nordic countries (in the early 1990s), partly to reduce personal direct taxes, and partly to change behaviour to achieve specific environmental objectives; they have since been more widely adopted. In the UK, the revenues generated from tax-shift programmes to reduce the employers' national insurance contributions (NICs) have been collected from the UK environmental taxes such as landfill tax introduced in 1996 and the levy on aggregates in 2002 (ECOTEC Research and Consulting et al, 2001). Aggregates that are genuine waste, disposed at landfill and subject to landfill tax are relieved from the Aggregates Levy (HM Revenue & Customs, 2015a). The rate of environmental tax is set to increase landfill cost, to reduce waste volume, and so to meet a defined target including to charge social cost from the negative externality involved in the taxation unit (Martin and Scott, 2003).

Based on the existence of environmental externalities, the implementation of taxes and levies as a part of environmental policy is intended as a mechanism for 'internalising' environmental cost as a side effect of production processes. Thus, EU members provide an incentive to the taxpayer to reduce their liabilities from the tax and levy (ECOTEC Research and Consulting et al, 2001). In the UK, environmental taxes are also used to avoid undesirable impacts on the environment, linking to a physical unit or a suitable proxy. However, Martin and Scott (2003) stated that they seem more concerned with revenue-raising purposes than addressing particular environmental objectives. Revenues raised in Great Britain provide some reduction in employers' national insurance contributions, and also fund environmental projects that delivered benefits to local communities (ECOTEC Research and Consulting et al, 2001).

From an administrative perspective, UK tax receipts for virgin resources (Aggregate Levy) are less than those generated from the Landfill Tax (**Figure 3-11**), thus encouraging substitution of secondary and recycled materials to influence waste disposal behaviour and potentially reducing the price difference between virgin and secondary and recycled materials (Böhmer *et al.*, 2008). As taxation on environmental externalities is considered a fair way of levying charges that can endorse the 'polluter pays principle', a tax escalator over time until achieving the requisite objectives is commonly used for both practical and political reasons. Particularly, it provides better results from the densely populated areas and stimulates recycling (Martin and Scott, 2003). Thus, changing the tax structure using environmental tax balances the new revenues in the medium and long term of the national economy and can reduce environmental impacts (ECOTEC Research and Consulting et al, 2001).

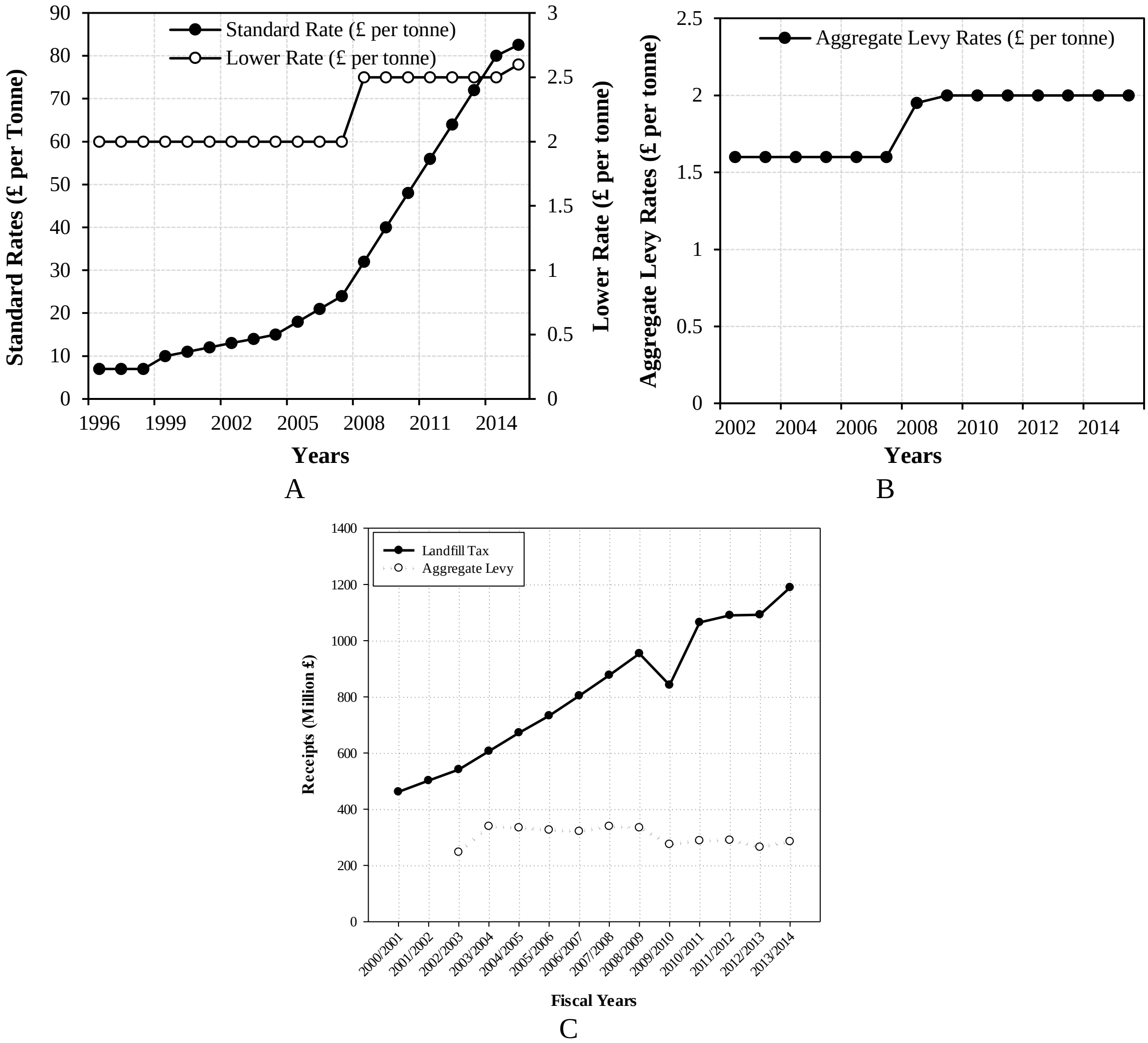


Figure 3-11 Rates of landfill tax (A) and aggregate levy (B) including UK environmental tax receipts (C)
Source: A and B: Author based on HM Revenue & Customs (2015a) and (2016)
C: Author based on Statista (2015a) and (2015b)

Furthermore, system boundaries considering environmental taxes from extraction, use and disposal stages of construction materials in **Figure 3-12** can explain the taxation relationship concisely. The Aggregate Levy controls virgin minerals for construction uses and encourages reuse of recycled materials. The Landfill Tax can reduce a quantity of waste to disposal and can increase use of recycled materials as an appropiate waste management activity.

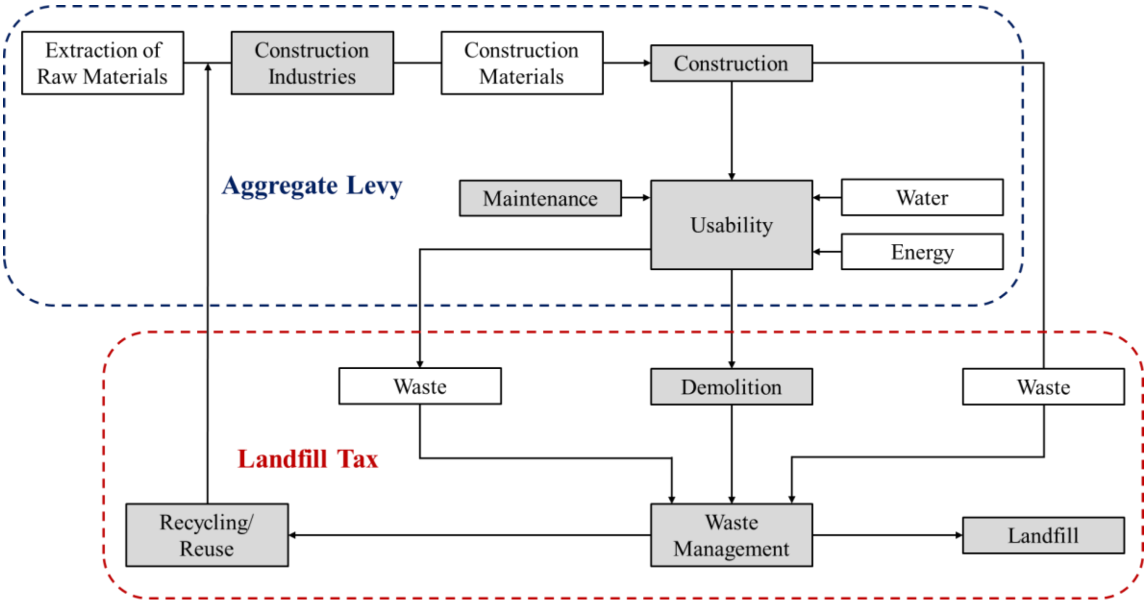


Figure 3-12 System boundaries considered environmental taxes from extraction, use and disposal stages of construction materials
Sources: Author

3.6.3.1 Landfill Tax

Better control of C&D waste and unauthorised landfills in the EU has originated from 1) the dramatic increase in C&D waste generated and 2) European policies such as Directive 99/31/EC on landfill, the old Waste Framework Directive 2006/12/EC and the revised Waste Framework Directive 2008/98/EC (Monier *et al.*, 2011). Volumes of waste can be significantly reduced by a landfill charge (Yuan *et al.* (2012), along with investment in waste management and stakeholder compliance with regulations.

Moreover, Yuan *et al.* (2011) stated that a higher landfill charge will lead to a higher net benefit and will suffer from a higher environmental cost caused by illegal dumping, requiring stricter enforcement of regulations. From the UK experience, the introduction of Landfill Tax led to an increase in illegal dumping of waste due to poor policing and limited sanctions in the early stage of the tax operation (Symonds Group Ltd. et al, 1999).

The Landfill Tax, introduced in 1996, encourages separation of specific waste for reuse, recycling or recovery, which become more attractive financially. The tax varies depending on the waste types sent to landfill (Böhmer *et al.*, 2008) and is charged by weight with two main rates: standard rate (£84.40/tonne) for active wastes and lower rate (£2.60/tonne, increasing to £2.65, 1 April 2016) for inert wastes. This tax implies increased gate fees (around 66%-200%) for the inert landfills (ECOTEC Research and Consulting et al, 2001; HM Revenue & Customs, 2016).

Bartelings *et al.* (2005) and ECOTEC Research and Consulting et al (2001) predicate that the landfill tax in the UK has certainly had a strong impact on C&D waste. The tax rate for inert waste is much lower in absolute terms, compared to active waste, but higher in relative terms, increasing the cost of landfilling for inert waste by up to 200%. Consequently, inert waste has been diverted away from the landfill to be recycled or reused, for example recycled and secondary aggregates in the construction industries or other uses such as spreading on farms as soil improvement or on golf courses for landscaping (Martin and Scott, 2003).

However, Martin and Scott (2003) stated that the Landfill Tax is intended to reduce waste to landfill using very few instruments and initiatives as only a part of a wider package and it is unable to achieve everything on its own. Local authorities have been allocated the tax revenue to develop facilities for the environmental provision for their citizens. By doing this, local authorities as the ultimate Council Tax payers and the greatest losers at the same time, have to transfer direct charging of householders to the HMRC.

3.6.3.2 Aggregate Levy

The other significant driver that enhances recycling and reusing C&D waste is the introduction of the Aggregate Levy in April 2002. A £2/tonne levy has been imposed on the primary production of sand, gravel and crushed rock for construction purposes since 1 April 2009. It increases average prices, affecting production from land-based quarries, marine dredging and imports, and has no effect on UK exported products and recycled aggregate (ECOTEC Research and Consulting et al, 2001; Martin and Scott, 2003; Böhmer *et al.*, 2008).

The UK government expects reduced demand for primary aggregates to increase uses of recycled and secondary aggregates, preserve non-renewable resources and minimise landfill space, and offsets benefits for firms supplying those materials. Therefore, the Aggregate Levy reflects the external costs of extraction broadly, increases recycling and provides revenues used to fund employment and environmental projects (Symonds Group Ltd. et al, 1999; ECOTEC Research and Consulting et al, 2001).

Supporting proper quality of recycled aggregates from C&D waste follows the European Aggregate Product Standard, ‘The Quality Protocol for the Production of Aggregates from Inert Waste’, first published and implemented in 2004. This protocol was funded by Defra, the Welsh Government and the Northern Ireland Environment Agency (NIEA) as a business resource efficiency activity. The protocol addresses compliance conditions when storing and processing waste. It has no effect on the obligation of producers to hold an environmental permit (including an exemption) and no effect on the permitting or any other legal requirement.

Moreover, the quality protocol was continuously developed by the Environment Agency, NIEA and WRAP in consultation with Defra, the Welsh Government, industry and other regulatory stakeholders, with a new version released in 2008. This is applicable in England, Wales and Northern Ireland to define waste criteria including its handling, transport and use of the fully recovered product as recycled aggregates from inert waste that requires mostly (MPA, 2011; WRAP, 2013):

(1) to be high quality for sale as construction materials or as components in products,

(2) to recommend minimum frequencies of inspection and testing, conforming to the requirements of the European Standards for Aggregates in the National Guidance Documents, produced by British Standards Institution (BSI) as:

- BS EN 12620 – Aggregates for concrete
- BS EN 13043 – Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas
- BS EN 13139 – Aggregates for mortar
- BS EN 13242 – Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction
- BS EN 13285 – Unbound mixtures specification,

(3) to provide adequate assurance that recycled products conform to relevant technical specifications and certified characteristics.

3.6.4 Environmental Funds

As a part of the introduction of environmental taxes, environmental funds have been established (ECOTEC Research and Consulting et al, 2001). Since the Landfill Tax introduced in 1996, the Landfill Communities Fund has delivered over £1.4 billion for over 52,500 local community projects across the UK. In 2013-14, the largest proportion of spend (77%) was on public parks and amenities, with 16% on the conservation of biodiversity and 7% on the restoration of culturally important buildings. The fund is regulated and administered by ENTRUST, a non-profit private company funded by around 2% of the collected tax. ENTRUST is responsible to (1) make guidance, (2) register and provide advice to Environmental Bodies (EBs) receiving contributions directly from landfill operators, (3) approve and audit projects and (4) undertake enforcement activities. In 2014-15, landfill operators can claim a credit of up to 5.1% against their Landfill Tax liability on 90% of the voluntary contributions they make to projects (HM Revenue & Customs, 2015c).

The revenue from the Aggregate Levy contributes to the Aggregates Levy Sustainability Fund (ALSF, Söderholm (2011); The European Environment Agency (2008)), and is redistributed in particular to English Nature, English Heritage and WRAP. The ALSF supports national policy by targeting the negative externalities from quarry activities, improving quality standards for aggregate, raising awareness and increasing end-user confidence, providing access to capital for reprocessing infrastructure to increase supply and delivering accessible robust information. It leads to targeted benefits for local quarry communities (The European Environment Agency, 2008). Then, the fund was suspended in March 2011, before which over £22.5 million was spent on research associated with marine aggregate extraction, to improve the industry (MPA, 2016a).

3.7 Summary

Global construction materials serve national economies and simultaneously provide effects of global warming. Developing countries rely currently on more production and consumption of construction materials than developed countries. Moreover, less concern in recycled activities of C&D waste, particularly concrete waste, is clearly seen in developing countries, together with no supporting protocols such as recorded data, central organisation, integrated policy and taxation. This thesis selected Great Britain to present the EU implementation and Thailand is used to represent current ASEAN limitations and situations on these issues.

Comparing the advantages of six Material Flow Methodologies (MFMs), this study decided to use Material Flow Analysis (MFA), including annual cement calculations based on the calcination process of clinker formation for both nations, and Stock Dynamic Analysis (SDA) in the housing sector. As developing methods comparing to other MFMs for ISO 9000 and 14000 series that can support annual and future concrete stocks, this thesis therefore selected MFA and SDA for calculation.

The strong awareness and practice on sustainability from all stakeholders in construction activities and materials can be clearly seen in Great Britain, following the EU sustainability strategy. Analysis shows that policy and taxation are supported by four main steps; systematic recorded data, integrated sustainable policy, environmental taxes and funds, that provide the EU and Great Britain with a mechanism to move further than ASEAN and Thailand. As a result, ratios of construction materials and wastes of the cement, concrete and construction industries including the aggregate market as systemic recorded data give more benefit in terms of the national prototype for this research, used for estimating figures of the other case study that is Thailand.

From an environmental perspective correlating with construction materials, the UK, an EU member, has clearly harmonised national policy and taxation using sustainability concepts from ongoing missions and operations of the EU in natural resources and C&D waste management achieving the EU recycling target. The uses of recycled and secondary aggregates help Great Britain achieve the highest recycled aggregate rate (29% of total aggregates used in 2012) which was three times higher than the European average. As presently seen, Great Britain has integrated systems of the trade association, regulation, professional body and cooperative performance. However, this country still can not fulfil the proposed target of recycled aggregate use as it is still lower than the real potential.

As previously described using the Thai case study and referring to ASEAN problems in natural resources and waste management, although the Thai government officially adopts and applies the Philosophy of Sufficiency Economy of His Majesty King Bhumibol Adulyadej strengthened through the depth of all invaluable aspects in the national economic and social development plans, natural resource and environmental issues seem to be of less concern in practice. For regional implementation, ASEAN seems concerned mainly with economic issues with less concern for regional resources and environment, including slow development of cooperation. Like other developing countries, business leads the national economy and appropriate policy is clearly required for Thailand and ASEAN region.

Chapter 4 Methods and Results

To describe each calculating step of the thesis methodologies, this Chapter provides summaries of the methodological frameworks. Original calcination calculations are used to connect with cement and concrete components for modelling annual concrete stock using Material Flow Analysis (MFA). Then, future concrete stock in only the housing sector (which is the highest use in Thailand) is computed with Stock Dynamic Analysis (SDA). Finally, the national policy and taxation for Great Britain and Thailand are compared, in the context of the results of MFA and SDA, including the influential regional strategies of the EU and ASEAN communities.

This Chapter then consists of all results from calculations of (1) annual concrete stocks by MFA and (2) future concrete stocks using SDA in the residential sector only. Then, these results are used to illustrate the differentiation of both national case studies, Great Britain and Thailand, including their regional strategies and implementations.

4.1 Methods

4.1.1 Overarching Methodological Frameworks

Concrete is widely used for current global construction, including for Great Britain and Thailand. This research, therefore, focuses on the present and future concrete stocks of both countries including their main supplies (e.g. cement, coarse and fine primary aggregates, coarse recycled aggregates and additives), waste and emission. Furthermore, using the comparison of the results from the annual and future concrete stocks, this study aims to establish an outline policy appropriate for Thailand, and by extension the other nine ASEAN countries, by lessons learned in policy and regulation of construction materials including the management of natural environment from the EU, especially from Great Britain. Overarching methodological frameworks of this research combine four main steps, briefly described in **Figure 4-1**.

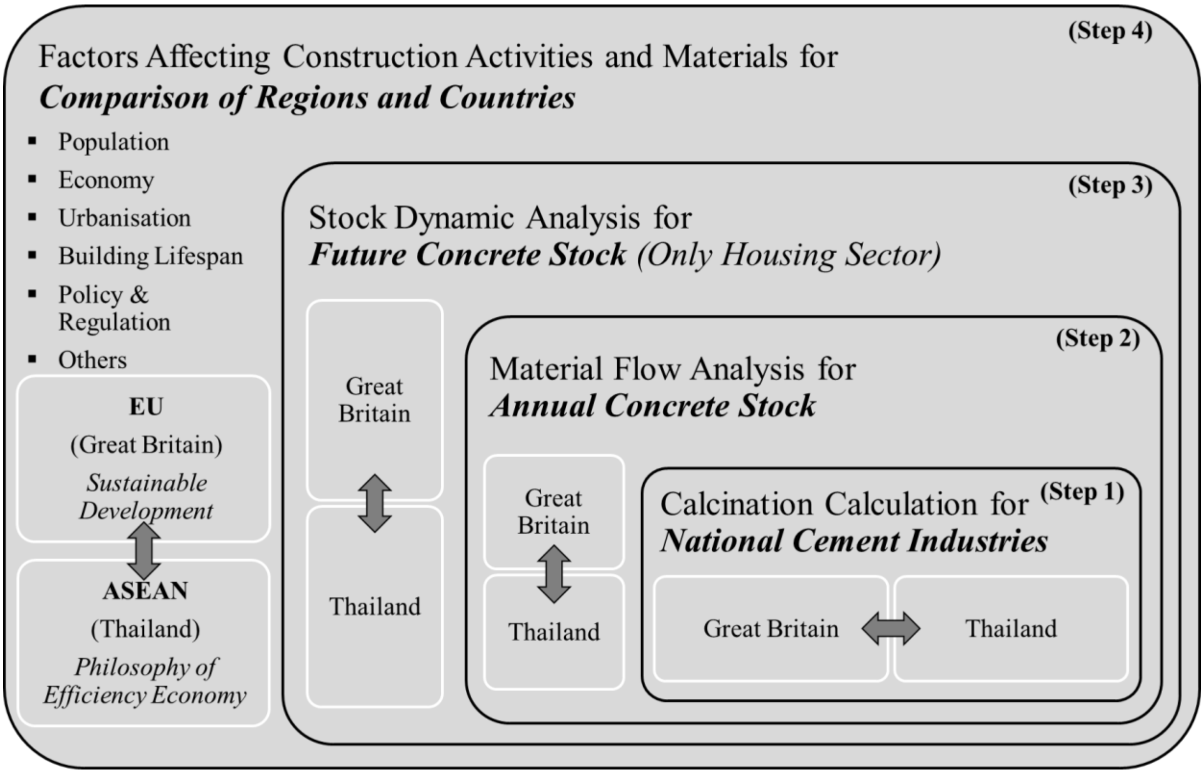


Figure 4-1 Overarching methodological frameworks
Sources: Author

- **Step one: national cement production**: this part utilises knowledge of the chemical reactions involved in calcination to estimate amounts of raw materials used in the clinker and cement manufacturing processes. The results are compared with the real situation of annual domestic cement used for the 2012 concrete industries of both national case studies, together with its main raw components and associated inputs and emissions, such as cement kiln dust (CKD), conventional and alternative fuels, CO_2 emissions and traded cementitious quantity.

- **Step two: annual concrete stock**: this used MFA to combine data for national cement production in Great Britain and Thailand from the calcination calculation (Step 1) with the quantity of concrete aggregates used in the 2012 aggregate market. For Great Britain, aggregates sent to the concrete industries consisted of both primary and recycled aggregates, and only primary aggregates were used by the Thai concrete industry. Lastly, MFAs of annual concrete stocks in both countries in 2012 are separately used for different construction sectors: single-residential building, multi-residential building, non-residential building and infrastructure, and are shown by Sankey diagrams e.g. **Figure 4-11** and **Figure 4-12**.

Recycled aggregates can be used to replace primary aggregates widely in the EU, and Great Britain consumes the highest rate of recycled aggregates among the EU for both concrete and construction industries. So two other Sankey diagrams (**Figure 4-9** and **Figure 4-10**) were produced to emphasise the whole aggregate market as primary and recycled aggregates, including secondary aggregates for concrete and construction industries in 2012, and the 2012 recycled aggregate activities by off-site operations in Great Britain.

- **Step three: future concrete stock (only housing sector)**: this research used SDA to investigate construction activities in the national housing sector using historical data to extrapolate to the future. According to the results of Thai annual concrete stock use in each construction sector, Thailand demanded the main part of concrete products for the housing sector. Moreover, higher requirement for this construction building comes from reasons such as increase in the well-being of population (measuring by GDP), a short lifespan of the residential building, rapid population growth and family expansion. At the end of residential lifetime, demolition waste consisting mainly of concrete waste needs to be properly disposed of. All in all, SDA results can explain the estimated amount of the future and expected demolition of housing, expressed as floor area in use, together with future concrete demand and waste arising until 2100.

- **Step four: comparison of regions and countries**: all results of annual and future concrete stocks in both nations and factors affecting construction activities and materials together with wastes are compared. These national distinguishing factors are the population, economy, urbanisation, building lifespan, policy and regulation including other factors such as the construction quality. Importantly, one main reason that makes Great Britain and other EU members more concerned in the management of resource environment than the ASEAN (including Thailand) is the effect of EU strategies since the beginning of EU integration.

  The EU strategies and targets in C&D waste management consist of the recycling of hard-inert C&D waste both in-site and off-site for construction and demolition areas, the conservation of natural resources, environmental taxes and the cooperation from all stakeholders such as government, education and private sectors. Finally, the outline of appropriate policy and environmental taxes adapting from the EU and Great Britain's experiences is illustrated for Thailand and considered for extension to the other nine ASEAN countries. This step will be further described in **Chapter 5**.

4.1.2 Step 1: Estimation of Raw Materials Using the Calcination Calculation

Calcination is a core part of the clinker manufacturing process. Its mechanism involves elevated temperatures at approximately 1450^{o}C to make finely-ground raw materials (e.g. limestone and shale) react by coalescing into a solid or porous mass without liquefaction in the rotating kiln. Then, these materials are transformed to be dark gray nodules with 3-25 millimetres in diameter named clinker. This process converts the raw materials into specific calcium silicates (Manning, 1995). The calculation part uses the chemical reactions involved in clinker formation to estimate the amount of main raw materials and carbon dioxide (CO_2) generated from clinker manufacturing processes.

The calcination calculation of national cement industries starts from the recorded volume of clinker produced in Great Britain and Thailand in 2012. The calcination reaction can be used to back-calculate the amounts of the principal raw clinker minerals and fuels (conventional and alternative fuels), together with CO_2 and CKD in a clinker manufacturing process. Those data also include import and export of cementitious products and other cement components. Moreover, each step of annual cement calculation in both countries uses some supporting references from global conventional cement compositions to re-check. Consequently, the results can represent real situations of the whole cement industry of Great Britain and Thailand in 2012, and consist of two main parts, as clinker and cement calculations. More descriptions of both national cement industries and cement manufacture can be found in **Chapter 2**.

4.1.2.1 Clinker Calculations

Clinker production comprises mainly of mined raw materials and fuels. Its processes also link to the generation of CKD and CO_2 derived from (1) the main raw materials (limestone and shale) in the calcining reaction and (2) fuel combustion as conventional and alternative fuels. All calculating figures are based initially on the national annual recorded volume of finished clinker, recorded by MPA (2015c) in Great Britain and Office of Industrial Economics (2013) for Thailand. These figures are used for:

1) Backward calculations: to estimate the volume of the main clinker minerals; CKD; clinker conventional and alternative fuels; fuel ash and CO_2, and
2) Forward calculations: to estimate volume of domestic and trading clinker.

4.1.2.1.1 Backward Calculations

1) Clinker Minerals

In the global cement industry, clinker is mostly formed by combining calcium oxide, CaO as main raw minerals from 75% limestone or other minerals (e.g. cement rock, marble and chalk) and 25% shale or other minerals which supply SiO_2 and Al_2O_3 (e.g. clay and marl, Manning (1995); Conneely *et al.* (2001); Worrell *et al.* (2001)).

Following each step of **Figure 4-2**, the main raw minerals after blasting at quarries are transferred to the cement plant. Then, the size of minerals is reduced to be smaller than 90 micrometres (μm), called 'raw meal' by one or more crushers and then a grinding mill (Domone and Illston, 2010). The raw meal can be divided into two key processes: dry powder and wet slurry (US.EPA, 1993). In a dry process, raw meal needs to pass a 'pre-calcining vessel or pre-heater' using exhaust gases from the furnace to reduce the moisture content less than 1% before feeding it to a cement kiln (US.EPA, 1993; Domone and Illston, 2010).

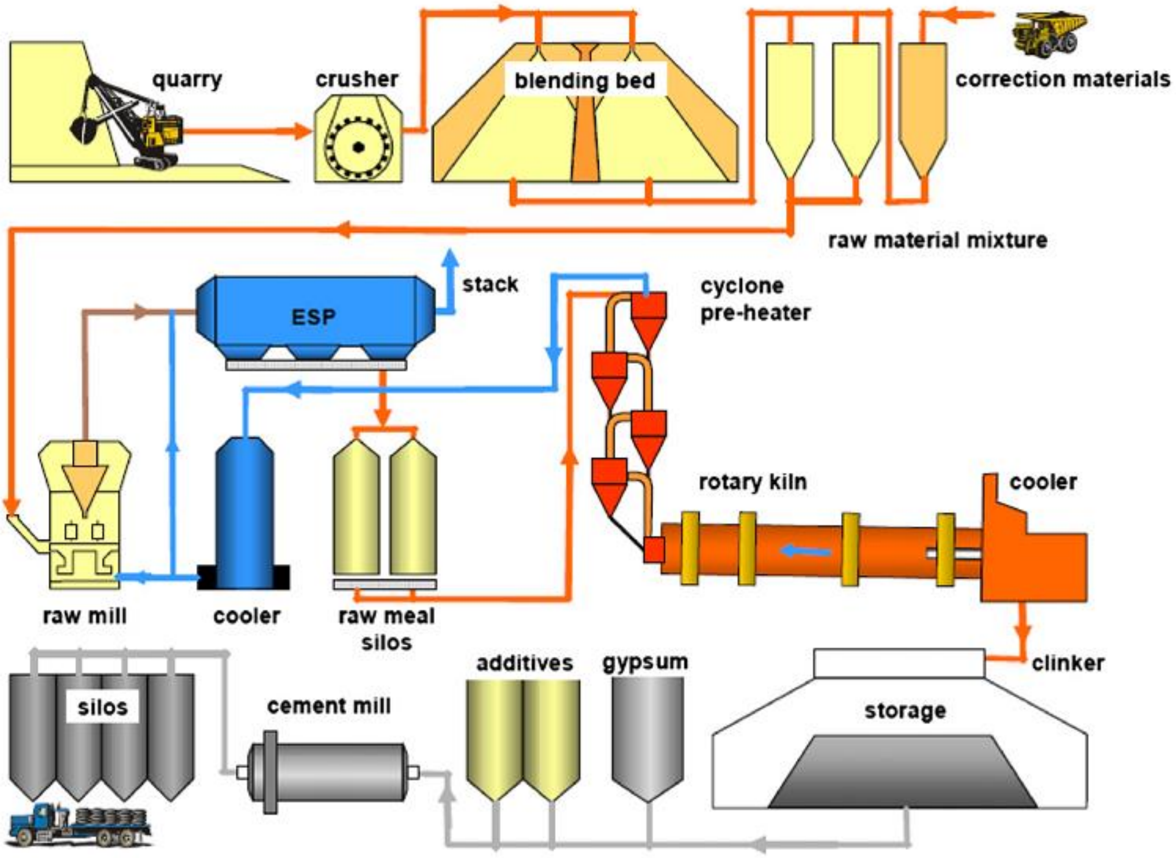


Figure 4-2 Schematic representation of cement
Source: Taken from Lamas *et al.* (2013)

For a wet process, raw meal is mixed with about 30-40% of water while grinding to form a well-homogenised slurry (US.EPA, 1993). As this process has higher moisture content it requires twice the energy used in the dry process to reduce the moisture content of the wet slurry. Most of cement plants, therefore, turn to use the raw meal as dry powder due to energy saving and so have no water removal process in the initial phase before calcining (Manning, 1995; Sjunnesson, 2005).

In Europe, more than 90% of cement production is based on dry processes (Schorcht *et al.*, 2013). Significantly, in Great Britain cement manufacturing still operates semi-dry and semi-wet processes at around 22% of total clinker capacity, and the remaining (78%) uses the dry process (BGS, 2014b). For Thailand, all cement plants presently use only the dry process (TFCM, 2015).

The most part (70%) of total CO_2 in cement manufacturing is derived from raw minerals by the calcination reaction in a cement kiln (MPA, 2014c). This reaction involves the release of CO_2

from the main raw materials, as limestone generates around 44% CO_2 by weight and shale typically 10%. Therefore, the remaining weight after firing from limestone is 56% and shale 90% (Manning, 1995; Conneely *et al.*, 2001; Worrell *et al.*, 2001).

2) Cement Kiln Dust (CKD)

Van Oss and Padovani (2003) reported that a 15-20% CKD to clinker ratio implies a significant disposal problem. In the US, about two-thirds of the generated CKD typically is returned to the kiln, leaving one-third for landfill disposal (mainly) or sale. Moreover, these authors reveal that cement businesses require an excess volume of raw clinker minerals to generate clinker following the cement demand for construction. This study selected 20% for CKD calculation due mostly to continued use of old cement plants in both countries with old equipment efficiency. It means one-third (6.67%) of CKD production were changed to be waste and required proper disposal in both countries.

3) Clinker Fuels

Fuels used in the cement industry have partially been replaced by alternative fuels from wastes since the mid-1980s because of reasons such as saving of costs, energy consumption, and natural resources, although there is considerable concern about possible environmental impacts. Production of one tonne of clinker, depending on the conditions of the raw meal, requires fuel with a calorific value 3.2-5 megajoules per kilogram (MJ/kg) (Lemieux *et al.*, 2004). Comparing to the study of Ecofys *et al.* (2009), the dry process consumes around 2.95 MJ/kg specific energy per tonne clinker, compared with 6.7 MJ/kg for wet processing.

Therefore, this study selected 3.2 MJ/kg for calculating fuel use for a dry process due to the inefficiency of old cement operations in both countries that require more energy, and 5 MJ/kg for a semi-wet and semi-dry process, saving more heat than the wet process. The net calorific value of conventional fuel such as coal is around 28.30 MJ/kg and 18.20 MJ/kg for alternative fuels (Hiromi Ariyaratne *et al.*, 2013).

In Great Britain, MPA (2013c) reported that 40% of fuels used in the cement industry in 2012 are derived from waste sources. Similarly, Thai cement manufacturing has been allowed to use wastes as alternative fuels at 40% of (1) heat value of alternative wastes comparing to the net calorific value or (2) alternative waste weight comparing with total fuel weight (Ministry of Natural Resources and Environment, 2006). Alternative fuels are also available for the clinker formation process, cement manufacturing, or concrete production (Schneider *et al.*, 2011;

Aranda Usón *et al.*, 2013; Kaddatz *et al.*, 2013). This study used 60% conventional fuels and 40% alternative fuels for clinker manufacturing in both Great Britain and Thailand.

4) Fuel Ash

After burning, one tonne of coal and alternative fuels is changed to be fuel ash at around 10% or 0.1 tonnes (Hiromi Ariyaratne *et al.*, 2013). The amount of fuel ash without separating from kiln chamber is entirely included into the clinker product.

5) CO_2 Emission

CO_2 is emitted mainly from mineral calcination and fuel combustion. This research calculates the amount of main CO_2 emission from clinker manufacturing by balancing weight from input and output of fuels and minerals after calcining and combusting.

4.1.2.1.2 Forward Calculations

1) Quantity of Domestic, Import and Export Clinker

This part used recorded volume of national clinker product to calculate forward by the amount of import and export clinker in Great Britain from BGS (2014a) and from Office of Industrial Economics (2013) for Thailand to comprehend the domestic clinker use for both case studies. Then, these domestic results are used as the starting figures for the next cement calculation.

4.1.2.2 Cement Calculations

The quantity of domestic clinker production from the previous calculation is used to calculate the quantity of cement product, combining with import and export cement data. Then, additives including gypsum were added to produce Portland and other cement. Generally, cement production can be separated into three main parts as (1) cement for concrete (mainly), (2) cement for mortar and (3) cement for other uses. Due to lack of Thai recording data, this study estimated figures for Thai cement industry, using recorded proportions for Great Britain to calculate the quantity of additives and cement for mortar.

4.1.2.2.1 Portland Cement (including Gypsum Quantity)

This calculation part also reveals the volume of gypsum and Portland cement in case studies. The cement manufacturing process requires 95% clinker and 5% gypsum to produce Portland cement (Worrell *et al.*, 2001). Without adding gypsum (a hydrated calcium sulphate), cement can immediately set after mixing with water allowing no time for concrete placing. Thus, the main reason for adding gypsum is to extend and to control the time for cement setting (Manning, 1995). The form of hydration is:

$$Ca_3Al_2O_6 + 3CaSO_4 \cdot 2H_2O + 25\text{-}26H_2O = Ca_6Al_2O_6(SO_4)_3 \cdot 31\text{-}32H_2O$$

4.1.2.2.2 Cement for Other Uses

WBCSD (2009b) identified that around 5% of national cement production can be used for other benefits such as soil and pH stabilisation. However, MPA (2015a) reported that percent of cement for other uses in Great Britain is only 3%. Therefore, this thesis determined to use 3% of cement production for calculating cement for other uses in both countries.

4.1.2.2.3 Additives for the Cement Industry

This part concerns a ratio of cement additives (1.60 Mt) and domestic Portland cement in Great Britain (2012) from the previous calculating results (MPA, 2015c). The Great Britain ratio can be used to estimate the quantity of additives for Thai cement industry because of no recorded data.

4.1.2.2.4 Cements for Mortar

This calculation part used the proportion of mortar use in Great Britain (2.20 Mt) in 2012 from MPA (2014b) and fine aggregates for mortar (5.47 Mt) from BGS (2014c). It includes the reasons given below to calculate Thai cement volume for mortar as:

- Great Britain uses brick and block as a double layer for construction with an inside cavity (Mortar Industry Association, 2013),
- Great Britain uses 46% brick and 41% concrete and mortar by weight for residential building (Cuéllar-Franca and Azapagic, 2012),
- Three main Thai construction materials are 79.4% concrete by weight followed by 13% brick and 5.6% steel respectively (Kofoworola and Gheewala, 2008) and
- Thai C&D waste is 74.9–79.4% concrete by weight (PCD *et al.*, 2007).

Therefore, this thesis uses a half proportion of mortar use in Great Britain to calculate Thai figures for the quantity of cement and fine aggregate for mortar.

4.1.2.2.5 Quantity of Domestic Cement including Import and Export Cement

Actual import and export cement figures are used for this calculation part to compute domestic cement consumption in 2012; BGS (2014a) for Great Britain and Thailand from Office of Industrial Economics (2013). Then, these domestic cement figures in Great Britain and Thailand (2012) can be combined with the following methodology to estimate the annual concrete stock.

4.1.3 Step 2: Annual Concrete Stock Using Material Flow Analysis (MFA)

MFA is a systematic evaluating technique, identifying a pattern of material stocks and flows by setting boundaries of space and time. This methodology, therefore, uses the following mass balance principles.

Total inputs (Mt) = Total outputs (Mt) + Net accumulation (Mt)

Total inputs (Mt)	=	Domestic mineral extraction, other compositions, fuels imports and indirect flows
Total outputs (Mt)	=	Air emissions, waste, exports and indirect flows
Net accumulation (Mt)	=	Stock, recycling and output materials to economy

This calculation part illustrates the importance of national construction materials to national economies and well-being in 2012 of Great Britain and Thailand. It also determines the physical mechanism of national economic reasons, together with the management of natural resources and environment, to describe material flows using key mineral-based components in cement and concrete industries including aggregate markets and construction industries. Besides, national recorded data from both governments and manufacturers in 2012 were used to support the reliability of MFA.

This methodology combines the results of the above calcination calculation from both national cement industries (**Figure 4-2**) and the annual outcomes of the aggregate markets for concrete manufacturing. Concrete aggregates consist of primary and recycled concrete aggregates for Great Britain and only primary aggregate is used in the Thai concrete industry (**Figure 4-3**, **Figure 2-14** and **Figure 2-15**). Importantly, to estimate figures missing for Thailand, ratios of recorded data of primary and recycled concrete aggregates, used for the concrete industry in Great Britain were applied to calculate figures of coarse and fine primary concrete aggregates in Thailand. Then, it also clarifies domestic concrete in 2012 from both concrete industries (**Figure 4-4**) distributed to each construction sector using ratios of the construction activities.

Figure 4-3 Schematic representation of a primary aggregate market
Source: Taken from Lafarge (2015)

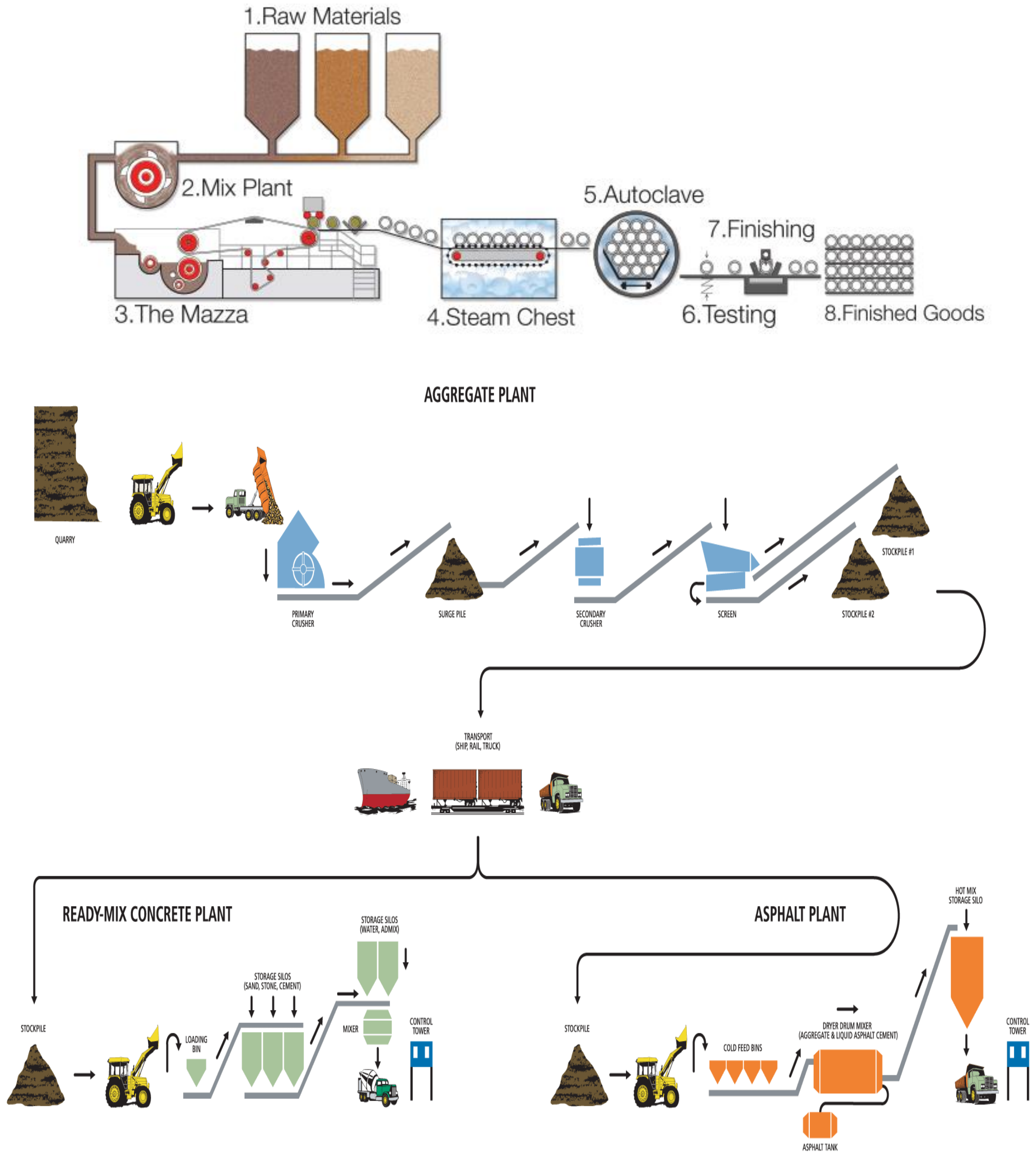


Figure 4-4 Schematic representation of concrete
Source: Taken from Python Group Mining Specialists (2010) and Vantage Pipes (2015)

Moreover, MFA results can compare problems of policy implementation of Great Britain and Thailand by indicating annual domestic concrete stocks of the whole nations, consisting of:

(1) Flows of raw minerals (limestone and shale), clinker, cement (for concrete, mortar and other uses) and additives including coarse and fine primary aggregates and coarse recycled concrete aggregate mainly used for making domestic concrete,
(2) Flows of import and export of clinker and cement,
(3) Waste and emission flows during manufacturing processes including CKD, CO_2, together with concrete waste during deliveries and construction, and
(4) Concrete consumption flows for the construction industry in single and multi-residential building as well as non-residential building and infrastructure.

Finally, all resulting figures are displayed as stocks and flows of construction materials including wastes and emissions in Great Britain and Thailand in 2012 by STAN 2.5 (Vienna University of Technology). All major steps and calculations are shown in **Appendix C**.

4.1.3.1 Aggregate Calculations

4.1.3.1.1 Primary Aggregates

Primary aggregates as fine aggregates (sand) and coarse aggregates (gravel and crushed rock) for construction are produced following the processes in **Figure 4-3**. The fine primary aggregates in Great Britain (2012) are produced mainly from mainland with 35% from marine dredged materials or 10,291,000 tonnes. For coarse aggregates, Great Britain used 20% gravel and 80% from crushed rock in 2012 (**Table 4-1**). These natural materials were used in several construction activities such as asphalt, road, mortar, concrete, fill and rail ballast. Then, primary aggregates together with recycled and secondary aggregates for both concrete and construction industries in Great Britain (2012) can be modeled and shown in **Figure 4-8** (MPA, 2013c; ONS, 2014d).

In Thailand, Great Britain proportions of the amount of coarse and fine primary aggregates, coarse recycled aggregates, cement for concrete, including fine primary aggregates and cement for mortar (**Table 4-1**) were compared with the amount of cement for Thai concrete and mortar. Then, they can be used to estimate the amount of coarse and fine primary aggregates that are used for the concrete industry and fine primary aggregates for mortar in Thailand (2012).

Table 4-1 Use of primary aggregates in Great Britain in 2012

Activities	Coarse aggregates (tonnes)			Fine aggregates (tonnes)
	Gravel	**Crushed Rock**	**Total Coarse Aggregates**	**Sand**
Asphalt (On site)	491,000	5,353,000	5,844,000	1,326,000
Asphalt (Off site)	-	5,814,500	5,814,500	
Uncoated road stone	-	16,001,000	16,001,000	-
Surface dressing chippings for road stone	-	1,391,000	1,391,000	-
Mortar	-	-	-	5,474,000
Concrete	12,592,000	15,744,000	28,336,000	19,697,000
Other screened and graded	5,480,000	12,572,000	18,052,000	-
Fill	2,492,500	-	2,492,500	2,492,500
Rail ballast	-	2,454,000	2,454,000	-
Other constructional uses	-	17,741,000	17,741,000	-
Armour stone & gabion	-	5,814,500	5,814,500	-
Total	**21,055,500**	**82,885,000**	**103,940,500**	**28,989,500**
Total Volume of Primary Aggregates			**132,930,000**	

Source: Author based on ONS (2014d)

4.1.3.1.2 Recycled Aggregates

The objective of this calculation part is to understand the pattern of recycled aggregates from the hard-inert component of construction, demolition and excavation waste (CD&E waste) generated in Great Britain. This study shows the quantity of recycled and secondary aggregates, based on the European Waste Catalogue (EWC) classifications of off-site waste management from waste treatment and transfer activities, recycled aggregate sites and landfills in Great Britain. Great Britain achieved the 70% target of reuse and recycling rate of C&D waste management of the EU, and the highest rate of use of recycled and secondary aggregates in the EU accounting for 29% of total aggregates in the 2012.

85% of recycled aggregates from C&D waste and 15% from other industrial and natural wastes classified as secondary aggregates were the proportions of recycled and secondary aggregates in 2005, according to DCLG (2007). Examples of secondary aggregates are: blast furnace slag, basic oxygen furnace steel slag, electric arc furnace steel slag, china clay waste, colliery spoils, power station pulverised fuel ash, power station furnace bottom ash, spent railway track ballast, slate waste, waste glass, municipal solid waste incinerator bottom ash, scrap tyres, fired ceramic waste, and spent foundry sand.

This study used multiple references from (1) volume of CD&E waste generation estimates in England (2008, Defra (2012a)), (2) CD&E waste arisings use and disposal for England 2008 including the quantity of recycled aggregates in England 2008 (WRAP, 2010) and (3) classification of CD&E waste from Chapter 17 of EWC classifications (EPA, 2002), to create a pattern of CD&E waste in England (2008, **Figure 4-9**). This research assumed that the 2012 recovery rates in each step of CD&E waste recycling in Great Britain were equal to the 2008 England rates. Then, these 2008 recovery rates from England can be used to model the amounts in a MFA diagram of recycled aggregates from the hard-inert CD&E waste in Great Britain (2012). As for off-site CD&E waste management, its processes consist of recycled aggregate activities of hard-inert CD&E waste, transferred from demolition sites to treatment and transfer facilities, recycled aggregate sites and landfills as seen in **Figure 2-14**.

The MFA diagram of recycled aggregates in Great Britain 2012 takes data from MPA (2013c). MPA reported that recycled and secondary aggregates in 2012 were 54 Mt, and 85% of recycled aggregates originated from hard-inert CD&E waste (DCLG, 2007). Besides, the estimated quantity of CD&E waste in Great Britain used the UK amount of CD&E waste that was 100 Mt in 2012 (Defra, 2015b), comparing to Great Britain population (97% of the UK population) (ONS, 2015d). Therefore, in 2012, Great Britain probably generated 97 Mt of CD&E waste. The final MFA results are shown in the other Sankey diagram to reflect the 2012 pattern of recycled aggregate activities in Great Britain (**Figure 2-14**).

4.1.3.2 Concrete Calculations

4.1.3.2.1 Concrete Ingredients

This calculation part used Great Britain recorded data of fine and coarse primary aggregates (ONS, 2014d) and cement for the concrete industry from the calcination calculation results including recycled aggregates used for the 2012 concrete industry (**Table 4-2**). Then, these figures were used to calculate and estimate the quantity of concrete used in Great Britain (2012). For Thailand, the volume of cement for concrete from annual cement product was combined with the amount of coarse and fine primary aggregates, calculated from ratios of primary and recycled aggregates including cement for the Great Britain concrete industry to be the estimated quantity of Thai concrete in 2012.

Table 4-2 Volume of recycled aggregate for concrete industry in Great Britain

Years	2008	2009	2010	2011	2012
Recycled aggregate for concrete industry (Mt)	5.3	3.9	5.8	5.3	5.0

Source: Author based on MPA (2013b)

4.1.3.2.2 Additives for Concrete

In addition to cement and aggregates, another important component in concrete is additives. From the MPA (2013a) data about dry concrete components (without 6.8% water), Great Britain used around 4.5% additives for producing concrete (**Table 4-3**). This figure is used to calculate the additive volume of both Great Britain and Thailand with the quantity of main concrete components from the previous calculating results.

Table 4-3 Concrete components in Great Britain

Components	Wet Components (%)	Dry Components (%)	
Cement or cement blends	8.9	9.55	9.55
Fly ash	0.7	0.75	
GGBS	3.2	3.43	4.51
Other additives e.g. slag, bottom ash	0.3	0.32	
Primary Aggregates	75.9	81.44	81.44
Secondary Aggregates	4.2	4.51	4.51
Water	6.8	-	-
Total	**100.0**	**100.00**	**100.00**

Source: Author based on MPA (2013a)

4.1.3.2.3 Concrete Waste during Deliveries

Typically, the amount of concrete waste generated by ready-mix deliveries can be reduced to as little as 0.4-0.5% of the total concrete production (WBCSD, 2009b). For precast concrete, WRAP (2008) reported that the production and use of this concrete type is resource efficient and can limit the generation of waste on site. Therefore, this study uses 0.5% waste generated during deliveries to calculate the amount of concrete waste during deliveries in both case studies.

4.1.3.2.4 Lime for Mortar Ingredients

The volume of cement for mortar can be used to estimate the other main component for producing mortar that is lime. This material helps the fresh mortar to retain water for combining with dry cement bricks and blocks, and to prevent cracking of the hardened mortar. The Cement & Concrete Institute (2009) states that there are two ratios of lime and mortar as class I (1 lime: 5 cement) and class II (1 lime: 2 cement). Thus, this study used an average ratio to calculate lime quantity for mortar as 1 lime: 3.5 cement.

4.1.3.3 Construction Calculations

4.1.3.3.1 Concrete and Mortar Waste during Construction

It was estimated that concrete and mortar lost during construction were around 5% (Building Research Establishment, 2002). However, a later study by the Building Research Establishment (2008) showed that construction activities had waste rates of both concrete and mortar higher than 5% depending on each site operation. This study, therefore, assumed 5% concrete and mortar as the minimum concrete waste generated during construction.

4.1.3.3.2 Concrete and Mortar for Construction

This study used main building types from initial values of new and repair/maintenance construction to calculate the volume of concrete and mortar in Great Britain (2012) as 37.01% residential building, 44.07% non-residential building and 18.92% infrastructure. Likewise, a proportion of new complete building for the 2012 housing was 68% houses and 32% flats. Thus, the residential sector in Great Britain (37.01%) was separated to be 25.17% single-residential building and 11.84% multi-residential building.

For Thailand, floor area in use of new and additional construction in 2012 was 41.90% single-residential building, 9.61% multi-residential building, 32.19% non-residential building and 16.30% infrastructure. In **Table 4-4**, ratios of Great Britian and Thai housing types were used to estimate quantity of concrete and mortar consumed in each construction sector in 2012. Finally, the annual concrete stocks in Great Britain and Thailand are presented in the results section in **Figure 4-11** and **Figure 4-12**.

Table 4-4 Great Britain and Thai housing types

Building Stock	Great Britain (Types, %)	Thailand (Types, %)
Residential building	37.01	51.51
Single-residential building	25.17	41.90
Multi-residential building	11.84	9.61
Non-residential building	44.07	32.19
Infrastructure	18.92	16.30
Total	**100.00**	**100.00**

Sources: DCLG (2014); ONS (2013b) and National Statistical Office (2013a)

4.1.4 Step 3: Future Concrete Stock Using Stock Dynamic Analysis (SDA)

4.1.4.1 Methodological Overview

Over the past decades, the intensity of use for construction materials in the UK has experienced cyclical fluctuations. It has presently changed little, mainly driven by inter-sectoral shifts in the national economy, and nearly 90% of the output from the UK construction sector is used in the service sector (Moore *et al.*, 1996). All construction materials come from natural resources. As shown in **Figure 4-5**, research concepts of this part of the thesis indicate that natural resources are demanded for construction especially for the housing sector in urban areas, and can be estimated from the increase in national population and its lifestyle. Thus, this study uses GDP to demonstrate the national lifestyle since GDP is a monetary measure of the national value of final goods and services produced in some period (such as quarterly or yearly). Furthermore, several issues can affect GDP directly/indirectly to the construction industry such as natural disasters, political stability, financial crisis and inflation.

Due to the logical coherence of the national economy and construction activities, not only is GDP commonly used to determine the national economic performance and to comprehend international comparisons but it can also reflect the growth in construction particularly in the housing sector. In this study, demand for housing construction increased by higher GDP is measured by more demand in floor area in use (FAU) which requires more supply or concrete in use (CU) which is measured by concrete 'density' as the main material for present housing construction. The amount of future concrete demand is estimated by future FAU input and concrete density. It also includes the future expectation of demolishing FAU and concrete waste prediction from future FAU, concrete density and residential lifetime. During the use of housing, some more reasons can extend its lifespan before demolishing and changing to be waste, such as renovation activities and a good building quality in the construction stage.

4.1.4.2 Overview of Lifetime Distribution and Forecasting Future Scenarios

Lifetime distribution is used to predict the future concrete demand and waste. This research uses the normal lifetime distribution to predict housing lifespan in both Great Britain and Thailand. Great Britain housing has a longer lifetime than Thailand. As seen, regarding UK building lifespan, half of its residential buildings have a lifespan more than 50 years and a fifth is more than 100 years old with a small proportion of new dwellings built after 2000 (7%, the ENTRANZE Project (2008c); The Chartered Institute of Building (2013)).

For forecasting future scenarios, Sartori *et al.* (2008) suggested to use a final value in the last year of ±15% prediction comparing to the medium scenario. This study used both national recorded data and results of 'what-if analysis' to predict future trends for national housing sectors such as persons per dwelling, as Suh (2009) suggested that what-if analysis can be applied to a variety of future scales.

Moreover, to improve uncertain predictions, Wang *et al.* (2015) investigated them by means of Monte Carlo methods and sampling analysis. Then, Fishman *et al.* (2016) introduced a national typology for accumulating stock trajectories using Autoregressive Integrated Moving Average (ARIMA) to inspect and forecast time series for explaining dynamics of national material stocks in Japan and the US. Its results can create scenarios for future demand and accumulation of building materials in societies, including uncertainty estimates.

4.1.4.3 Stock Dynamics Model

Following the conceptual model of Müller (2006), research concepts are shown in **Figure 4-5**, in which processes are presented in rectangles and hexagons show drivers and determinants. Moreover, the relationship between variables is shown by dashed lines. There are three main stocks in this study: population, FAU and CU, representing by P, F and C respectively. Furthermore, dP/dt, dF/dt and dC/dt are the net accumulation of three main stocks. The input flows to stocks are P_{in}/dt, F_{in}/dt and C_{in}/dt, while P_{out}/dt, F_{out}/dt and C_{out}/dt are output flows of stocks.

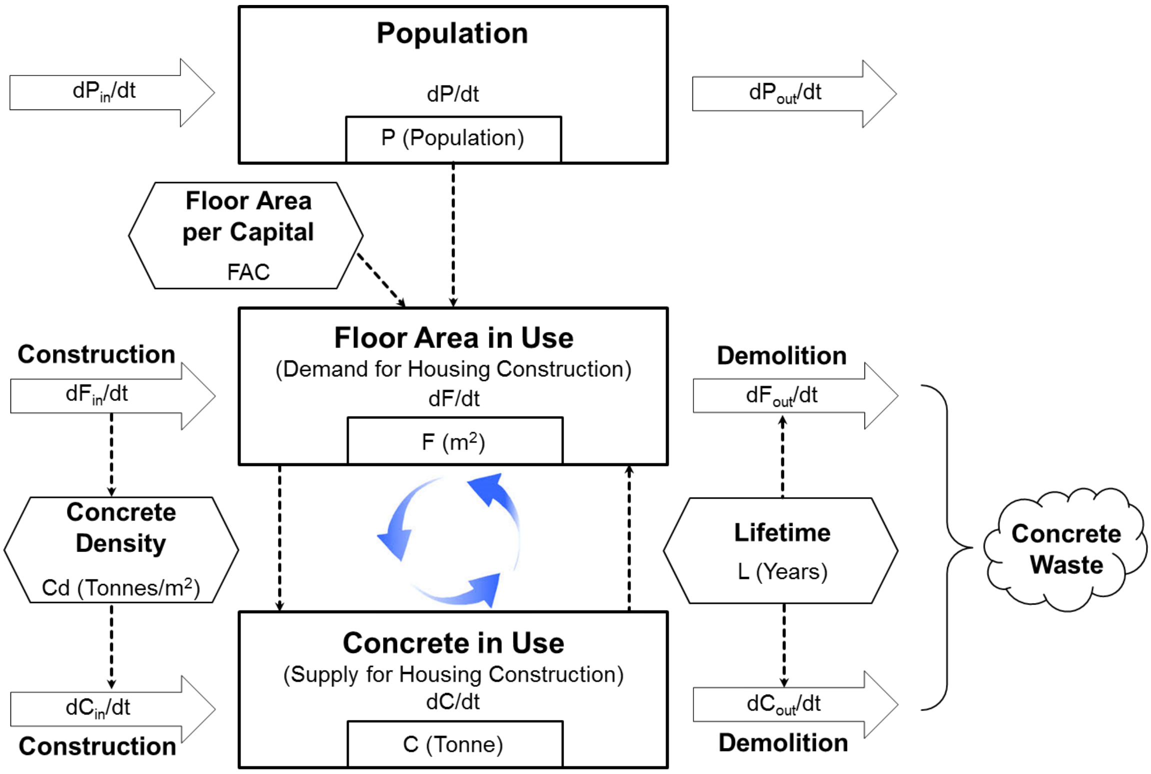


Figure 4-5 Research concepts
Source: Modified from Müller (2006)

The increase in floor area per capita (FAC) relating to increasing GDP can convey the population demand for housing and their lifestyle. Using equation 1 (Eq.1) can answer the annual demand of floor area stock. After construction, housing stock is demolished following its lifespan. This study used a normal lifetime distribution by the NORMDIST function in Excel (Eq.2). This function used τ as an average housing lifespan with σ for the standard deviation. For Great Britain, values of τ are 75, 100 and 125 years, and τ = 25 and 50 years for Thailand (Sartori *et al.*, 2008; Hu *et al.*, 2010c). For the NORMDIST standard deviation, all scenarios are assumed σ = 0.25τ (Sartori *et al.*, 2008).

$$F(t) = P(t) \times FAC(t) \tag{1}$$

$$L = 1 - NORMDIST\ (x, \tau, \sigma, cumulative) \tag{2}$$

x = value for which you want the distribution

τ = arithmetic mean of the distribution

σ = standard deviation of the distribution

Cumulative = a logical value that determines the form of the function. If cumulative is TRUE: 1, NORMDIST returns the cumulative distribution function; if FALSE: 0, it returns the probability mass function

Then, an output of floor area stock is demolished at time t (Eq.3). Demolition of the initial stock equals to F_0(t)/100 in the previous 100 years (1800-1900) for calculating the initial stock of floor area in use by the lifetime profile. This calculation for demolition activities is used with the mathematical convolution concept to support the demolition profile. A mathematical operator of convolution is shown between f and g functions. There is a calculation by expressing the amount of overlapping one function as it is shifted over the other. The convolution of f and g over a time period (t_0, t) is formally written as Eq.4 (Sartori *et al.*, 2008). Then, balancing of floor area input and output (F_{in}/dt and F_{out}/dt) can present the demolition activities at that time (Eq.5).

$$\frac{F_{out}(t)}{dt} = F_0(t) + \int_{t_0}^{t} L(t,t') \times \frac{F_{in}(t')}{dt} dt' \qquad (3)$$

$$f \times g = \int_{t_0}^{t} f(t') \times g(t-t') dt' (Convolution) \qquad (4)$$

$$\frac{dF(t)}{dt} = \frac{F_{in}(t)}{dt} - \frac{F_{out}(t)}{dt} \qquad (5)$$

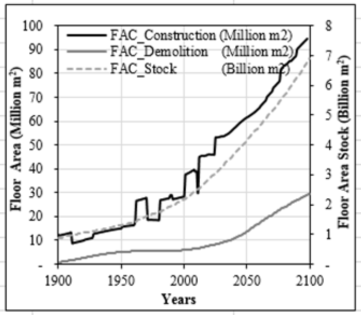
For the calculation of the floor area in use, it should be concerned with the previous data before 1900, but there is no need to involve the previous 1900 data in the calculation of concrete demand. This is because the Thai cement industry was set up in 1913 (SCG Cement Public Co. Ltd., 2014) and a great deal of the use of cement in European countries is from the Second World War (1939 – 1945) onwards ((Kurdowski, 2014), although cement was invented in 1824 in England (Manning, 1995; Domone and Illston, 2010). Concrete density (Cd, tonnes/m^2) is used to predict concrete demand for new floor area in use in the construction stage mostly (Eq.5). In addition, it can illustrate the future quantity of concrete waste by considering housing lifespan, as in Eq. 6, Eq. 7 and Eq. 8.

$$\frac{C_{in}(t)}{dt} = \frac{F_{in}(t)}{dt} \times Cd(t) \qquad (6)$$

$$\frac{C_{out}(t)}{dt} = \int_{t_0}^{t} L(t,t') \times \frac{C_{in}(t')}{dt} dt' \qquad (7)$$

$$\frac{dC(t)}{dt} = \frac{C_{in}(t)}{dt} - \frac{C_{out}(t)}{dt} \tag{8}$$

To sum up, SDA calculations mainly used a structure of the NORMDIST functions for lifetime distribution to understand future demolition activities calculated by Excel spreadsheet. All these details can be separated into two main parts as (1) floor area in use and floor area for demolition and (2) concrete in use and concrete waste. **Figure 4-6** and **Figure 4-7** are examples of the general structure of spreadsheet files for both future calculating parts. All details can be seen in the CD-ROM file named ‘SDA calculating results’.



Lifetime Profile

Mean	Standard Deviation	Cumulative
75	18.75	1

Demolition Profile

Mean	Standard Deviation	Cumulative
75	18.75	0

Eq.1 Eq.5 Eq.3 F0(t)/100 Eq.2

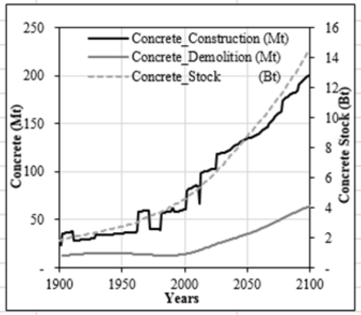
NORMDIST Columns
1 fiscal year, 200 years, 1900-2100

Raw Data Rows
1 fiscal year, 200 years, 1900-2100

Years	Population	FAC (m²)	FAC_Stock (Billion m²)	FAC_Change (Million m²)	FAC_Construction (Million m²)	FAC_Demolition (Million m²)	1900 1	1901 2	1902 3	1903 4
1900	36,602,761.20	23.50	860,164,888.20			8,601,648.88	8,601,308.06	8,600,882.82	8,600,353.72	8,599,697.16
1901	36,999,943.00	23.55	871,480,800.30	11,315,912.10	12,192,766.19	876,854.09	11,315,812.27	8,601,214.53	8,600,767.88	8,600,212.86
1902	37,383,087.90	23.61	882,507,896.50	11,027,096.19	11,973,319.12	946,222.92	11,026,998.91	11,315,689.22	8,601,099.58	8,600,627.01
1903	37,766,232.80	23.66	893,576,043.93	11,068,147.43	12,087,017.63	1,018,870.20	11,068,049.78	11,026,879.00	11,315,538.00	8,600,958.71
1904	38,149,377.70	23.71	904,685,242.60	11,109,198.67	12,203,944.65	1,094,745.98	11,109,100.66	11,067,929.43	11,026,731.64	11,315,352.67
1905	38,532,522.60	23.77	915,835,492.51	11,150,249.91	12,324,027.75	1,173,777.84	11,150,151.54	11,108,979.86	11,067,781.52	11,026,551.04
			927,026,793.66	11,191,301.15	12,447,174.99	1,255,873.84	11,191,202.42	11,150,030.29	11,108,831.40	11,067,600.25
			938,259,146.05	11,232,352.39	12,573,275.17	1,340,922.78	11,232,253.29	11,191,080.73	11,149,881.28	11,108,649.46
			949,532,549.68	11,273,403.63	12,710,724.00	1,437,320.37	11,273,402.63	Eq.4	11,191,079.73	11,149,880.28
[illegible]	[illegible]	[illegible]	960,847,004.55	11,314,454.87	12,848,172.83	1,533,717.96	11,314,355.05		11,232,102.18	11,190,896.43
1910	40,448,247.10	24.04	972,202,510.65	11,355,506.11	12,982,834.65	1,627,328.54	11,355,405.92	11,314,232.02	11,273,129.39	11,231,918.22
1911	40,831,392.00	24.09	983,599,068.00	11,396,557.35	13,119,806.56	1,723,249.21	11,396,456.80	11,355,282.45	11,314,080.81	11,272,944.75
1912	41,025,172.70	24.14	990,464,883.76	6,865,815.76	8,687,097.11	1,821,281.36	6,865,755.18	11,396,332.88	11,355,130.69	11,313,895.51
1913	41,218,953.40	24.20	997,351,461.73	6,886,577.98	8,807,741.86	1,921,163.89	6,886,517.22	6,865,680.53	11,396,180.58	11,354,944.72
1914	41,412,734.10	24.25	1,004,258,801.93	6,907,340.19	8,930,052.80	2,022,712.61	6,907,279.25	6,886,442.34	6,865,588.77	11,395,993.93
1915	41,606,514.80	24.30	1,011,186,904.34	6,928,102.41	9,053,796.17	2,125,693.75	6,928,041.29	6,907,204.15	6,886,350.30	6,865,476.33

Floor Area 75 LTD | Concrete 75 LTD | NORMDIST_GB | NORMDIST_TH

Figure 4-6 Example of SDA calculations of floor area in use and floor area for demolition
Sources: Author



Lifetime Profile

Mean	Standard Deviation	Cumulative
75	18.75	1

Demolition Profile

Mean	Standard Deviation	Cumulative
75	18.75	0

Eq.6 **Eq.8** **Eq.7**

NORMDIST Columns
1 fiscal year, 200 years, 1900-2100

Raw Data Rows
1 fiscal year, 200 years, 1900-2100

Eq.4

Years	Floor Area Stocks (Billion m^2)	Concrete Intensity (t/m^2)	Concrete_Stock (Bt)	Concrete_Change (Mt)	Concrete_Construction (Mt)	Concrete_Demolition (Mt)	1900 1	1901 2	1902 3	1903 4
1900	860,164,888.20	2.10	1,806,346,265.22							
1901	871,480,800.30	2.10	1,830,109,680.64	23,763,415.42	23,763,415.42		23,762,473.83	23,762,240.60	23,761,953.56	23,761,601.30
1902	882,507,896.50	2.10	1,853,266,582.64	23,156,902.00	35,394,996.82	12,238,094.82	23,156,697.71	23,762,215.44	23,761,923.04	23,761,564.38
1903	893,576,043.93	2.10	1,876,509,692.25	23,243,109.61	35,650,189.85	12,407,080.24	23,242,904.55	23,156,445.91	23,761,897.88	23,761,533.86
1904	904,685,242.60	2.10	1,899,839,009.46	23,329,317.21	35,898,823.40	12,569,506.19	23,329,111.39	23,242,651.81	23,156,136.44	23,761,508.70
1905	915,835,492.51	2.10	1,923,254,534.27	23,415,524.81	36,140,883.36	12,725,358.55	23,415,318.23	23,328,857.71	23,242,341.19	23,155,757.18
[illegible]	[illegible]	[illegible]	1,946,756,266.69	23,501,732.42	36,376,379.09	12,874,646.67	23,501,525.07	23,415,063.62	23,328,545.94	23,241,960.52
[illegible]	[illegible]	[illegible]	1,970,344,206.71	23,587,940.02	36,605,342.21	13,017,402.20	23,587,731.92	23,501,269.52	23,414,750.70	23,328,163.86
[illegible]	[illegible]	[illegible]	1,994,018,354.33	23,674,147.62	36,926,098.14	13,251,950.52	23,674,146.62	[illegible]	23,501,268.52	23,414,749.70
[illegible]	[illegible]	[illegible]	2,017,778,709.55	23,760,355.22	37,246,854.07	13,486,498.85	23,760,145.60	[illegible]	23,587,415.69	23,500,883.61
1910	972,202,510.65	2.10	2,041,625,272.37	23,846,562.83	37,455,393.86	13,608,831.04	23,846,352.44	23,759,887.24	23,673,572.81	23,587,029.36
1911	983,599,068.00	2.10	2,065,558,042.80	23,932,770.43	37,657,401.34	13,724,630.92	23,932,559.28	23,846,093.14	23,759,569.71	23,673,185.08
1912	990,464,883.76	2.10	2,079,976,255.89	14,418,213.09	28,252,244.15	13,834,031.06	14,418,085.89	23,932,299.05	23,845,774.46	23,759,180.56
1913	997,351,461.73	2.10	2,094,438,069.64	14,461,813.75	28,398,888.65	13,937,074.90	14,461,686.16	14,417,929.11	23,931,979.21	23,845,383.91
1914	1,004,258,801.93	2.10	2,108,943,484.04	14,505,414.41	28,539,418.27	14,034,003.87	14,505,286.43	14,461,528.91	14,417,736.42	23,931,587.25
1915	1,011,186,904.34	2.10	2,123,492,499.11	14,549,015.06	28,674,001.35	14,124,986.29	14,548,886.71	14,505,128.71	14,461,335.64	14,417,500.29

Floor Area 75 LTD | Concrete 75 LTD | NORMDIST_GB | NORMDIST_TH

Figure 4-7 Example of SDA calculations of concrete in use and concrete waste
Sources: Author

4.2 Results

4.2.1 National Cement Production

This calculation part considers both clinker and cement manufacturing. All calculation results are cross-checked with other trustworthy references to confirm the reliability of figures for the national cement industries. Then, the results are combined with other concrete components, such as concrete aggregates and additives, and outputs including concrete waste from deliveries and during construction, to generate annual concrete stocks using MFA.

4.2.1.1 Clinker Manufacturing

In global clinker manufacturing, controlled proportions are 75-85% for limestone or similar rocks such as cement rock, marble and chalk, and 15-25% of clay or shale (Manning, 1995; Van Oss and Padovani, 2002; Low, 2005; Domone and Illston, 2010). Moreover, to produce clinker it may be necessary to add other minerals such as sand or iron oxide (Domone and Illston, 2010). The principal chemical components of clinker are 65% calcium oxide (CaO) and 22% silicon dioxide (SiO_2), with smaller amounts of aluminium oxide (6% Al_2O_3) and iron oxide (3% Fe_2O_3). CaO is derived mainly from limestone (or chalk), and shale is the dominant source of SiO_2 and Al_2O_3 (Manning, 1995).

Generally, clinker minerals and other raw materials in the cement industry can be categorized into three main groups: (1) mined or non-fuel materials: limestone, clay, shale, sandstone and iron ore (2) fuels: conventional fuels as natural gas, coal and coke, and alternative fuels as tires, sludge wastes and liquid wastes, and (3) additives: e.g. slags, fly ash and bottom ash (Van Oss and Padovani, 2002; Petavratrzi and Barton, 2007).

This study used the actual amount of clinker in 2012 as a beginning of the calculations in both Great Britain and Thailand. The results indicated that both national cement industries consume approximately 1.65 tonnes of main minerals (1.24 tonnes from limestone and 0.41 tonnes of shale) to produce a tonne of clinker. These results are similar to the study of Van Oss (2005) who reported that a total of non-fuel raw materials of about 1.7 tonnes are required to make a tonne of clinker and about 1.5 tonnes of this come from limestone or similar calcareous rocks. Thus, for 2012 clinker manufacturing, Great Britain and Thailand used approximately 10.85 Mt and 65.39 Mt respectively of mined raw material; Thailand used more than six times as much of the main raw materials than Great Britain.

4.2.1.1.1 Traded Clinker

For import and export of clinker in 2012, Great Britain had less volume of import (0.21 Mt) and export (0.03 Mt). Thailand imported around 0.37 Mt clinker and exported it as one of the important export products, at around 7.22 Mt or 18.26% of production (39.55 Mt). Thus, the amount of domestic clinker used for manufacturing cement in Great Britain and Thailand (2012) was 6.74 and 32.70 Mt respectively.

4.2.1.1.2 Conventional and Alternative Fuels

A variety of conventional and alternative fuels are used to heat and maintain the temperature inside the kiln. Examples of these fuels are (1) conventional fuels – natural gas, coal, coke and oil which provide typical calorific value of 28.30 MJ/kg and (2) alternative fuels – tires, sludge wastes and liquid wastes with typical calorific value 18.20 MJ/kg (Lemieux *et al.*, 2004; Hiromi Ariyaratne *et al.*, 2013). Following the global concerns in natural resources and environment presently, The European Cement Association (2013) stated that using alternative fuels gives more benefits to resource efficiency consumption and security supply.

The ratio of conventional and alternative fuels used in both countries (2012) were 60% conventional fuels and 40% alternative fuels (Ministry of Natural Resources and Environment, 2006; MPA, 2013c). For cement manufacturing types, Thailand presently uses only the dry process in all cement plants (TFCM, 2015). In contrast, Great Britain uses the dry process for 78% of total clinker capacity and the remaining 22% still operates by semi-dry and semi-wet processes (BGS, 2014b). The dry process requires lower heat for calcination and combustion in the cement kiln than other cement processes. Lemieux *et al.* (2004) estimated that one-tonne clinker, depending on the conditions of clinker processes, requires specific heat capacity between 3.2-5 MJ/kg.

The results show that Great Britain used 0.62 Mt of conventional fuels and 0.41 Mt alternative fuels for 2012 clinker manufacturing. Thailand used a higher amount of fuels than Great Britain, because of a greater quantity of cementitious products, as 3.29 Mt conventional fuels and 2.19 Mt alternative fuels. Lastly, this study showed that for all fuels Great Britain used around 0.16 tonnes for one tonne of clinker manufacture.

Due to operating only the dry clinker process, the Thai cement industry used 0.14 tonnes of all fuels for producing a tonne of clinker. Thus, overall, Thailand requires a lower quantity of heat and fuel for clinker manufacturing than Great Britain because of using only the dry process. Additionally, it relates to the study of Van Oss and Padovani (2003), who stated that the average amount of fuels for making clinker is around 0.2 tonnes.

4.2.1.1.3 Fuel Ash

This study assumed that 0.1% of the amount of conventional and alternative fuels is changed to be fuel ash (Hiromi Ariyaratne *et al.*, 2013). This contributes to produce cement as it is combined with clinker in the kiln. In 2012, Great Britain is estimated to have fuel ash from clinker manufacturing around 0.1 Mt, and 0.55 Mt for Thailand.

4.2.1.1.4 Pollution

1) Cement Kiln Dust (CKD)

The results showed that Great Britain possibly had around 0.44 Mt CKD waste in 2012, and 2.64 Mt for Thailand, required proper disposal. As a manufacturing inefficiency, this dust causes higher consumption of minerals and fuels for calcination and combustion processes due to its loss during the process. In addition, using more fuels and raw materials is the main cause of the increasing CO_2 emissions from the cement industry. Thus, reducing CKD by higher recovery techniques and more equipment should be concerned to conserve raw clinker minerals and fuels, and to reduce CO_2 emission especially in Thailand, which produces more cementitious materials annually.

2) Carbon Dioxide (CO_2)

The verification of Van Oss (2005) for a total of CO_2 per one-tonne clinker was about 0.94 tonnes. As seen in **Figure 2-2**, most of the CO_2 emission unavoidably released from the cement making process is 55-60% from its limestone supply, because of the calcination process, and 30-35% CO_2 originates from natural and alternative fuels used in the combustion process. It also includes indirect emissions of CO_2 from electricity supply (5-10%) and transportation (5%, Sjunnesson (2005); WBCSD (2009a) and MPA (2013d)). This study focussed mainly on only CO_2 emissions from the calcination and combustion processes of the clinker manufacturing as these are the dominant sources of CO_2 release.

In 2012, it can be estimated that Great Britain had CO_2 emissions from clinker manufacturing around 4.88 Mt, while, Thailand had CO_2 emissions greater than Great Britain by around 5.88 times or 28.68 Mt. This study is concerned with only the CO_2 emission from the calcination process of mineral supplies and the combustion process from alternative and conventional fuels. It can be estimated that around 0.74 tonnes of CO_2 emissions came from one tonne of clinker production in Great Britain and 0.73 tonnes from the Thai cement industry. These similar figures are due to the dry process that causes the amount of CO_2 released per tonne clinker in Thailand to be a little bit lower than Great Britain.

4.2.1.2 Cement Manufacturing

4.2.1.2.1 Cement Types

1) Portland Cement

After the clinker cools down, to make Portland cement it needs to be blended with gypsum (and other additives) depending on each cement type and then ground to become a fine powder. As widely known, Portland cement contains 95% clinker and 5% gypsum (Worrell *et al.*, 2001). The results showed that Great Britain and Thailand produced 7.09 Mt and 34.42 Mt Portland cement respectively, with the addition of around 0.35 Mt and 1.72 Mt gypsum for Great Britain and Thailand respectively. All in all, Thailand produced 4.85 times more Portland cement than Great Britain in 2012.

2) Additives

Alternative raw materials obtaining from recycled materials such as filler, blast furnace slag and fly ash, can be used as controlled cement additives. Adding these materials to cement can make ‘low CO_2‘ cement, by reduction of raw material extraction and potentially diverting waste from the waste stream. These alternative raw materials provide cement products with various unique properties such as improved strength, setting time, workability, durability and colour (WBCSD, 2009b). Moreover, they can be added at the last step of both cement and concrete manufacturing (WBCSD, 2009b). To sum up, these materials can be used as non-fuel replacements in clinker recipes, or can substitute conventional fuels (hence are called alternative fuels), but also can be additives in the final stages of cement and concrete manufacturing processes (Petavratrzi and Barton, 2007).

In 2012, MPA (2015b), reported that Great Britain used approximately 1.6 Mt additives for cement production (including 0.35 Mt gypsum) and the trend of annual additive use relates directly to the annual quantity of cement product. Using Great Britain's additive ratio, Thai cement manufacturing is estimated to use around 7.54 Mt additives (including 1.72 Mt gypsum) for other cement types in 2012. Besides, the average clinker to cement ratio of all cement types among the EU-27 is 73.7% (The European Cement Association, 2013). This association also estimated that the clinker to cement ratio (which reflects the amount of additives) of the EU can be reduced to 70%, saving a further 4% CO_2. From this study, clinker to cement ratio in both countries is 78%. Therefore, CO_2 from cement manufacturing can be reduced if both government and cement industry develop some appropriate approaches such as producing low CO_2 cement by adding some controlled additives and reducing CKD from clinker manufacturing processes.

4.2.1.2.2 Cement Uses

1) Cement for Other Uses

Not only is cement used as a binding agent in concrete, but it is also used for other benefits such as soil and pH stabilisation (around 3-5% of cement production; WBCSD (2009b) and MPA (2015a)). The calculated results indicate that Great Britain used around 0.21 Mt cement for other used (3% following the MPA data) in 2012, while in Thailand 1.03 Mt cement were used for other requirements and were not transferred to concrete industry.

2) Cement for Mortar

A small part of cement production is used for mortar. MPA (2014b) reported that Great Britain used 2.2 Mt cement for mortar in 2012, and the estimated calculation of lime used as a mortar component was 0.63 Mt. This study used a factor of 0.5 of Great Britain figure to calculate the Thai use of cement for mortar. This is because Great Britain used 41% concrete and mortar and 46% brick by weight for residential building (Cuéllar-Franca and Azapagic, 2012) and 96% of the bricks in the UK are produced from clay and need a mortar cement as a binding agent (Mortar Industry Association, 2013). Moreover, due to the cold weather conditions, the majority of construction of UK residential buildings has masonry or brickwork cavity wall with a double masonry layer and an inside cavity (Mortar Industry Association, 2013).

Thailand used concrete as the main construction material (around 80% by weight), and around 80% of demolition waste by weight in the residential building was concrete (PCD *et al.*, 2007;

Kofoworola and Gheewala, 2008). Therefore, Great Britain has more requirement of mortar cement for binding brickwork than Thailand by around two times. Based on this reasoning, the estimated volume of cement for mortar in Thailand (2012) was 3.88 Mt. This volume included 1.11 Mt from lime as another mortar component.

3) Cement for Concrete

Domestic cement for concrete as the main consumption in Great Britain was around 7.43 Mt, and 30.07 Mt for Thailand. All in all, Thailand had greater quantity and requirement of domestic cement consumption by around 4 times that of the concrete industry of Great Britain.

4.2.1.2.3 Trading Cement

A pattern of cement trade in Great Britain (2012) is that import (1.46 Mt) is greater than export (0.31 Mt, BGS (2014a)). Conversely, Thailand imported small amounts of premium grade cement (about 0.02 Mt in 2012) and exported more Portland cement: around 7.00 Mt or 16.68% of its cement product (Office of Industrial Economics, 2013), similar to the amount of Thai clinker exports (7.22 Mt). Thailand exported in 2012 the same quantity of domestic cement as consumption for the whole Great Britain (7.43 Mt), or it can be stated that all cementitious exported products were two times the amount of cement used for making annual concrete stock in Great Britain.

4.2.2 Annual Concrete Stock from Material Flow Analysis (MFA)

The above calculations for the national cement industries are combined with concrete aggregates from the aggregate markets to make the complete MFA diagrams of annual concrete stocks for Great Britain and Thailand in 2012.

Great Britain has the proper management of C&D waste under current EU strategies. This country achieved the 70% target for reuse and recycling rate of C&D waste (Monier *et al.*, 2011; Defra, 2015a) and the highest rate of use of recycled and secondary aggregates, accounting for 29% of the 2012 total aggregates (The European Environment Agency, 2008; The Concrete Centre, 2009; MPA, 2013c).

Therefore, this MFA part also illustrates and emphasises the whole aggregate market in both primary and recycled aggregates used in each construction type and the recycled aggregates activities of off-site operations in Great Britain. Then, all final outcomes are presented by using Sankey diagrams.

4.2.2.1 Aggregate Market

1) Primary Aggregates

Primary aggregates for the concrete industry are fine aggregates (sand) and coarse aggregates (gravel and crushed rock). These materials are used for many activities in Great Britain such as asphalt, uncoated road stone, surface dressing chippings for road stone, mortar, concrete, other screened and graded, fill, rail ballast, armour stone and gabions, together with other minor construction uses. As seen, these aggregates are used mainly in the concrete industry (36.14%). Therefore, there is a strong emphasis for Great Britain to reduce primary aggregates use for the concrete industry.

The Great Britain aggregate market also includes an amount of recycled and secondary aggregates. In 2012, MPA (2013c) reported that 54 Mt of recycled and secondary aggregates were consumed in both concrete and construction industries and 5 Mt of that were used in the concrete industry (MPA, 2013b). **Figure 4-8** summarises the amount of primary aggregate including recycled and secondary aggregates utilised for each construction activity in Great Britain (2012), with a thin line and italic font as recorded data, and a bold font representing the calculated figures (MPA, 2013c; ONS, 2014d). More details of the recycled activities of reused concrete aggregates from the hard-inert C&D waste in Great Britiain (2012) will be explicitly discussed in the next section.

For the concrete industry, ONS (2014d) reported that in 2012 Great Britain consumed 19.70 Mt fine primary aggregates and 28.34 Mt coarse primary aggregates, including 5.47 Mt of fine primary aggregates for mortar in 2012. Conversely, Thailand has no report of annual aggregate uses. This study, therefore, used proportions of coarse and fine primary aggregate (including coarse recycled aggregates) from Great Britain's concrete industry with the quantity of cement for concrete in Thailand to predict coarse and fine primary aggregates consumed for the 2012 Thai concrete industry.

For the Thai concrete industry, it used the Great Britain proportions as 7.43 Mt cement: 19.70 Mt fine primary aggregates: 28.34 Mt coarse primary aggregates, plus 5 Mt coarse recycled aggregates (MPA, 2013b; ONS, 2014d). This led to estimates that Thailand used 79.73 Mt fine primary aggregates and 134.93 Mt of coarse primary aggregates for making the Thai concrete stock in 2012. For mortar, following a half ratio of Great Britain: 2.20 Mt mortar cement: 5.47 Mt fine primary aggregates and cement for mortar in Thailand due to reasons described in Chapter 3 (3.2.2.4), the result illustrated that Thailand used around 9.65 Mt fine primary aggregates for mortar.

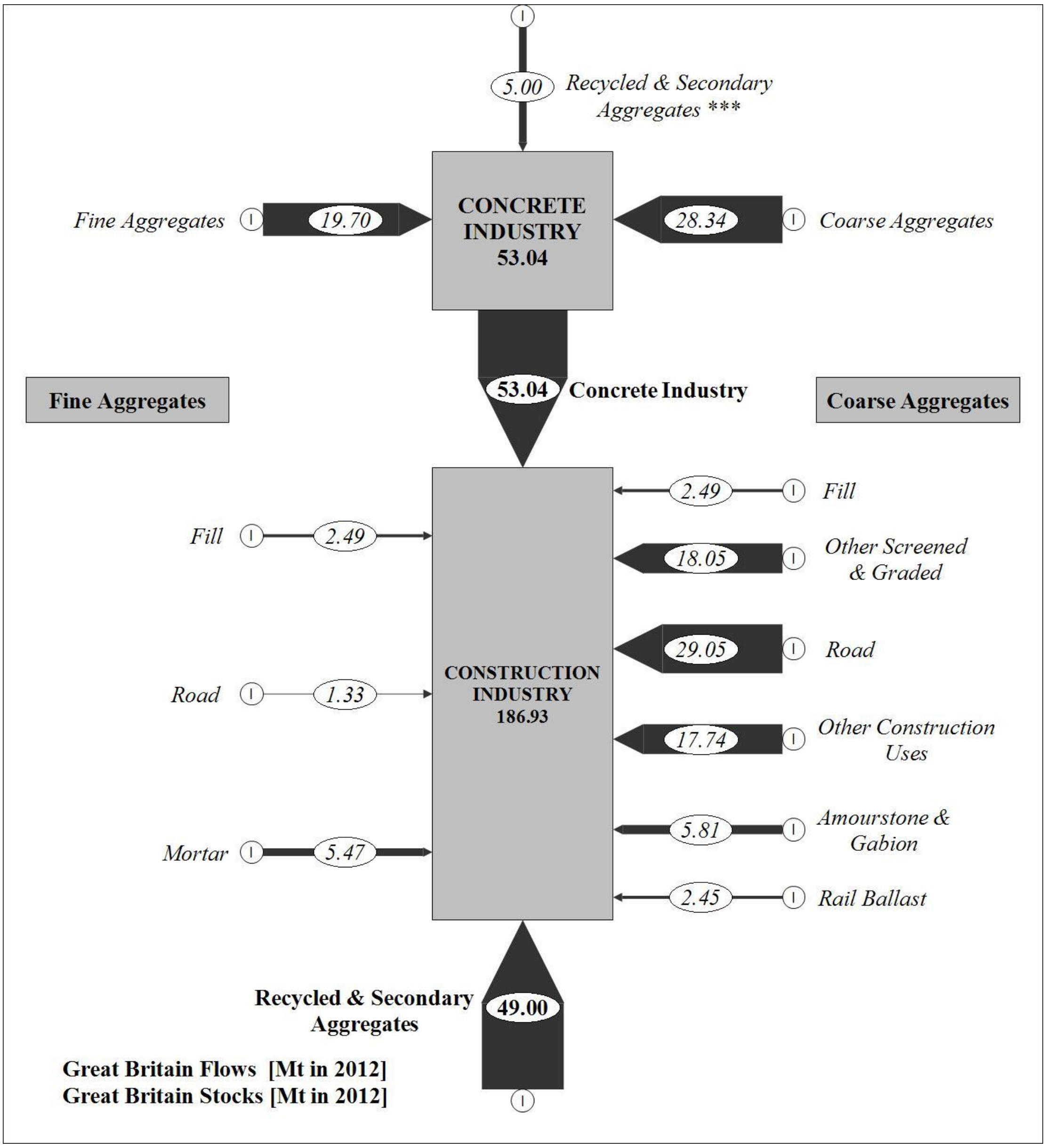


Figure 4-8 Schematic summary of the aggregate market in Great Britain (2012)
Sources: Author based on MPA (2013c) and ONS (2014d)
Note: A thin and italic font means recorded data, a bold font means calculated data

2) Recycled Aggregates

Coarse primary aggregates can be replaced by the appropriate quantity of recycled aggregates in the new concrete. Besides, these reused aggregates should have very little adhered mortar as this may disturb requirements for the absorption capacity, humidity level, chemical and mineral admixtures for the proper concrete specification (Etxeberria *et al.*, 2007; Garber *et al.*, 2011). For fine recycled aggregates, some researchers suggested that these aggregates are not typically used for new concrete mixtures, because they may be contaminated with greater proportions of adhered mortar, causing increased water demand and shrinkage, together with reduced strength and workability (Chisholm *et al.*, 2011; Garber *et al.*, 2011; Va´zquez, 2013). However, these fine recycled aggregates can be used as a raw material for cement manufacture, in certain cement admixtures, or as a soil stabiliser (Shima *et al.*, 2005).

Some UK studies suggested that 20-30% replacement of coarse primary aggregate by coarse recycled aggregates from C&D waste can be used in new concrete (WRAP, 2007). Moreover, a new standard of aggregates for concrete with particle densities greater than 1,500 kilograms per cubic metre (kg/m^3), named BS EN 12620:2013 Aggregates for Concrete, was revised and then proclaimed in 2013. This standard also gives the guidance on coarse recycled aggregates such as (1) classification of the constituents of coarse recycled aggregates, (2) water soluble sulfate content of recycled aggregates, (3) chlorides in recycled aggregates and (4) alkali-silica reaction with recycled aggregates (British Standards Institution, 2013). However, quality concerns require more elaborate recovery processes and equipment than primary aggregates, meaning that recycled aggregates are less attractive to contractors due to their increased production cost (Garber *et al.*, 2011).

In 2008 (the closest data to 2012), CD&E waste generated in England was estimated at 94.55 Mt (Defra, 2012a). This figure was combined with the volume of recycled aggregates in England (2008, 43.52 Mt) and the amount of each type of CD&E waste from off-site operations of recycled activities in England (2008, WRAP (2010)). Moreover, the amount of each CD&E waste type from treatment and transfer facilities, recycled aggregate sites and landfill in England (2008) was identified by the EWC waste classification as ‘chapter 17 C&D wastes’ (including excavated soil from contaminated sites, EPA (2002); WRAP (2010)). Finally, a pattern of CD&E waste management including recycled aggregate activities in England (2008) can be seen in **Figure 4-9**.

The 2008 England pattern can be used to illustrate a new MFA diagram of CD&E waste arisings, use and disposal for Great Britain (2012, **Figure 4-10**). This diagram used the amount of recycled and secondary aggregates (54 Mt) for concrete and construction industries in 2012 and the 2005 ratio of recycled and secondary aggregates in England as 85% recycled aggregates from the hard-inert C&D waste (DCLG, 2007; MPA, 2013c). Thus, the estimation of recycled aggregates in Great Britain (2012) was 45.90 Mt. Likewise, CD&E waste arising in the UK (2012) was 100 Mt (Defra, 2015b) and percent of Great Britain population was 97.17% of the UK population (ONS, 2015d). Therefore, the approximation of CD&E waste arising in Great Britain (2012) is 97% of the UK CD&E waste, or 97 Mt.

In addition to **Figure 4-10**, the six items of hard-inert CD&E waste (according to the EWC waste classification from treatment and transfer facilities including landfills) have more potentiality to be used as recycled aggregates. They are shown in a black and underlined font. For unknown figures, these may also change to be recycled materials or aggregates in the aggregate market (WRAP, 2010). In addition, contaminated soil with hazardous waste needs to be disposed of at the landfill, but uncontaminated soil is higher quality soil that can be used for landscaping (WRAP, 2003). Finally, approximately 19% of the CD&E waste in Great Britain (2012) went to disposal in landfills.

Although Great Britain has recycled activities for the hard-inert CD&E waste and achieves the highest rate of reused aggregates among the EU aggregate markets, the practical uses of these materials are still low (The European Environment Agency, 2008; The Concrete Centre, 2009; MPA, 2013c). Great Britain targeted to increase the proportion of recycled and secondary aggregates to 25% of total aggregates in precast concrete by 2012 (based on 2008). However, only 21.3% of aggregates used in 2012 were from the recycled or secondary origin for this concrete sector (The Concrete Centre, 2013).

There are no recorded data for recycled aggregates in Thailand. PCD *et al.* (2007) found that random samplings of C&D waste in illegal dumping by the roadside were 88% concrete waste with minor elements such as 8.6% clay and the other waste including plastic, paper, glass, and fragments of lightweight block, tile and glass. More than 80% of remaining demolition waste after recycling in some demolition sites and warehouses in Bangkok was also a concrete waste (Glauser, 2007; PCD *et al.*, 2007). These data indicate that Thailand has no recycled aggregates to reuse in the concrete industry, because of the high amount of concrete waste that may be associated with the lack of any environmental taxes like Great Britain and a low price for primary aggregates.

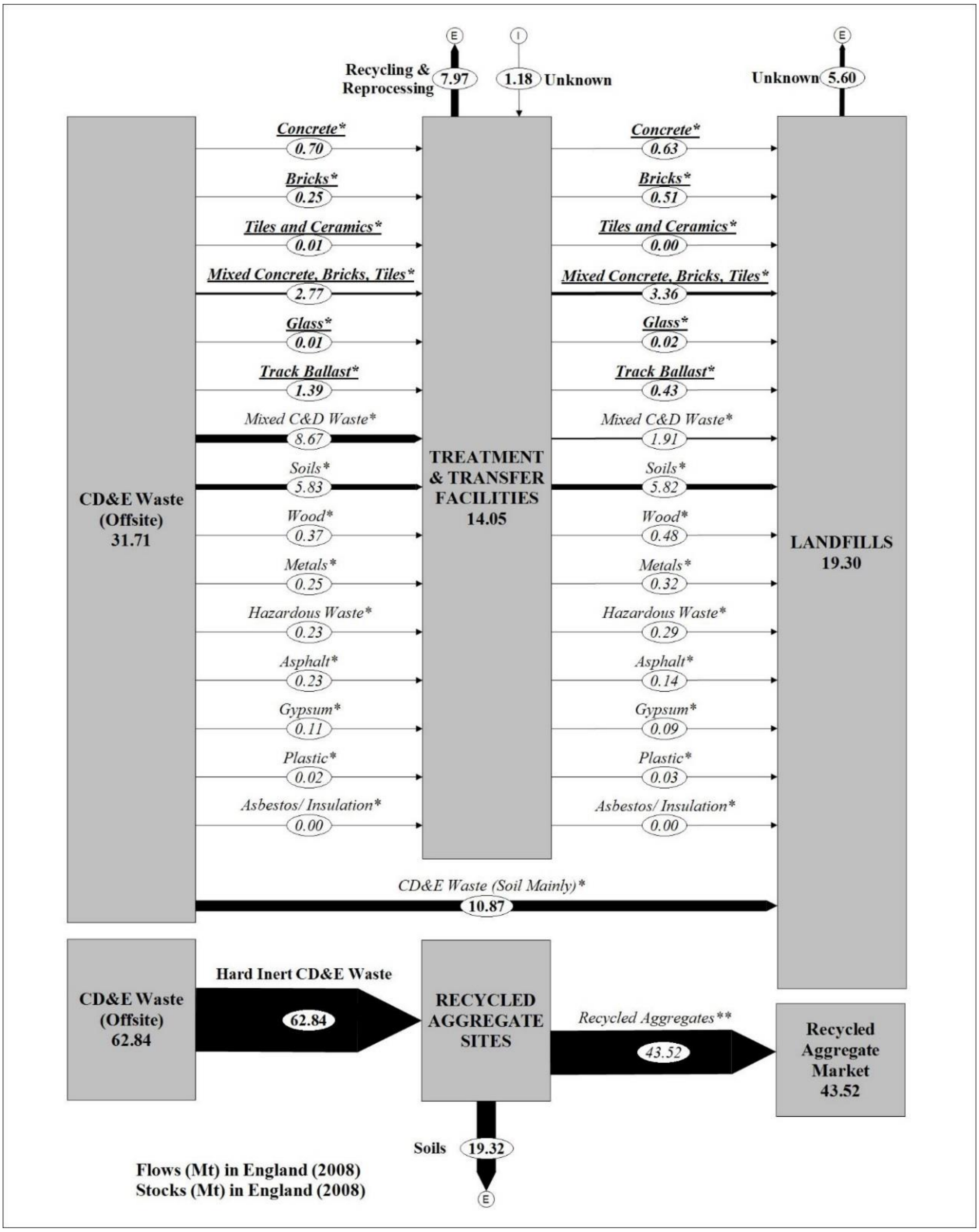


Figure 4-9 CD&E waste management and recycled aggregate activities in England (2008)
Sources: * WRAP (2010)
** WRAP (2010) and Defra (2012a)
Note: A thin and italic font is recorded data including a bold font means calculated data.

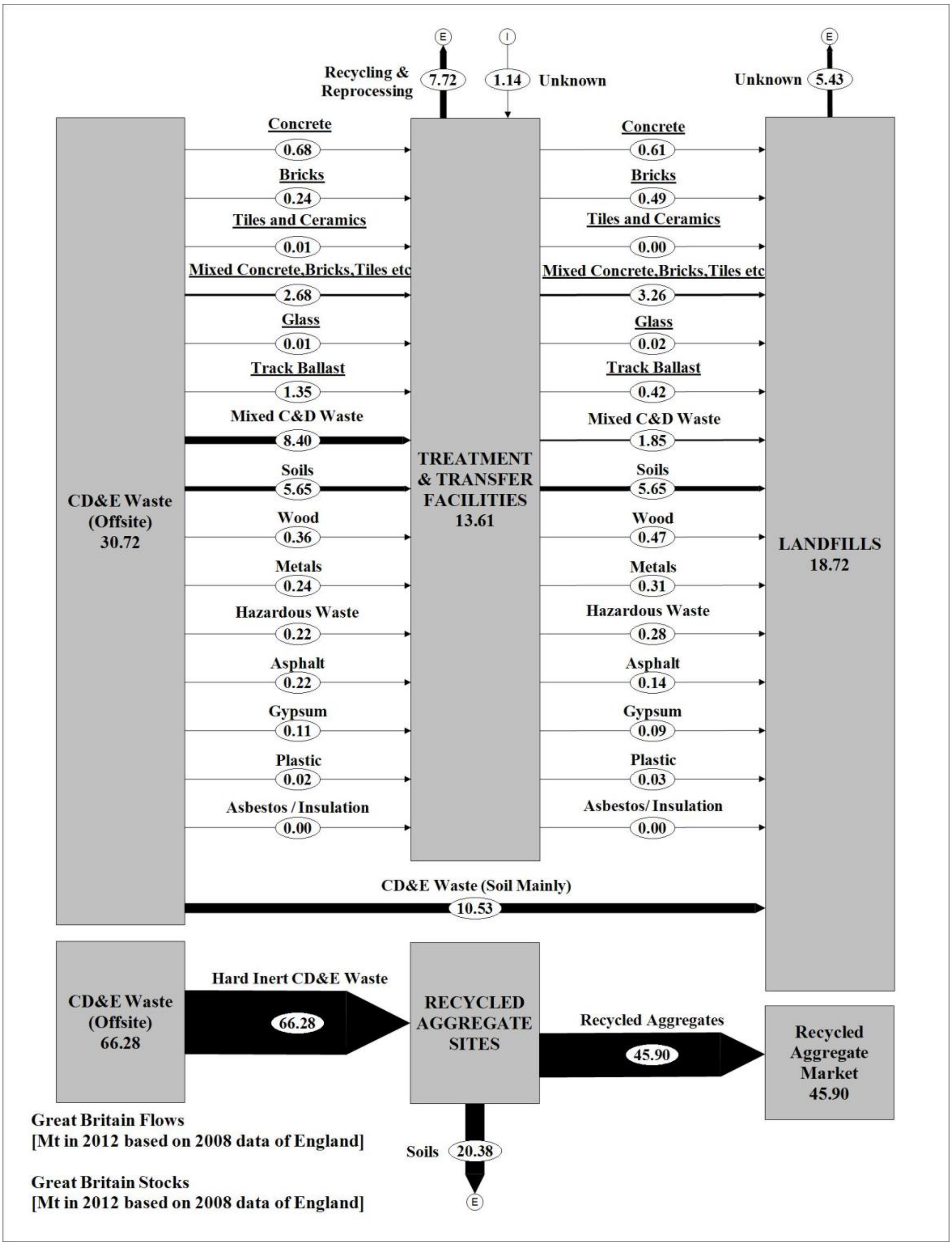


Figure 4-10 CD&E waste management and recycled aggregate activities in Great Britain (2012) based on England data (2008)

Sources:

97 Mt for the waste in Great Britain (2012) came from:

- Defra (2015b) reported that C&D waste arising in the UK (2012) was 100 Mt.
- 97.17% of UK population lived in Great Britain (2012, ONS (2015d)).

Note: A bold font means calculated data.

4.2.2.2 Concrete Industry

Concrete creates a basic structure of modern construction due to its durability, strength and physicochemical characteristics. Supply chains of the concrete industry (excluding bulk mortar, screeds or render products) include: (1) cement products, (2) aggregates (e.g. coarse crushed rock or gravel aggregate and sand), (3) mineral admixtures (e.g. ground granulated blast furnace slag (GGBS) from iron and steel manufacture, fly ash from coal-fired power stations, silica powder and lime), (4) chemical admixtures (e.g. water-reducing, plasticising, air entrainment agents, viscosity modifying products and super plasticisers) and (5) reinforcement bar (MPA, 2013a; British Ready-Mixed Concrete Association, 2014).

As Sjunnesson (2005) defined, general concrete proportions are 70-80% aggregates, 10-20% cement and 7-9% water. Chemical admixtures (less than 1%) are also added to enhance concrete specific characteristics. Furthermore, the important factors that influence concrete workability are the amount of water and cement (w/c ratio), aggregate grading, the amount of fine aggregate and particle shape. Lastly, the proportions and materials of individual concrete mixtures, importantly required as the concrete property, are controlled by the end usage and performance (British Ready-Mixed Concrete Association, 2014).

From the concrete calculation results, Great Britain (2012) produced around 63.32 Mt concrete from 7.43 Mt cement, 19.70 Mt fine primary aggregates and 28.34 Mt coarse primary aggregate including 5 Mt coarse recycled aggregates (MPA, 2013c; ONS, 2014d). Besides, Great Britain used around 4.5% other additives for the concrete industry (MPA, 2013a). Therefore, around 2.85 Mt of additives were used to produce concrete. Typically, the amount of concrete waste generated by ready-mix deliveries can be as little as 0.4-0.5% (0.5% selected) of total concrete volume (WBCSD, 2009b). Therefore, Great Britain had around 0.32 Mt concrete waste during deliveries. Overall 63 Mt concrete went to Great Britain construction industry (2012).

The estimation volume of Thai annual concrete manufacture in 2012 was 256.26 Mt. Using the result of domestic cement consumption and recorded quantity of primary and recycled aggregates for concrete components in Great Britain (ONS, 2014d) as 7.43 Mt: 19.70 Mt: 28.34 Mt plus 5 Mt (cement: fine primary aggregates: coarse primary aggregates plus coarse recycled aggregates), the amounts of Thai concrete components were 30.07 Mt cement: 79.73 Mt fine primary aggregates: 134.93 Mt coarse primary aggregates. Then, this study used the same ratios as Great Britain to calculate the volume of 4.5% concrete additives (e.g. siliceous fly ash, ground granulated blast furnace slag (GGBFS or GGBS), superplasticizer such as polycarboxylate or retarding admixtures) and concrete waste during deliveries (0.5%). Therefore, the estimated amount of additive components for Thai concrete industry was around 11.53 Mt and concrete waste from transportation generated around 1.28 Mt. All in all, the estimated amount of concrete in Thailand (2012) was 254.98 Mt.

4.2.2.3 Construction Industry

The UK construction sector represented 7% of GDP or £110 billion in 2010 and the UK government ultimately is the biggest customer as 40% of the industry's workload was for the public sector (The Cabinet Office, 2011). Like Great Britain, Thai construction has followed economic growth and has been encouraged by the government. The trend of permitted construction areas in all Thai municipalities for both new and refurbished construction in Thai residential and non-residential building is likely to expand significantly in the future, particularly in Bangkok and five perimeters including many main provinces of each region (National Statistical Office, 2012b; Bank of Thailand, 2015c). This is consistent with the study of UNEP (2013) relating to the typology of urban metabolic profiles. This study explained the distribution of the global construction materials and showed that both metropolises, Bangkok and London, stay in the same level as the medium of construction mineral consumption. Higher concrete uses and construction activities in Thailand are not presently concentrated only in Bangkok.

The Building Research Establishment (2002) forecasted the green guide wastage rates and measured waste rates for concrete and mortar lost during construction around 5% at the construction sites. However, from the new study of Building Research Establishment (2008), the real construction activities had higher waste rates of concrete and mortar than the previous estimations. This study used 5% concrete and mortar lost during construction as the lowest amount of concrete and mortar waste. Thus, Great Britain probably had the minimum quantity of concrete and mortar waste lost during construction at around 3.57 Mt, and 13.48 Mt for Thailand.

The data from ONS (2013b) were used to calculate the final volume of concrete and mortar used in Great Britain (2012) by launched value of three main building types as 37.01% residential building, 44.07% non-residential building and 18.92% infrastructure. Moreover, the proportion of new residential completion was houses (68%) and flats (32%, DCLG (2014)). Therefore, this study used four main building types as 25.17% single-residential building, 11.84% multi-residential building, 44.07% non-residential building and 18.92% infrastructure to calculate concrete and mortar uses. The results showed that the 2012 concrete stock in Great Britain was 67.73 Mt concrete and mortar, used as follows: 17.05 Mt single-residential building, 8.02 Mt multi-residential building, 29.85 Mt non-residential building and 12.81 Mt infrastructure.

In Thailand, the National Statistical Office (2013a) announced floor area in use for Thai new and modified construction in 2012 as 41.90% single-residential building, 9.61% multi-residential building, 32.19% non-residential building and 16.30% infrastructure. Therefore, the estimation of Thai annual concrete stock in 2012 was 256.14 Mt which subdivides into 107.32 Mt single-residential building, 24.62 Mt multi-residential building, 82.45 Mt non-residential building and 41.75 Mt infrastructure.

The previously identified calculations and results allow explicit comparison between the two countries so that the contribution to material flows at every step is clearly identified. These outcomes can support policymakers to compare and comprehend the present situations and the differences in operations, and can also emphasise some overlooked weaknesses requiring coherent policies to support in both national case studies. All summarising results from the cement, concrete and construction industries, including the aggregate market in 2012, made for MFA flows of Great Britain are shown in **Figure 4-11** and **Figure 4-12** for Thailand.

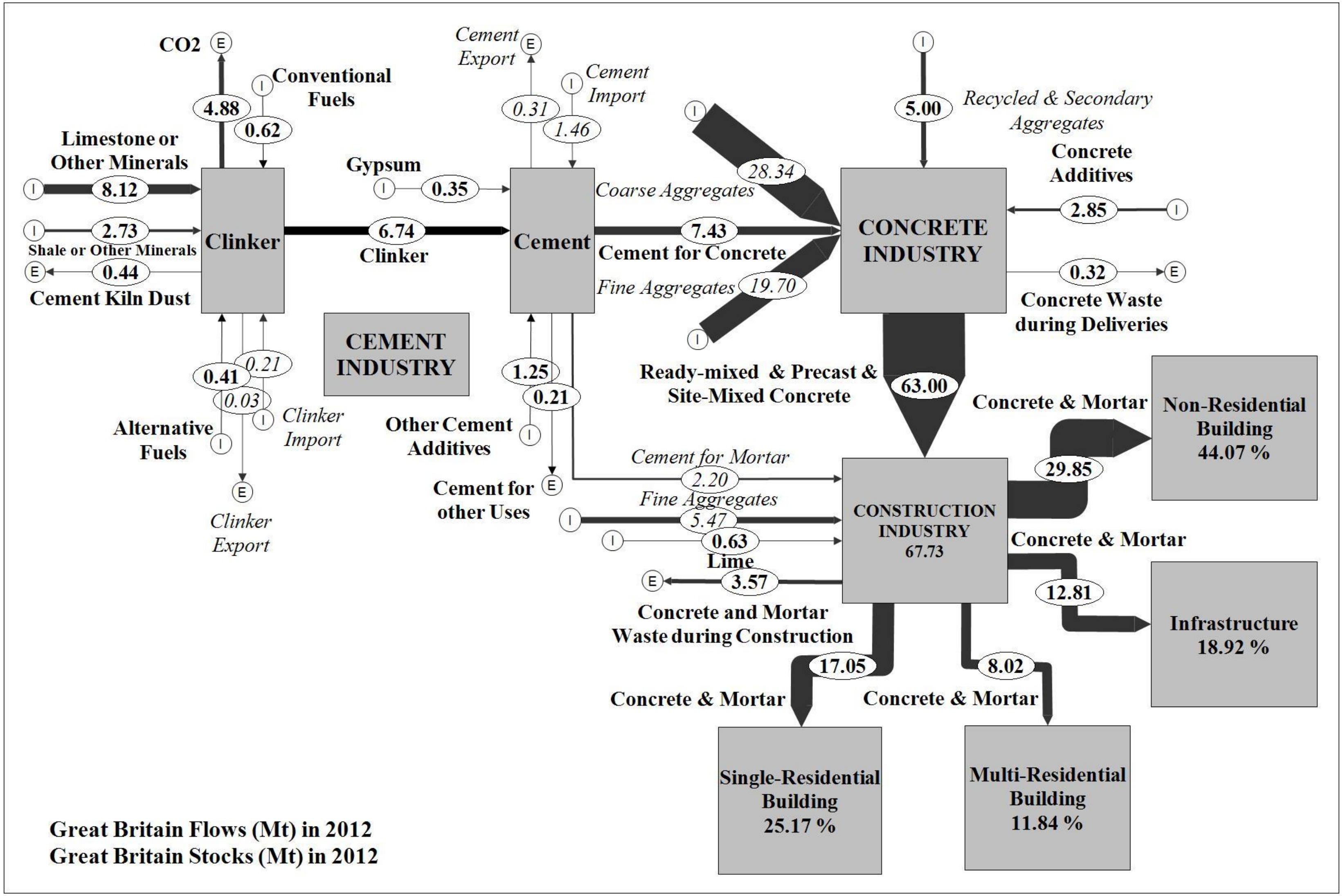


Figure 4-11 MFA of cement, concrete and construction industries of Great Britain (2012)
Sources: Author

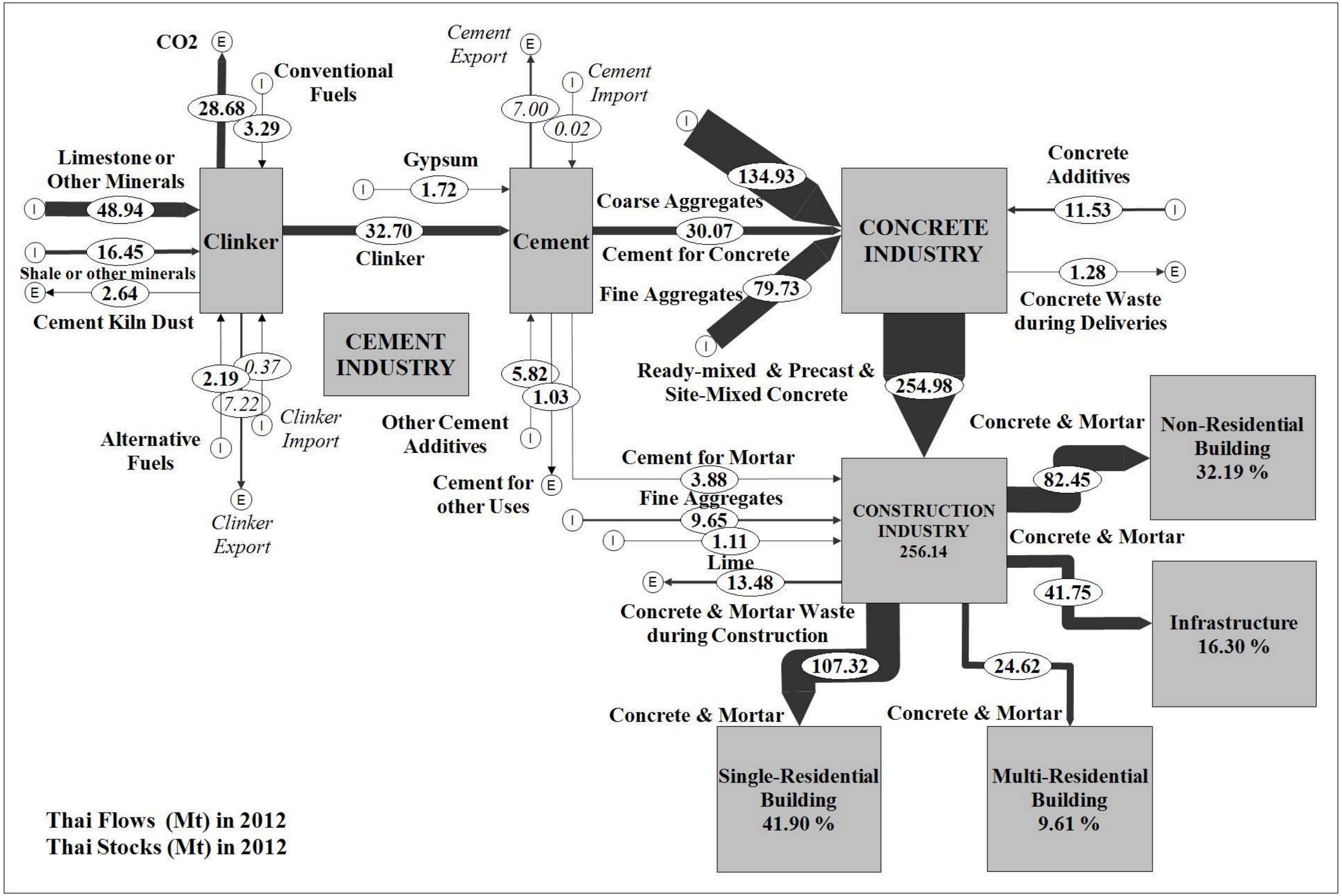


Figure 4-12 MFA of cement, concrete and construction industries of Thailand (2012)
Sources: Author

4.2.3 Future Concrete Stock from Stock Dynamic Analysis (SDA)

By 2030, the world economy is expected to double, with a one-third increase in the global population. These events lead to a significant growth of global energy and material consumption together with manufacturing activities for driving modern industrialisation, infrastructure and housing, particularly in developing nations. These situations put more pressure on the natural resources and environment as the global economy tends to grow faster than a sustainable rate of consumption of natural resources (Matthews *et al.*, 2000; OECD, 2011; Fishman *et al.*, 2015).

Rapid economic growth not only requires use of more natural resources, but also leads to an increase in the amount of waste that requires proper disposal. Construction in Thailand presently is dominated the housing sector, shown by the previous MFA results of the annual concrete stock and this relates directly to the national well-being. Using national historic, present and forecasting data to predict the future trends until 2100, SDA illustrates future housing construction and demolition in terms of floor area in use (FAU). It also includes prediction of the future quantity of concrete in use (CU), as the principal construction material consumed for the housing sector and the upcoming amount of concrete waste derived from the demolition of old residential buildings. The steps relating to the SDA are summarised in **Figure 4-13**.

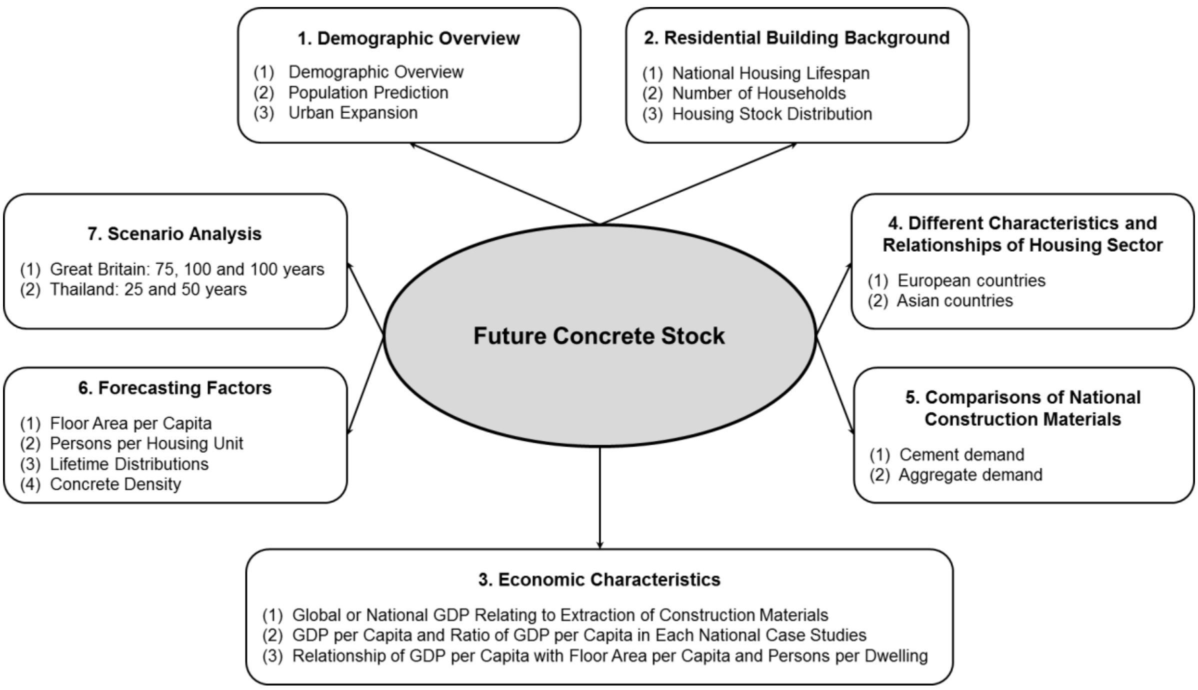
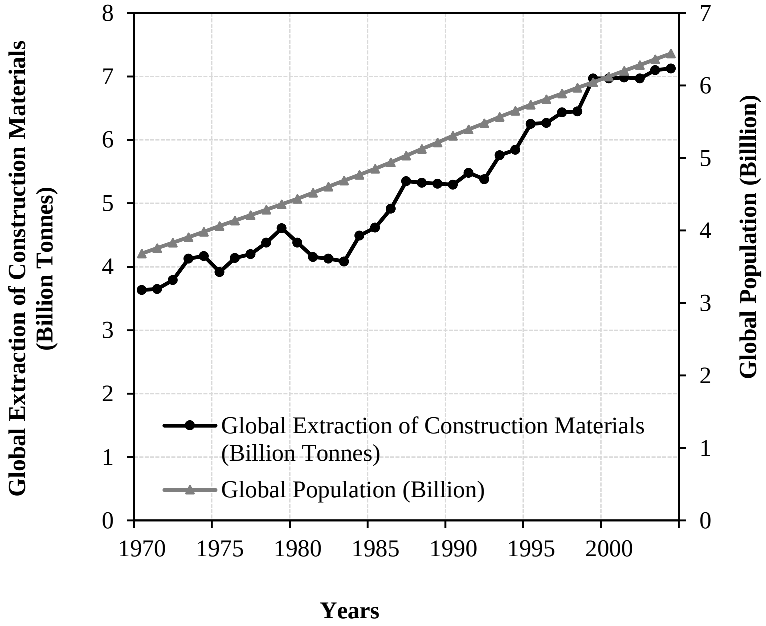


Figure 4-13 Summarised steps of SDA
Sources: Author

4.2.3.1 Demographic Overview

4.2.3.1.1 Demand for Construction Materials Comparing to Global Population Growth

In mid-2015, UN (2015b) reported that world population reached 7.3 billion. Most of the global population lived in Asia (60%, 4.4 billion) and 738 million (or 10% of that) inhabited Europe. In 2100, Asia will still rank as the biggest inhabitant group in the world with 44% or 4.9 billon. In contrast, European population will decrease slightly to be 646 million or 6%. **Figure 4-14** shows that there is a linear correlation between global extraction of construction materials and global population with an R^2 of 0.9493 making it an almost linear fit. As the most populous continent, Asia consumes nearly 20% of global natural extraction (UN, 2004; Behrens *et al.*, 2007). A significant part of this global requirement from natural resources, hugely disturbing natural environments, is for construction materials, mainly used in the cement and concrete industries. Thus, Asia requires more natural materials for its construction activities than Europe.



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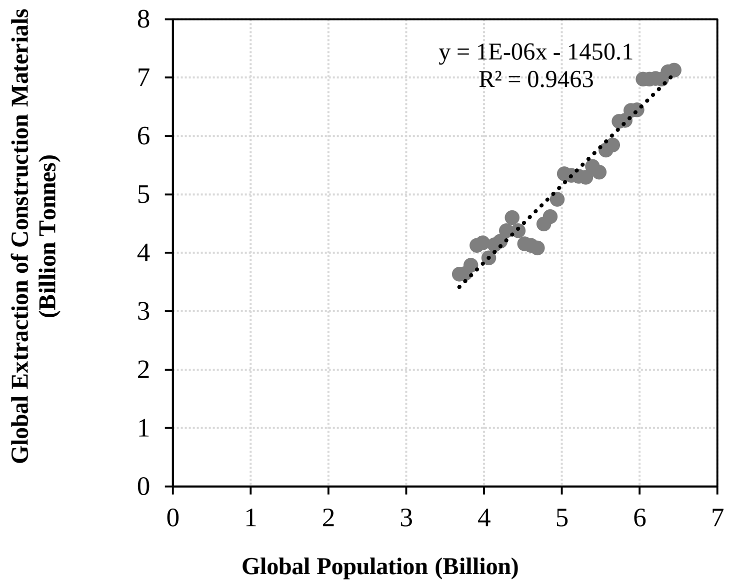


B

Figure 4-14 Global population and extraction of construction materials (A) and their correlation (B)
Sources: Author based on Rogich and Matos (2008) and UN (2015a)

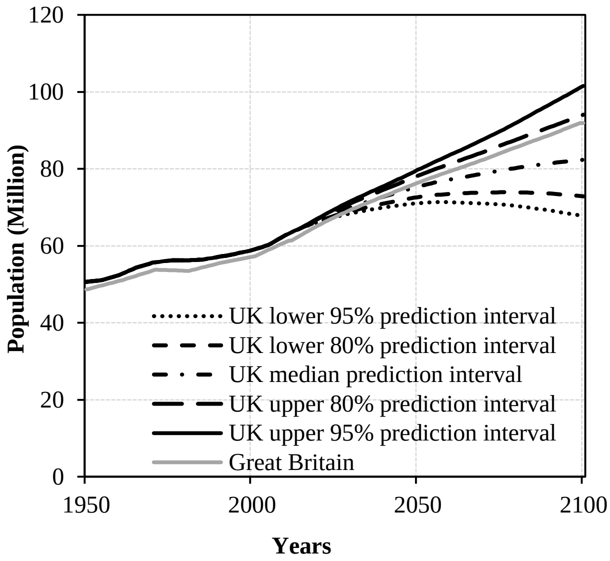
4.2.3.1.2 Population Prediction

Asia is notable not only for its overall large population size but also for unusually dense and large settlements as well as vast barely populated regions. Importantly, its members are mostly developing countries (excluding Japan and South Korea). Some of Continental Europe has the most developed countries in the world such as France, Germany, Italy, Spain and the UK. Presently, European countries have developed their single market with several standardised systems that are applied to all member nations. Not only in its common regional economy, regulations and policies, this confederation also shows a common approach to its natural resources and waste management.

The calculation of future population uses the probabilistic UK and Thai population projections that originated from 2012 and 2015 revisions of the world population prospects (UN (2012); (2015a)). For predicting the Great Britain population, this study used Great Britain data in **Figure 4-15A** to adjust UK population projections from the United Nations (UN) statistics to be the Great Britain population with prediction intervals in **Figure 4-15B**.

For the Thai population (1900-2100), some recorded data from 1985-2013 of the Department of Provincial Administration (2015) were included in these Thai population trends. The historical, present and forecast statistics of both Great Britain and Thai populations with five prediction intervals from 1800-2100 are shown in **Figure 4-15B** and **Figure 4-15C** respectively.

Moreover, the Great Britain and Thai upper 80% prediction interval were chosen for calculation by SDA due to the close correlation between the Great Britain and UK predictions from other references and the UN statistics in **Figure 4-15A**, assuming a similar relationship for Thailand.



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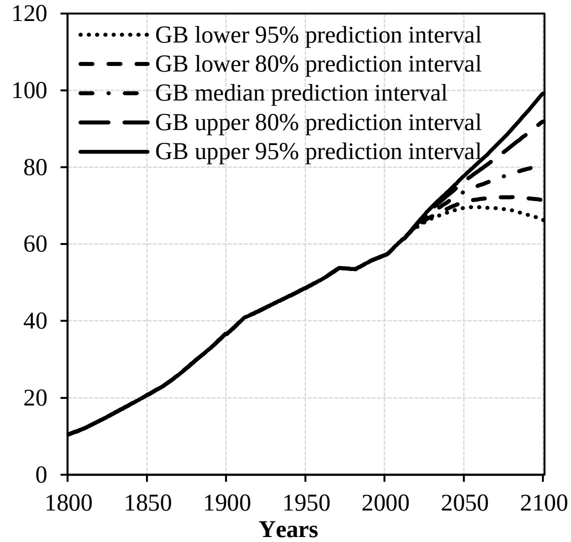

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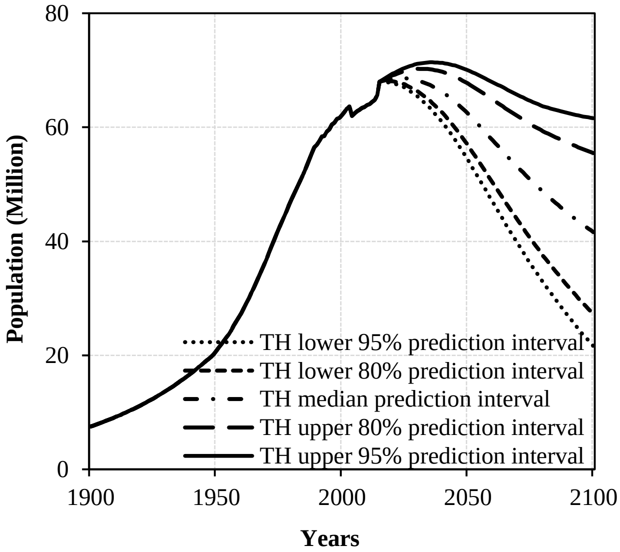
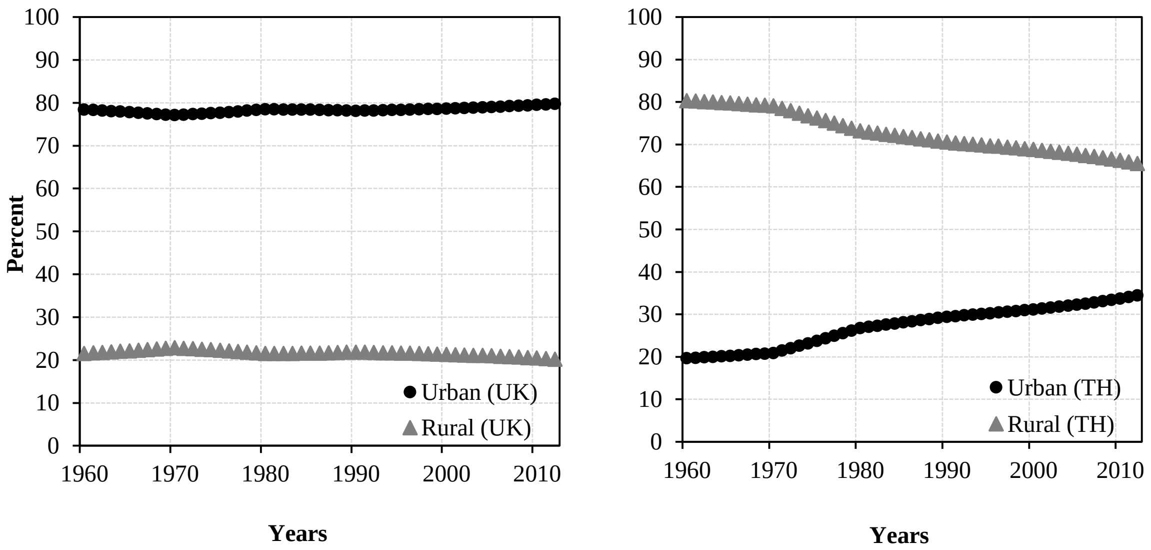


C

Figure 4-15 UK data is based on UN data, and Great Britain population is calculated (1800-2100, A and B) and Thai population (1900-2100, C)
Sources: Author based on forecasting Great Britain population from Kyd (1952); National Records of Scotland (2013); Online Historical Population Reports (2012a), (2012b), (2012c); ONS (2011a), (2012c) and (2012d) and UK forecasting population from UN (2012) and (2015a) in A and B figures including Department of Provincial Administration (2015) and UN (2012), (2015a) for Thai population (C).
Note: Adjusting UK population data to be Great Britain data by the ratio of Great Britain population

4.2.3.1.3 Urban Expansion

The UK has a higher number of urban population comparing to Thailand. Tallon (2013) stated the ‘spectacularisation’ of UK urban space is a transformation from industrial manufacturing landscapes to spaces of consumption dominated by housing. This situation is supposed to increase demand for UK construction materials. However, Andrews *et al.* (2012) predicted that the UK current demographics seem less favourable and urbanisation is mostly complete, shown in **Figure 4-16**. These reasons cause the UK to have low long-term cement and construction growth potential, as seen from the output of cement/construction to GDP growth multipliers that are near zero (Andrews *et al.*, 2012). In contrast, less cement demand and higher GDP growth can probably be linked to higher renovation activities and long lifespan of UK housing. For Thailand, urban society has a continuously magnified size and reflects changing lifestyle. Thus, Thailand still has more potential for construction growth and requires more construction materials, especially concrete, to supply a modern Thai housing demand expanded by rapid urbanisation and higher well-being.



A B

Figure 4-16 Percent of urban and rural population in the UK (A) and Thailand (B)
Source: Author based on World Bank (2015f) and (2015e)

4.2.3.2 Residential Building Background

As stated by The Chartered Institute of Building (2013) for UK building lifespan, half of its residential buildings have a lifespan more than 50 years and a fifth is more than 100 years old. In addition, the proportion of new dwellings built after 2000 is only 7% of the whole UK housing stock (the ENTRANZE Project, 2008c). According to the construction date among EU dwellings (**Figure 4-17**), it can be seen that the UK has the greatest number of old dwellings, following closely by Belgium and Denmark. Throughout their operation period, buildings experience some major refurbishments every 20-30 years (The Chartered Institute of Building, 2013). Furthermore, because of the UK weather, a double masonry layer separating by a cavity is dominant structuring of the UK residential building (Mortar Industry Association, 2013), increasing demand for construction materials.

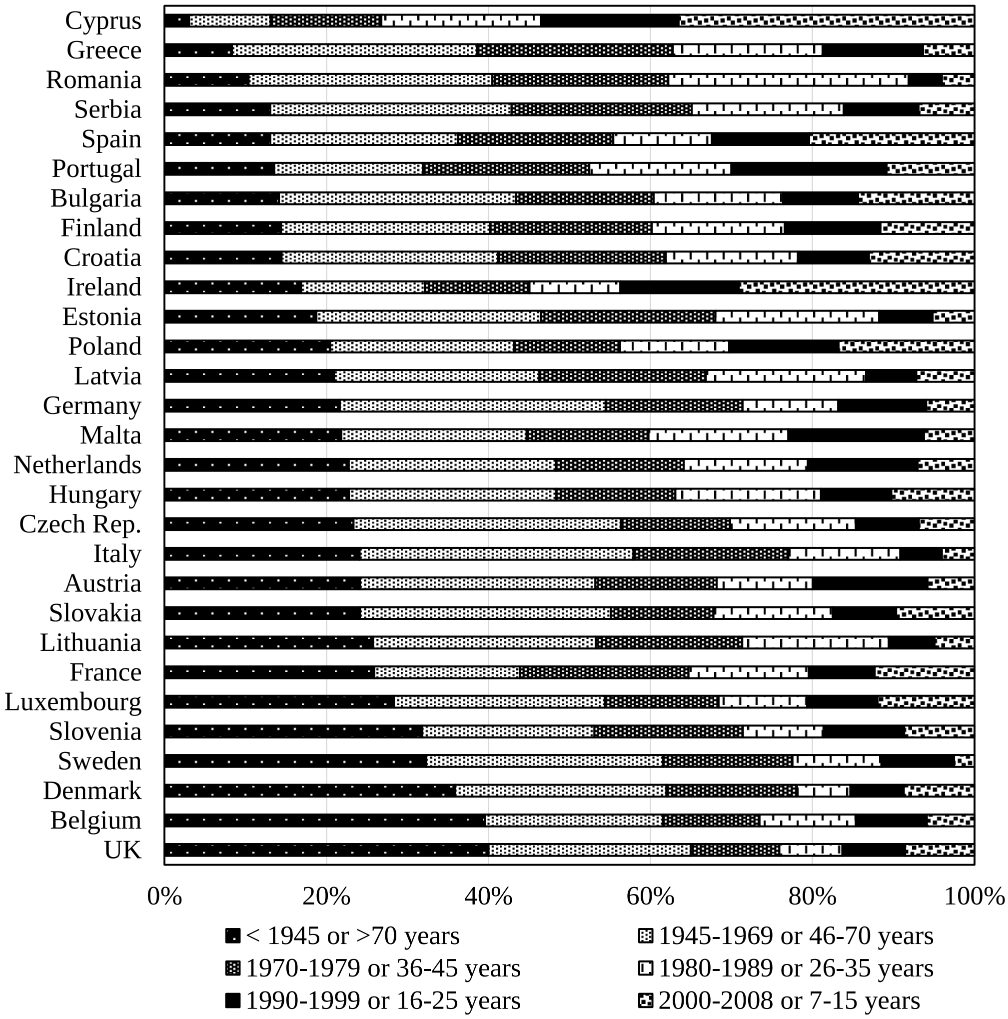


Figure 4-17 The EU dwelling according to construction date
Source: Taken and amended from The ENTRANZE Project (2008b)

The lifetime of buildings in Thailand can be estimated from other Asian countries in the absence of specific information. For example, an average lifespan of Chinese old residential buildings is around 15-30 years (Song, 2005; Shi and Xu, 2006; Yang, 2006) and 25-50 years for new housing (Hu *et al.*, 2010c), and 30 years for a multi-storied commercial building in Singapore (Kua and Wong, 2012). This turnover of stock encourages consumption of more materials for construction especially for the residential sector. Due to limitations of Thai data, this study used Asian GDP between 1990 and 2014 (providing published information in the residential sector) to select appropriate figures of housing lifespan for Thai calculations. As seen in **Figure 4-18**, Chinese GDP looks quite similar to Thai GDP presently. Therefore, this study used some characteristics of the Chinese figures, such as per capita floor area (square meters, m^2), to calculate representative Thai housing figures and then represent as Thai housing aspects.

As seen in **Figure 4-19**, the housing sector in Thailand has quickly grown up compared to Great Britain in the same period. For housing stock, semi-detached and terraced houses are the main housing types of Great Britain (**Figure 4-20A**). In Thailand, housing types (using permitted areas) in 2012 showed that the detached house is quite popular for the present Thai housing construction (**Figure 4-20B**). Moreover, **Figure 4-20C** also emphasises that a single house is the most common type of Thai residential building.

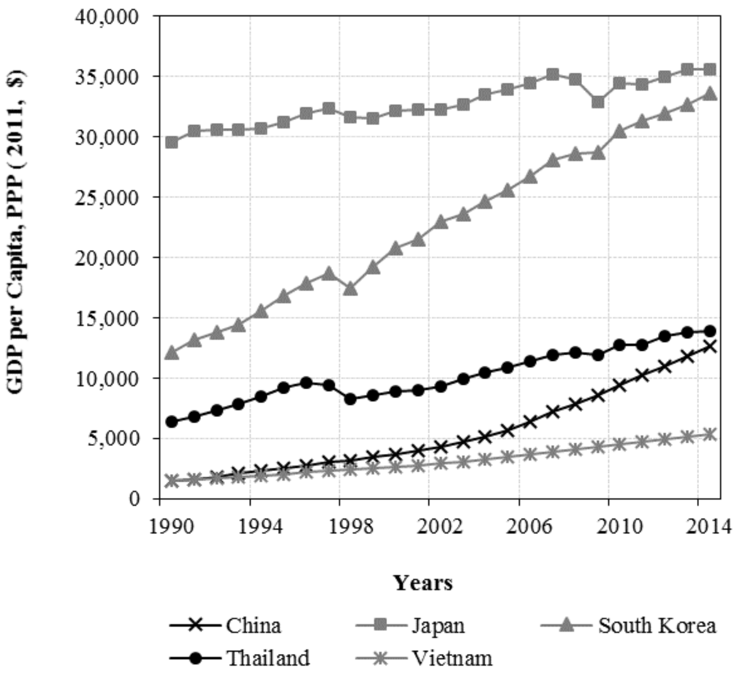


Figure 4-18 GDP per capita (PPP, 2011, US$) in some Asian countries
Sources: Author based on World Bank (2015b)

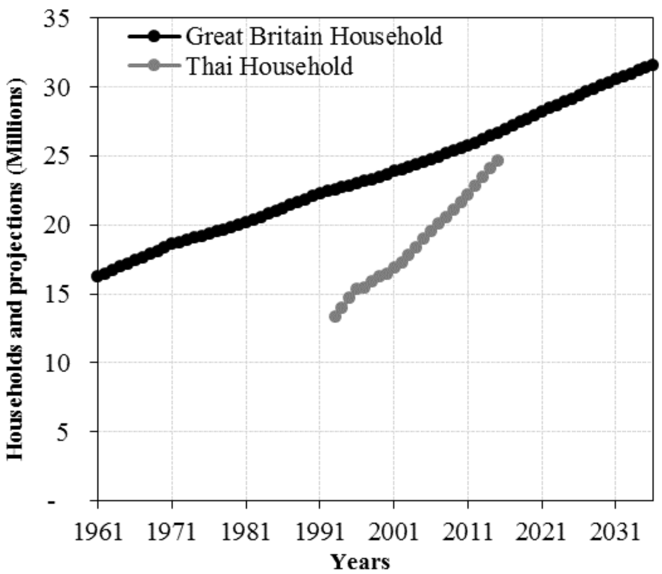
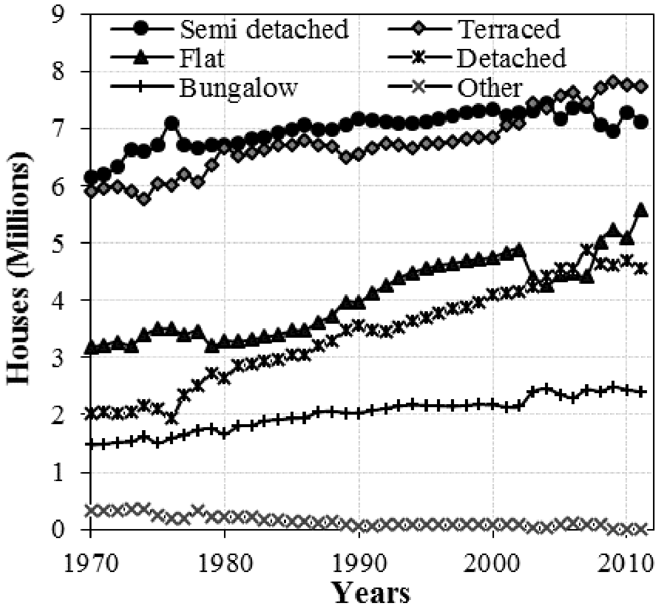


Figure 4-19 Number of households in Great Britain and Thailand
Sources: Author based on DCLG (2015b) and Bureau of Registration Administration (2015)



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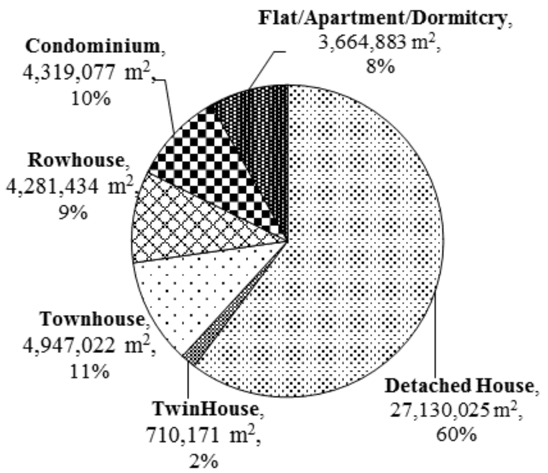
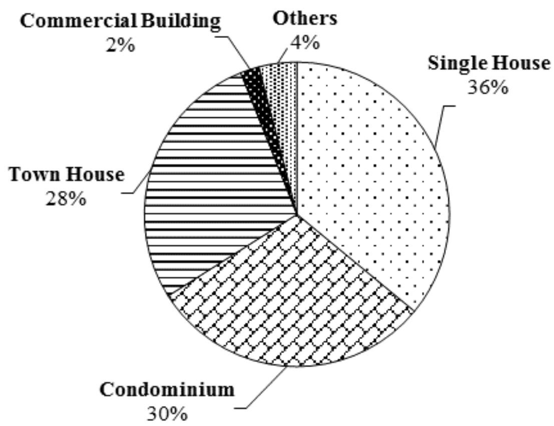




B- Great Britain C- Thailand

Figure 4-20 Housing stock distribution by types in Great Britain (A) including permitted areas of Thai housing in 2012 (B) and types of residential housing in Thailand (C)
Sources: Author based on A: Palmer and Cooper (2013) including B: National Statistical Office (2013a) and C:Tikul and Srichandr (2011)

4.2.3.3 Economic Characteristics

As it is well known, increase in GDP representing national economic performance and national standard of living reflects the construction activities of the whole country. Consequently, global GDP (2010, US$) also affects the global extraction of construction materials (tonnes) from natural resources, increasing continuously all over the world (**Figure 4-21A** and **B**). For example, the US Geological Survey estimated that construction activities consume the largest quantities of natural resources (around 60% of raw materials), other than food and fuel used in the US economy (EPA, 2008).

Moreover, West *et al.* (2010) reported a fluctuating trend of domestic extraction of Thai construction minerals with Thai GDP between 1970 and 2004 that also related closely to the global trend in the early stage (1970-1996, **Figure 4-21C** and **D**). Then, Thai growth in GDP and extraction of construction materials was interrupted after 1996 before returning to increase. Thailand may have other factors to disturb the linear extraction pattern, such as political and social problems that make construction activities slow down for a while.

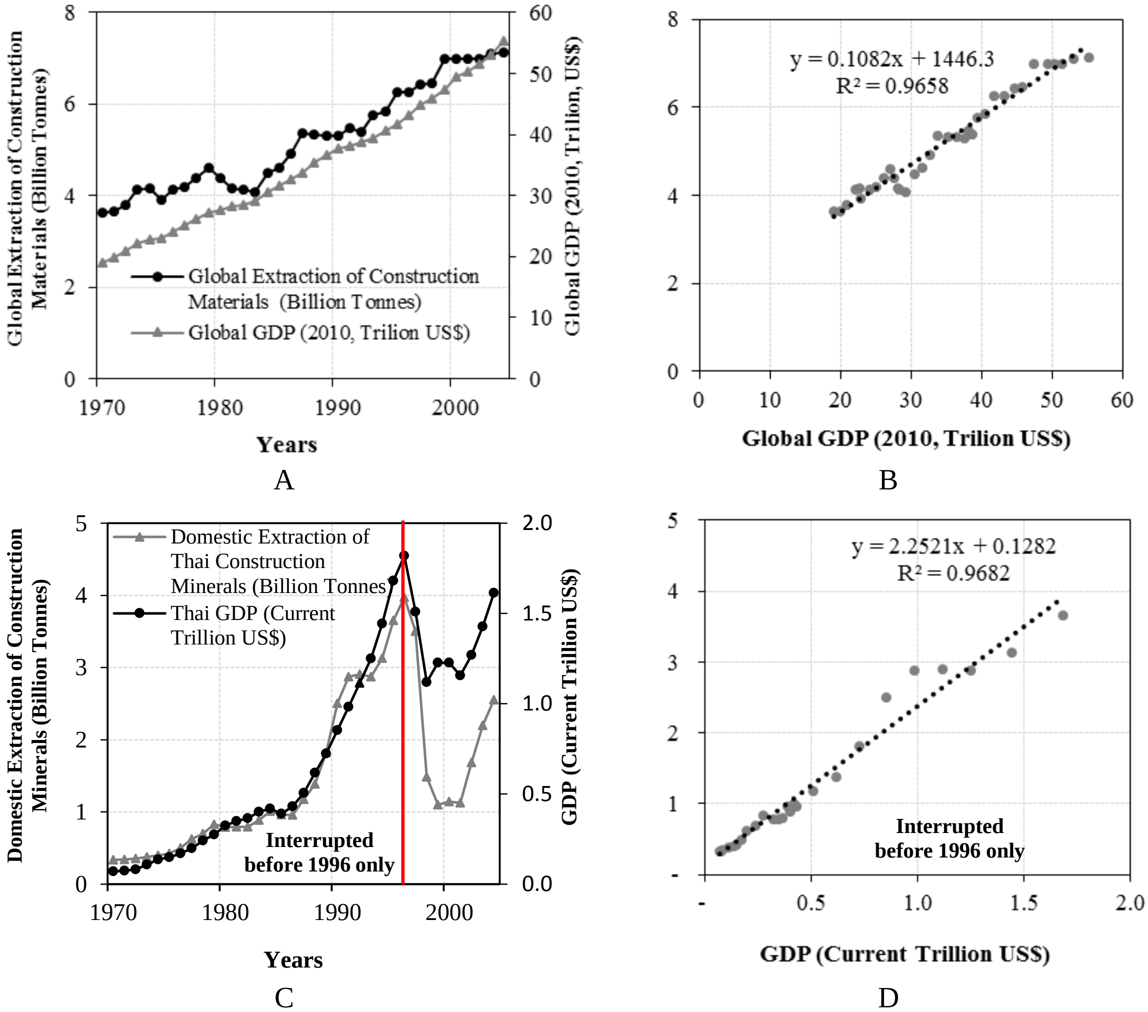


Figure 4-21 Global GDP and extraction of construction materials (A) and their correlation (B) including Thai GDP (C) and domestic extraction of Thai construction minerals (1970-1996, D)
Sources:
A and B: Author based on Rogich and Matos (2008) and USDA (2015b) for global GDP and extraction of construction minerals
C and D: Author based on West *et al.* (2010) and World Bank (2015e) for Thai GDP and its extraction of construction minerals

The correlation between personal consumption (kg) in cement and economic growth measuring from GDP per capita (US$, 2011) can be compared in **Figure 4-22**. As seen, some developing countries, having a strong association between a low income and a high population growth, demonstrate higher expansion rates in their cement consumption than other economically developed countries with their higher personal incomes.

Moreover, per capita GDP (US$, 2011) and cement consumption of UK and Thailand can explain the above principal difference between developing and developed countries in **Figure 4-22**. According to cement demand that requires more in the developing countries, this upsurge is expected by Private Sector & Development (2011), who report that the cement market share in these nations will rise consistently from 80% to over 90% of the world's cement consumption by 2025.

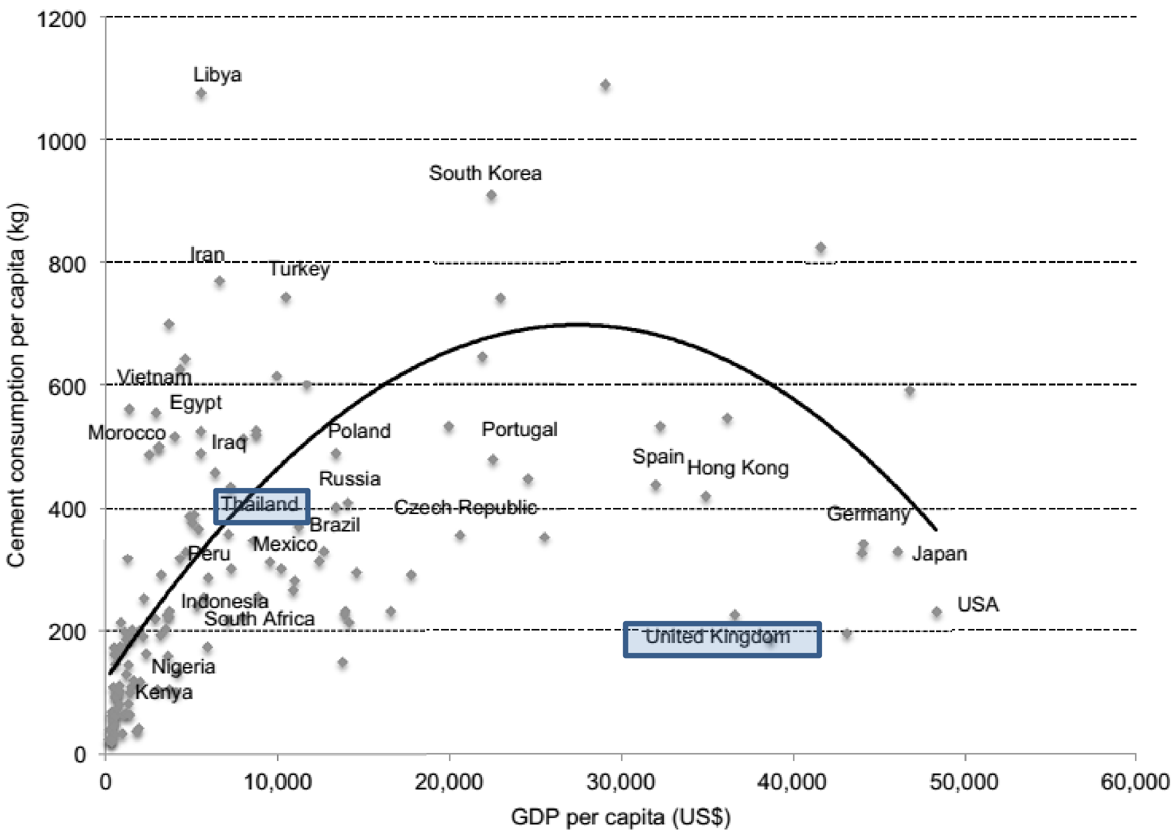
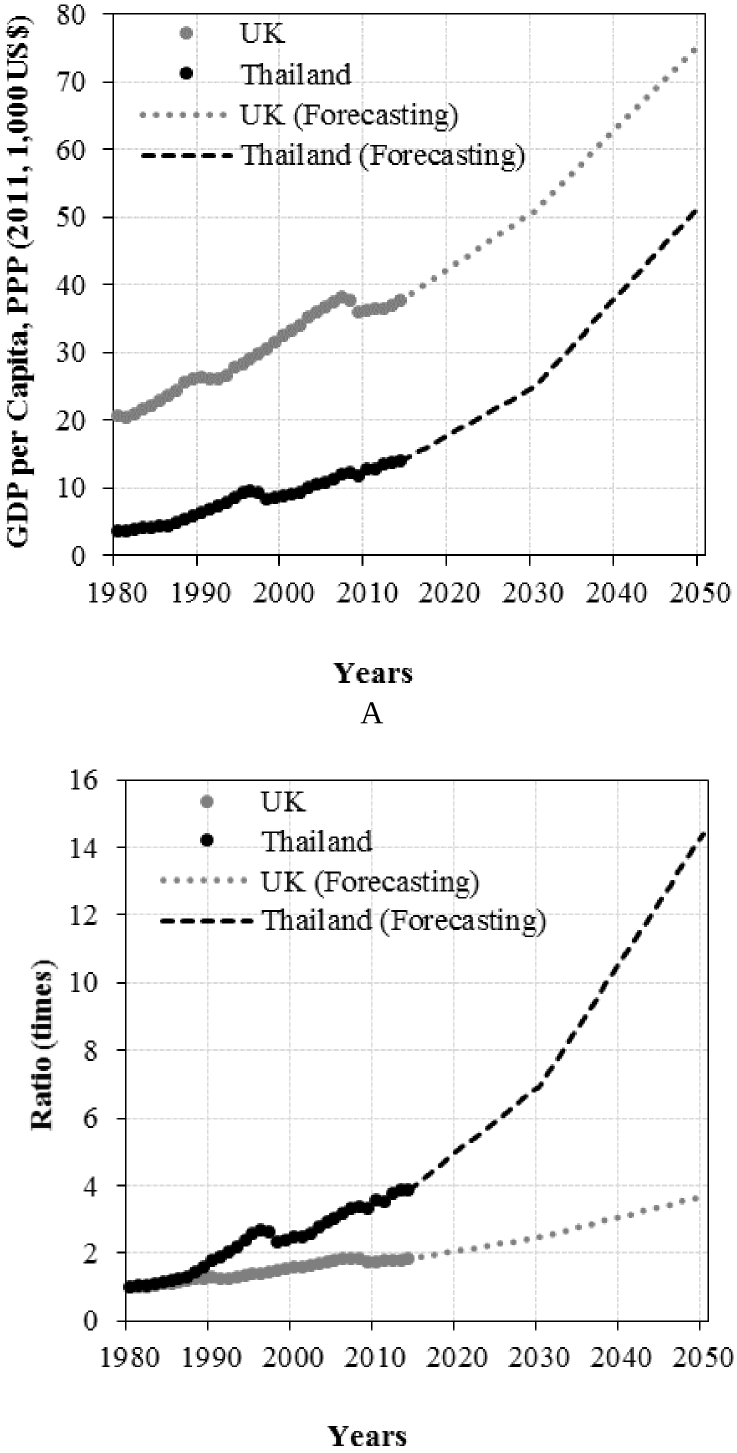


Figure 4-22 Correlation of cement consumption per capita and GDP per capita (US$) in 2011
Source: Taken from International Cement Review (2013)

As shown in **Figure 4-23A**, although Thailand has lower GDP per capita (PPP, 2011, US$) than the UK by nearly three times, Thailand required two times more personal cement consumption (around 430 Kg per capita) than the UK in 2011 (about 225 Kg per capita, **Figure 4-27**). Importantly, this situation likely originates from a higher ratio of GDP (PPP, 2011, US$) that grows continuously and rapidly in Thailand like other developing countries compared to the UK (**Figure 4-23B**). In addition, an overview of the world economic outlook projections (2015-2016) shows that Asian countries will have a regional economic growth higher than the

European region (IMF, 2015). Consequently, these causes impel Thailand to produce and consume more cement for construction activities than the UK (also shown in **Figure 3-2**).

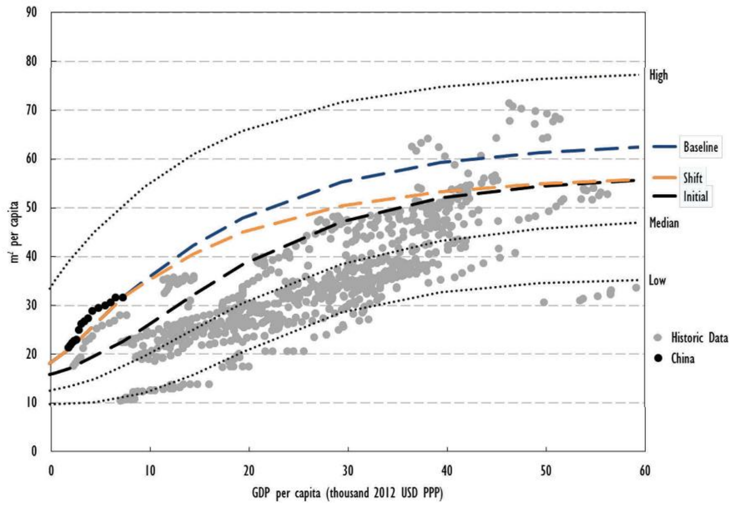


A

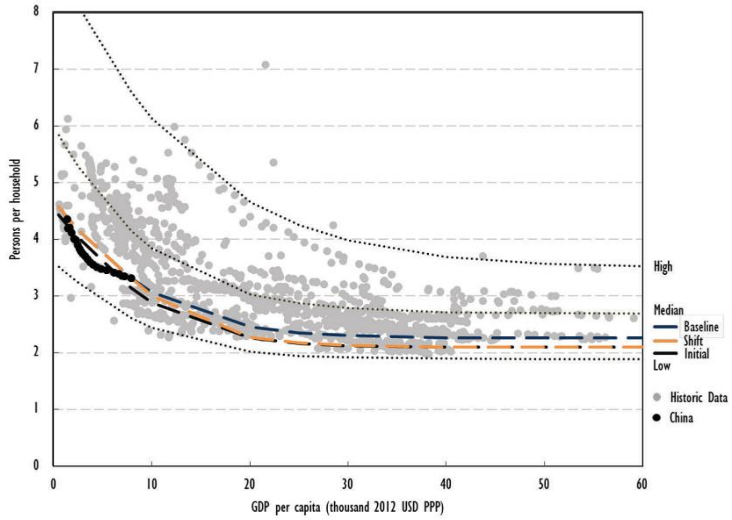
B

Figure 4-23 GDP per capita (PPP, 2011, 1,000 US$) in the UK and Thailand (A) and ratio of GDP per capita, PPP (2011, US$) in UK and Thailand (B)
Sources: Author based on PricewaterhouseCoopers LLP (PWC) (2015) and World Bank (2008), (2015b)

Likewise, GDP per capita (PPP, 2012, US$) also has a relationship to floor area per capita and persons per dwelling. As seen in **Figure 4-24A** and **B**, higher GDP per capita correlates with an increase in construction activities and demand for construction materials, shown by increasing personal floor area. It also is affected by a reduction of the household size. Emphasising the residential sector in EU-25 members, this situation also occurs as structural changes in construction activities of the EU housing. There are annual increases in personal floor area by 4%, and a 5.5% decrease in a household size, due to higher EU economic status (Broin (2007), **Figure 4-24C**).



A



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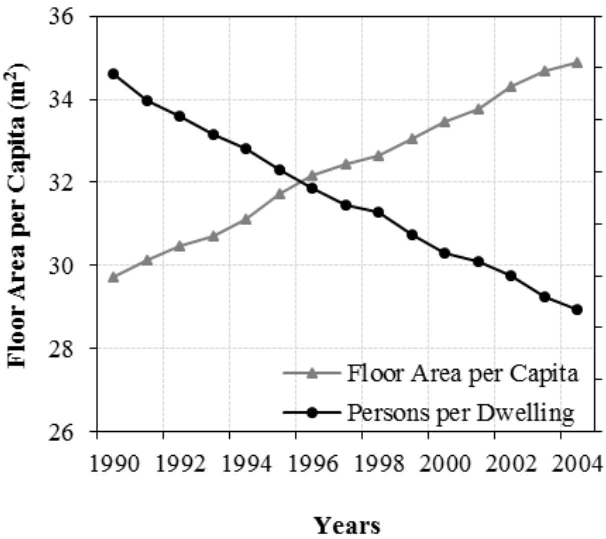


C

Figure 4-24 The relationship of international GDP per capita (PPP, US$) with their FAC (A) and persons per dwelling (B) in some nations including indicators of structural changes in a residential sector for EU-25 (1990-2004, C)

Source: A and B: Taken from The International Energy Agency (IEA) and Tsinghua University (2015)
C: Author based on Broin (2007)

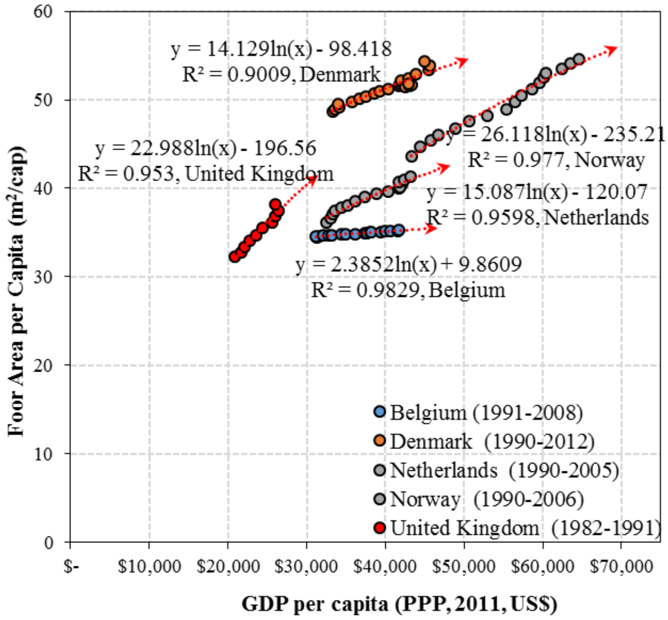
4.2.3.4 Different Characteristics and Relationships of Housing Sector among European and Asian Countries

The housing sector probably has some different characteristics and relationships among European and Asian countries. This stage selected two EU countries Belgium and Denmark, which have similar high proportions of old residential buildings by construction date as the UK (**Figure 4-17**). Moreover, these EU comparisons also include some more countries, the Netherlands and Norway, using data from Hu *et al.* (2010c).

For Asian countries, there are some published data relating to the above variations such as China, Japan, South Korea, and Vietnam. They are comparable to corresponding data for Thailand, and reflect essential characteristics of Asian residential building. This background information on these countries is used to establish correlation trends of (1) floor area per capita comparing to GDP per capita, PPP (2011, $) and (2) persons per dwelling comparing with GDP per capita, PPP (2011, $).

4.2.3.4.1 Historical Regression of Floor Area per Capita to GDP per Capita (PPP in Some European and Asian Countries

In **Figure 4-25**, because of higher GDP per capita (PPP, 2011, US$), European countries appear to require bigger floor area per capita than Asian countries. As developing countries mostly, floor area per capita has rapidly increased in Asian countries compared to European counties, with quite smooth trends.



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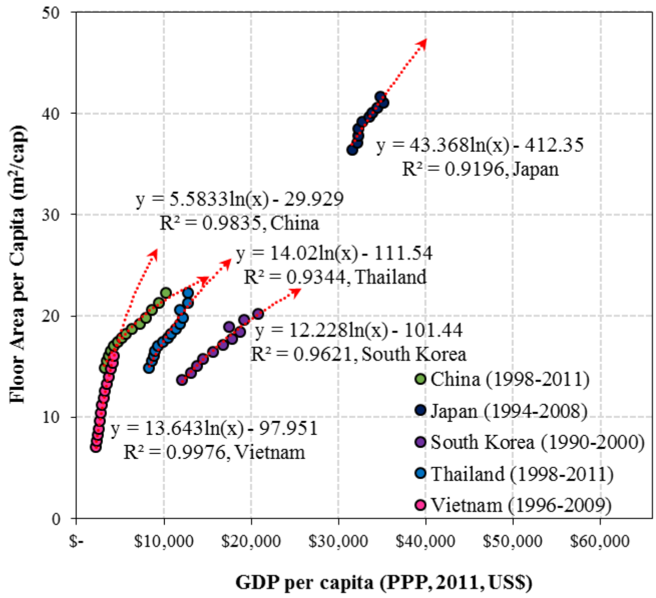


B

Figure 4-25 Historical regression of floor area per capita to GDP per capita (PPP, 2011, US$) in some European (A) and Asian (B) countries

Sources: Author based on:

A

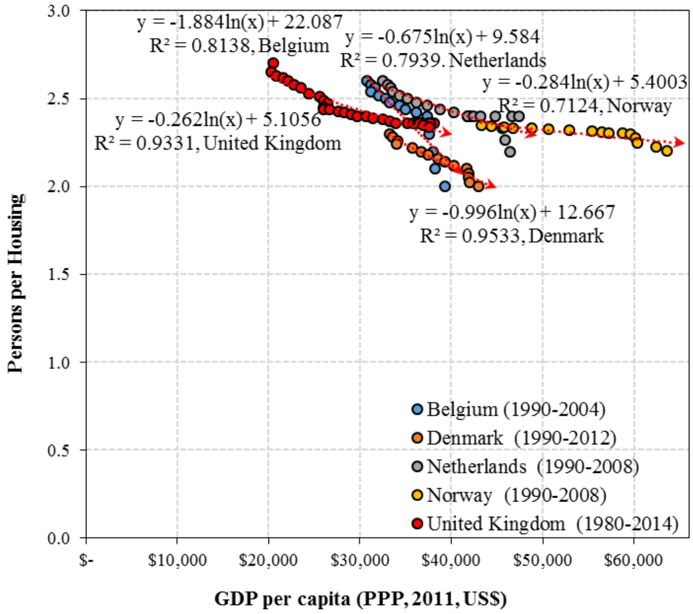
1. GDP per capita, PPP (2011, $) from PricewaterhouseCoopers LLP (PWC) (2015), Ward (2012) and World Bank (2015b), (2008)
2. Floor area per capita in EU from International Energy Agency (2007), Rector R (2007), The ENTRANZE Project (2008a), Ministry of the Interior and Kingdom Relations (2010) and Ozcebe *et al.* (2014)
3. Floor area per capita in The UK from Boardman *et al.* (2005), DCLG (2010), DCLG (2013) and ONS (2014c)

B

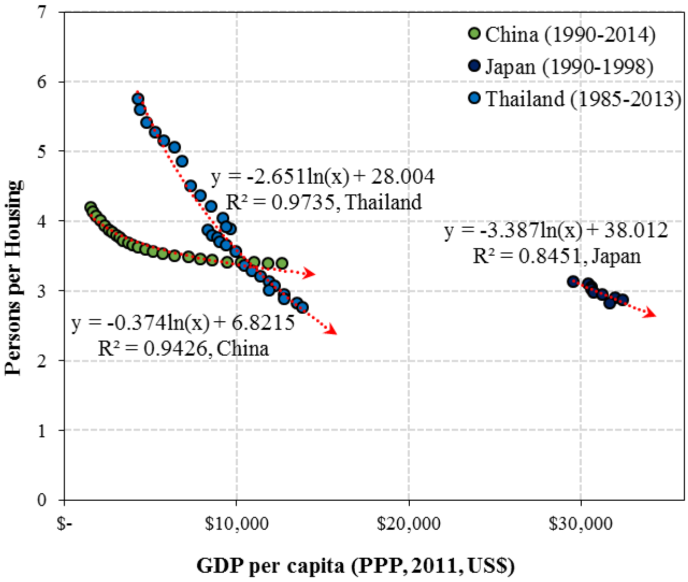
4. GDP per capita, PPP (2011, $) from PricewaterhouseCoopers LLP (PWC) (2015), Ward (2012) and World Bank (2015b), (2008)
5. Floor area per capita in China and Thailand from OECD (2013) and World Bank (2015e), (2015d)
6. Floor area per capita in other Asian countries from HelgiLibrary (2015)

4.2.3.4.2 Historical Regression of Persons per Dwelling to GDP per Capita, PPP in Some European and Asian Countries

Relating to higher GDP per capita (PPP, 2011, US$), average numbers of people in European houses seem slightly lower, as changing to be a single family occurred over a long time. Asian countries, with lower average income per person, have rapidly reduced family size or by turning from multi-families per dwelling to a single family per dwelling (**Figure 4-26**).



A



B

Figure 4-26 Historical regression of persons per dwelling to GDP per capita (PPP, 2011, US$) in some European (A) and Asian (B) countries

Sources: Author based on

A

1. GDP per capita, PPP (2011, $) from PricewaterhouseCoopers LLP (PWC) (2015), Ward (2012) and World Bank (2015b), (2008)
2. Persons per housing in EU from Ministry of Infrastructure of the Italian Republic (2006), Bergsdal *et al.* (2007b), Ministry of the Interior and Kingdom Relations (2010), Eurostat (2015a) and Eurostat (2015b)
3. Persons per dwelling in The UK from Boardman *et al.* (2005), DCLG (2010) and ONS (2014c)

B

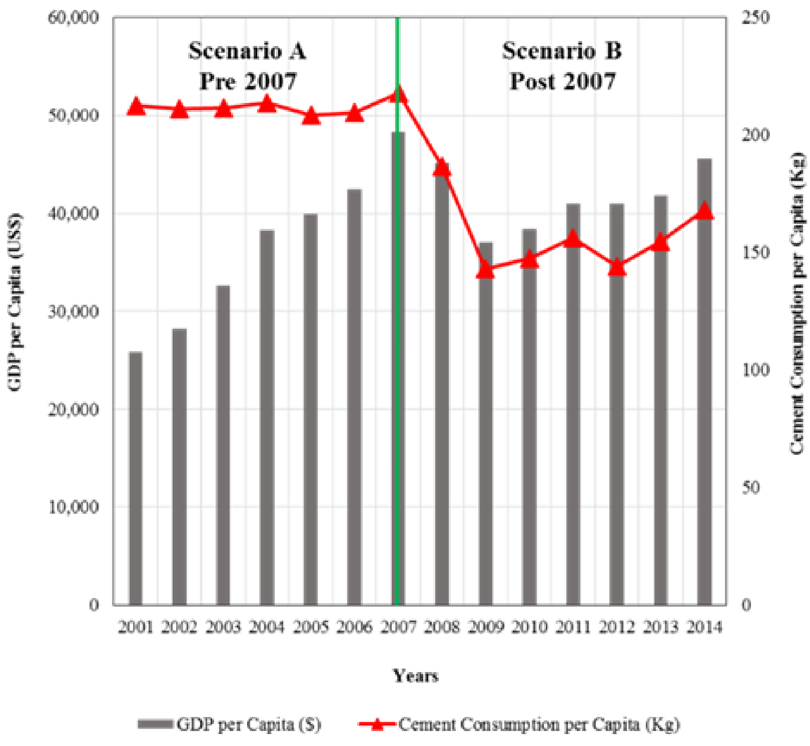
4. GDP per capita, PPP (2011, $) from PricewaterhouseCoopers LLP (PWC) (2015), Ward (2012) and World Bank (2015b), (2008)
5. Persons per housing in China from Zhou *et al.* (2008)
6. Persons per housing in Thailand from Bureau of Registration Administration (2015)
7. Persons per housing in Japan from Flath (2002)

4.2.3.5 Comparisons of National Construction Materials

In Thailand, Kofoworola and Gheewala (2008) reported that three main construction materials for a Thai office building presently are 79.4% concrete by weight followed by 13% brick and 5.6% steel respectively. For Thai housing, Tikul and Srichandr (2011) reported that concrete is also a main material at 75% by weight, followed by 20% brick and 5% others currently. Moreover, they reported that concrete has the greatest environmental impact representing up to 2.55×10^7 gCO_2eq or 54.80% in Thai residential building with 50 years of its lifespan (Tikul and Srichandr, 2011). In contrast, important construction materials for a UK housing sector are bricks and concrete in equal ratios (45% by weight), followed by 10% other materials such as gypsum, ceramic tiles, insulation, inert matter, lumber and U-PVC (Cuéllar-Franca and Azapagic, 2012). Due to the dominance of concrete components, this part emphasises only on cement and aggregate demands.

4.2.3.5.1 Cement Demand

Figure 4-27 shows main characteristics of cement consumption per capita (kg) relating to GDP per capita (US$) in Great Britain and Thailand. This study separated characteristics of Great Britain and Thailand cement consumption into two main scenarios as (1) Scenario A-pre 2007 and (2) Scenario B-post 2007. As seen, cement consumption was previously influenced by business as usual as the rapid growth in construction. Since 2007, present cement consumption in both countries has more directly followed the fluctuation of economic constraints measured by GDP per capita.



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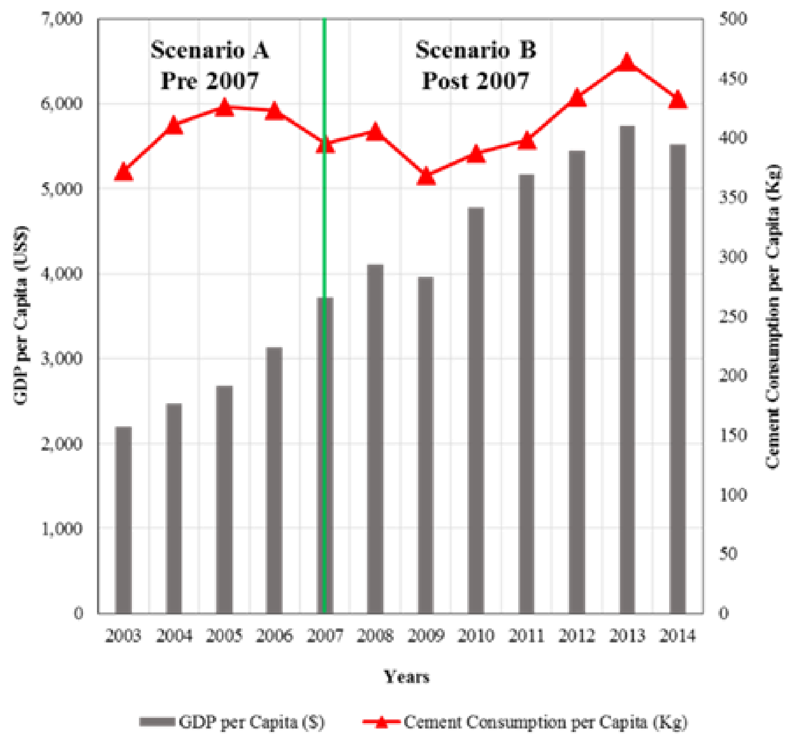


B

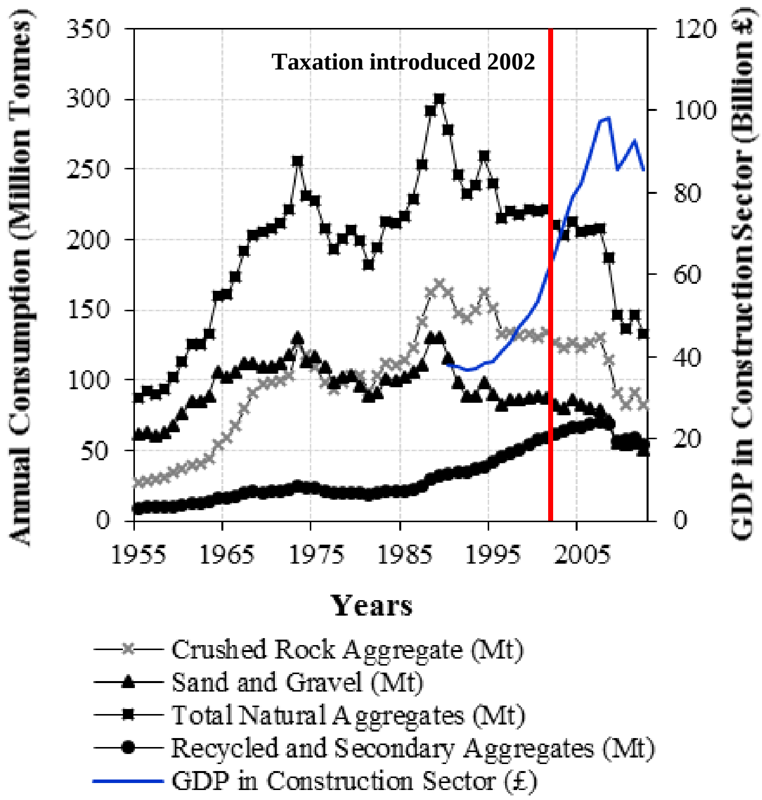
Figure 4-27 Comparison of cement consumption per capita and GDP per capita ($) in Great Britain (A) and Thailand (B)

Sources: Author based on A: ONS (2011a), ONS (2012d), ONS (2012c), ONS (2012a), National Records of Scotland (2013), ONS (2013d), ONS (2014a), World Bank (2015a) and MPA (2015c) including B: TFCM (2015) and (World Bank, 2015a)

4.2.3.5.2 Aggregates Demand

Primary aggregate consumption in Great Britain fluctuated independently and then its consumption trends were significantly reduced due to the operation of the Aggregate Levy since its enforcement in 2002 (red lines, **Figure 4-28A** and **B**). However, a direct connection, like both national cement demands, can be clearly seen in the recycled aggregate trend of Great Britain with both GDP UK construction sector and total UK GDP. Moreover, apart from the GDP relationship, other reasons (e.g. changes in construction design and efficiency) may relate to the reduced demand of primary aggregate.

Without identifying types of aggregates and data concerning recycled and secondary aggregates for concrete and construction like Great Britain, Thailand uses only indigenous aggregates and reports only primary limestone for construction uses that has recently tended to increase in consumption (**Figure 4-29**).



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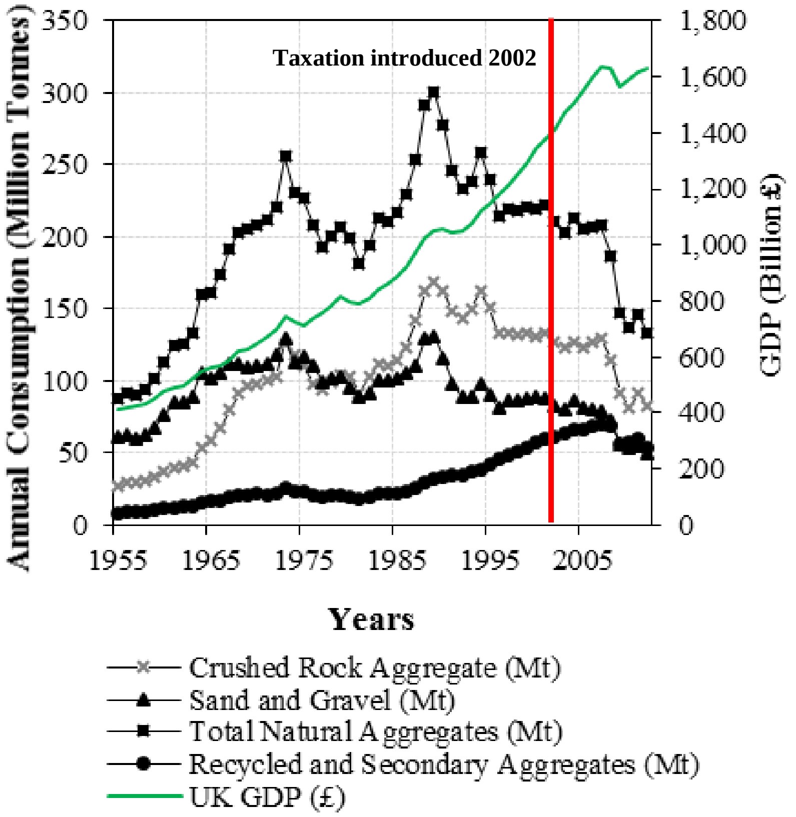


B

Figure 4-28 Great Britain estimated consumption of natural aggregates 1955-2012 comparing to UK GDP in construction sector (£, A) and comparing to UK GDP (£, B)
Source: Author based on BGS (2014c) and ONS (2013c) (A) including BGS (2014c) and ONS (2015b) (B)

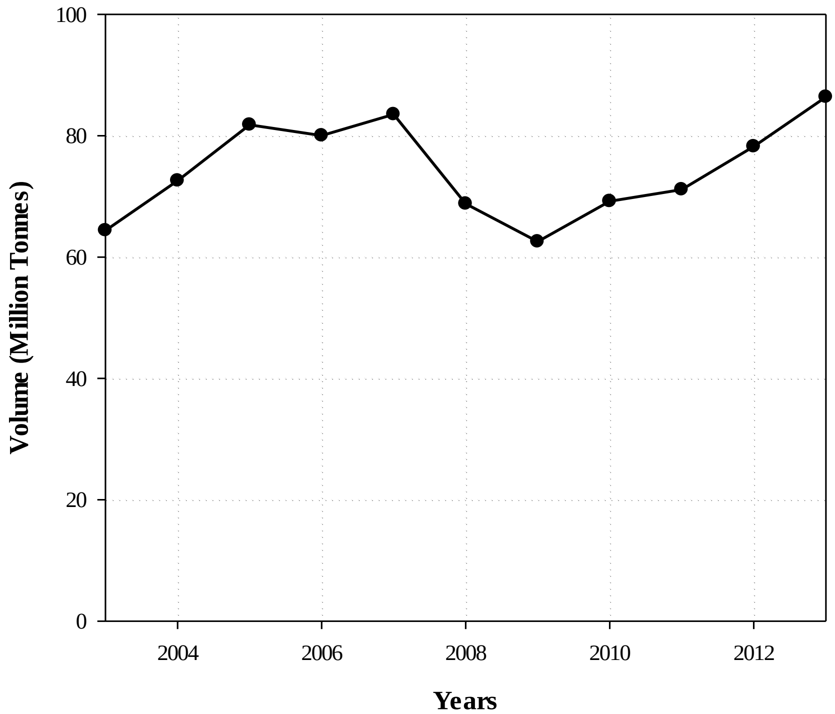


Figure 4-29 Limestone consumption for Thai construction
Source: Author based on Information Technology Centre (2006a); (2009a); (2012a) and (2014a)

4.2.3.6 Forecasting Factors

4.2.3.6.1 Floor Area per Capita

This forecasting part used historical regression equations from recorded floor area per capita (FAC) in Great Britain and Thailand supported by Chinese data, together with the past, present and future of GDP per capita (PPP, 2011, US$) of both national case studies from the World Bank. Then, these results were combined with 'what if analysis' to illustrate future predictions of FAC in Great Britain and Thailand until 2100 in three levels: low, medium and high (**Figure 4-30**).

For Thailand, historic data for SDA calculations used Chinese data for support. As seen in **Figure 4-30**, FAC trends of both Great Britain and Thailand have similar characteristics when compared with some European and Asian countries (**Figure 4-25**). This thesis selected only medium FAC patterns of Great Britain and Thailand for calculating their SDA scenarios assuming a continuous growth of GDP.

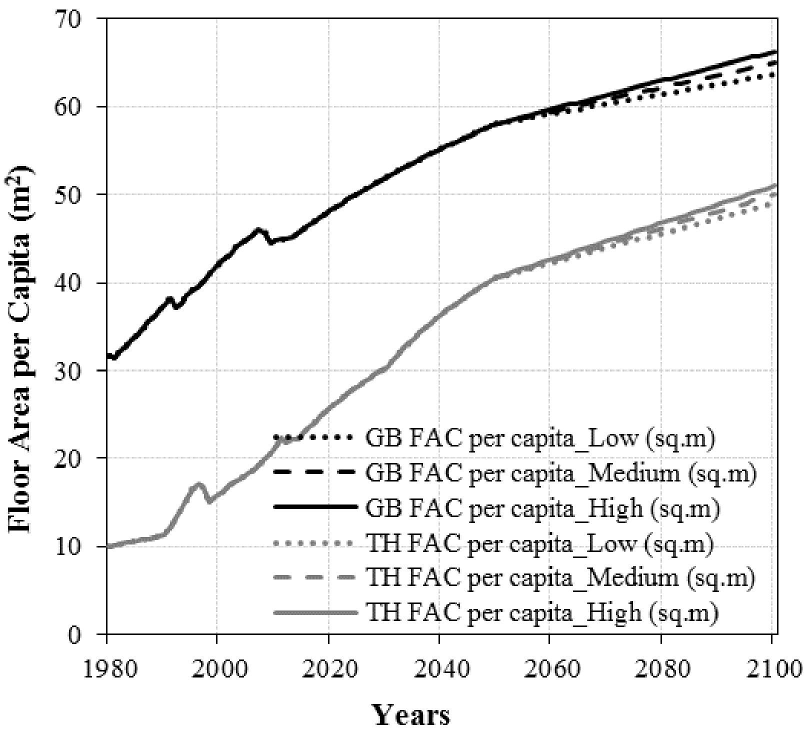
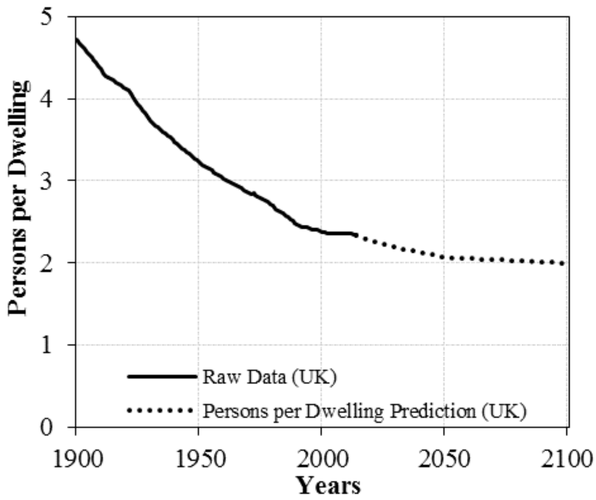


Figure 4-30 FAC Forecasts using the past, present and future of GDP per capita (PPP, 2011, US$) in the UK and Thailand (1980-2100)
Sources: Author based on

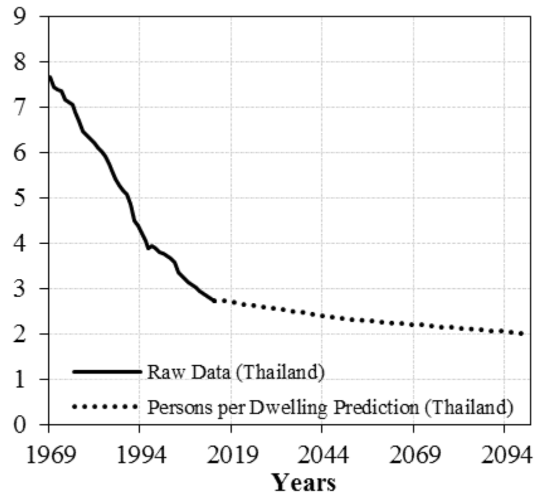
1. GDP per capita (PPP, 2011, US$) from PricewaterhouseCoopers LLP (PWC) (2015), Ward (2012) and World Bank (2015b), (2008)
2. FAC in the UK from Boardman *et al.* (2005), DCLG (2010), DCLG (2013) and ONS (2014c)
3. FAC in Thailand from OECD (2013) and World Bank (2015e), (2015d)

4.2.3.6.2 Persons per Housing Unit

Presently, a global housing size has reduced to be a single family mostly, as shown in **Figure 4-24B**. In Great Britain, household membership has decreased since 1900, from 4.7 people to 2 in 2100. For Thailand, reduction in family size has quickly fallen compared to the UK. Therefore, this important situation implies that Thai families require construction of more new houses because of a rapid expansion of the number of families. Using ‘what if analysis’, forecasts of the future number of persons per dwelling by GDP per capita (PPP 2011, US$) in the UK (A) and Thailand (B) are shown in **Figure 4-31**.



A



B

Figure 4-31 Forecasts of persons per dwelling using the past, present and future of GDP per capita (PPP 2011, US$) in the UK (A) and Thailand (B) between 1900-2100
Sources: Author based on:

A

1. GDP per capita, PPP (2011, $) from PricewaterhouseCoopers LLP (PWC) (2015), Ward (2012) and World Bank (2015b), (2008)
2. Persons per dwelling in The UK from Boardman *et al.* (2005), DCLG (2010) and ONS (2014c)

B

3. GDP per capita, PPP (2011, $) from PricewaterhouseCoopers LLP (PWC) (2015); USDA (2015a); Ward (2012) and World Bank (2015b), (2008)
4. Persons per dwelling in Thailand from Bureau of Registration Administration (2015)

4.2.3.6.3 Lifetime Distributions

The definition of lifetime distribution and renovation cycles are not well understood (Sandberg *et al.*, 2016). This research adopted a normal distribution function and defined the mean (τ) in lifetime and demolition profiles of Great Britain (75, 100 and 125 years) and Thailand based on the Chinese experiences (25 and 50 years) following Sartori *et al.* (2008) and Hu *et al.* (2010c) respectively. In addition, all scenarios assumed that standard deviation (σ) = 0.25τ (Sartori *et al.* (2008), **Figure 4-32**). More widely, lifetime distributions represent housing age of both countries. Great Britain housing, like other European countries, has a longer lasting time for use than Asian housing on account of its longer lifespan, more renovation activities and better construction quality.

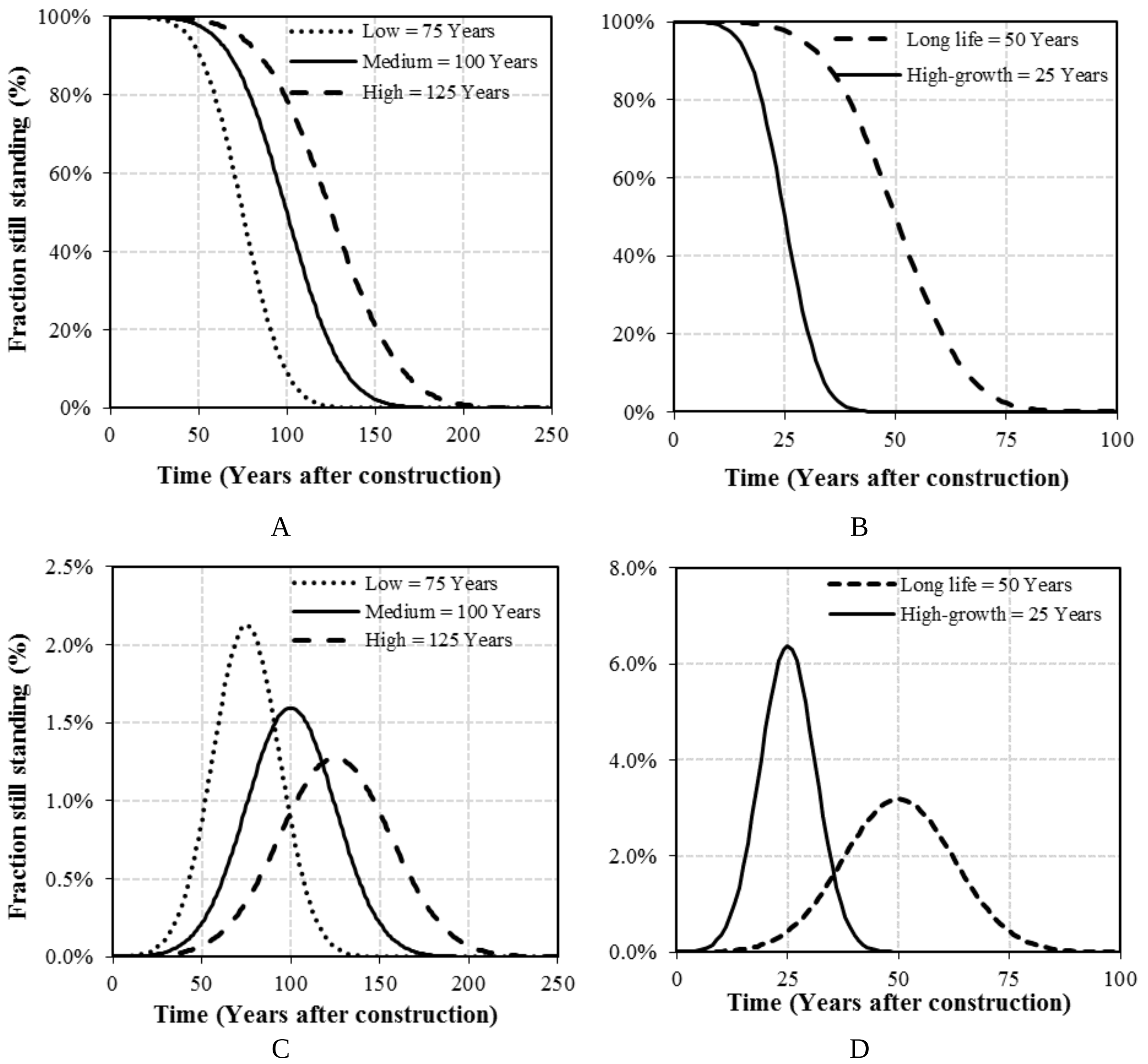


Figure 4-32 Lifetime profile for Great Britain (A) and Thailand (B) including demolition profile after construction for Great Britain (C) and Thailand (D)
Sources: Great Britain and Thai used figures of demolition and lifetime profiles from Sartori *et al.* (2008) and Hu *et al.* (2010c) (Chinese figures) respectively

4.2.3.6.4 Concrete Density

For both Great Britain and Thailand, this research used a figure of concrete density following the Dutch and Chinese researches by Müller (2006) and Hu *et al.* (2010c) that is 2.1 tonnes per square meter floor area (t/m^2).

4.2.3.7 Scenario Analysis

It can be clearly seen from SDA scenarios of Great Britain and Thailand that longer housing lifespan is linked to lower amount of concrete demand for construction and concrete waste occurring in the future (**Figure 4-33** and **Figure 4-34**). Although Great Britain and Thailand have a similar amount of population presently, the requirement of new housing and concrete for housing construction is different, as Great Britain demands lower concrete for construction than Thailand in the same time period due to the longer lifespan of the Great Britain housing. Other important reasons include that Great Britain has more renovation activities and better housing quality that are required to support its weather.

Moreover, **Figure 4-33** and **Figure 4-34** also show the predicted volumes for FAC and concrete for the residential sector of Great Britain and Thailand. The modelled curves for construction have many spikes and this reflects the input data. The key output from these graphs is the predicted waste production. For Great Britain, it rises slowly to 30-70 Mt depending on the assumed lifespan, by 2100. For Thailand concrete waste production rises to 40-50 Mt, but by 2050.

These SDA outcomes help Thailand to know the critical time for preparing the integrated policy to support the increase in construction activities and materials presently and to protect the environment in the future for disposal of waste from housing with a shorter lifespan. **Figure 4-34** illustrates that Thailand requires more construction materials, particularly concrete, to support the housing construction than Great Britain. It can also be expected that Thailand will have more concrete waste from the housing sector between 2020 and 2050 which is quite a similar volume to Great Britain in 2100, using 25 years for a Thai housing lifespan scenario.

Because of a longer lifetime of the housing sector, Great Britain has longer-lived stocks of floor area, and uses a lower amount of concrete with less volume of future concrete waste than Thailand. More importantly, Great Britain has more support than Thailand to cope with national housing construction and waste, including integrated policy and environmental taxes for construction materials and waste, and the recycled aggregate system.

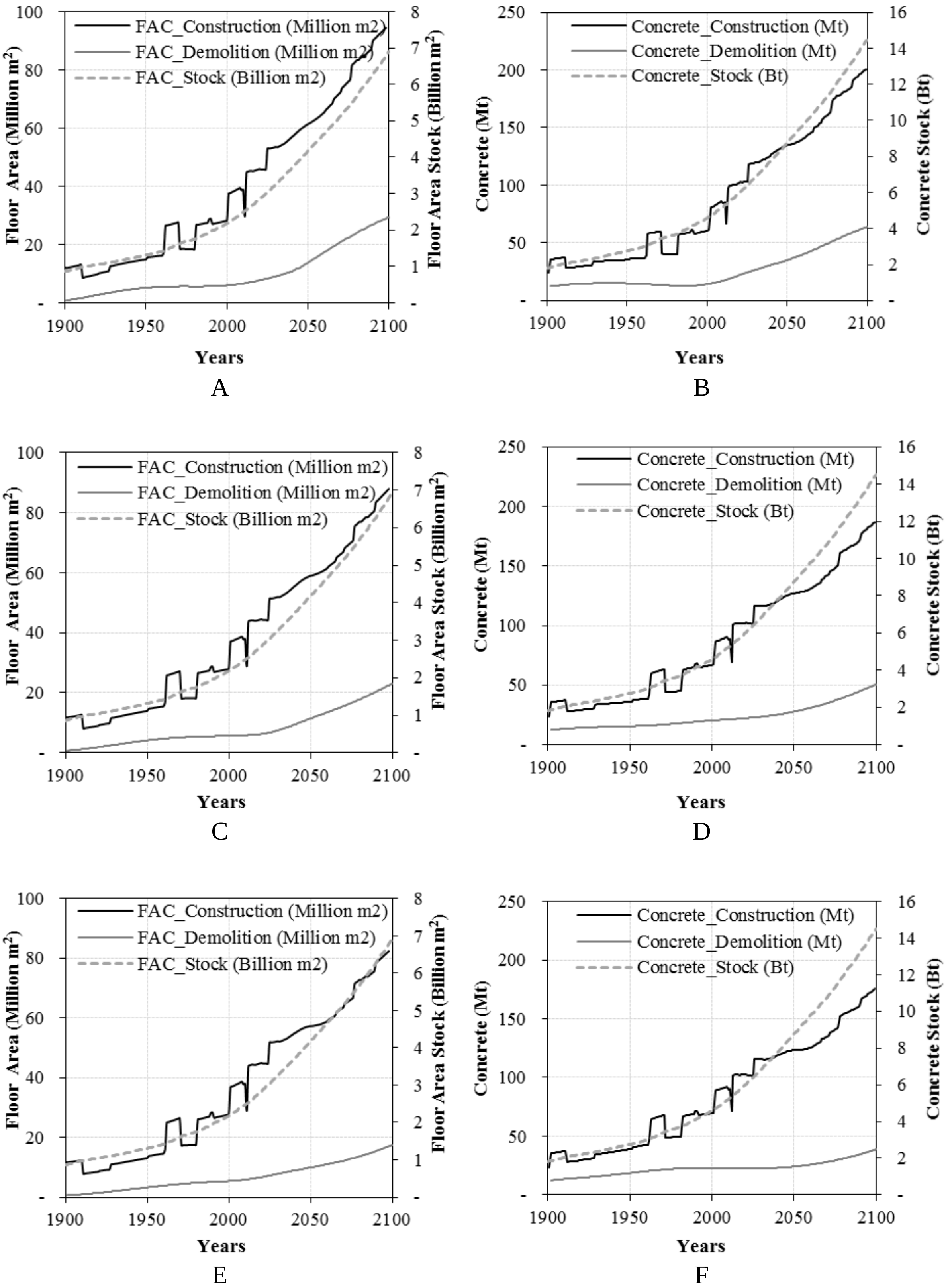


Figure 4-33 SDA results: FAC (m^2) in construction and demolition including concrete demand and waste (tonnes) for a housing sector in Great Britain by different housing lifespan (75, 100 and 125 year respectively)

Note: construction and demolition including concrete demand and waste for a housing sector by different housing lifetime: 75 years (A and B), 100 years (C and D) and 125 years (E and F)

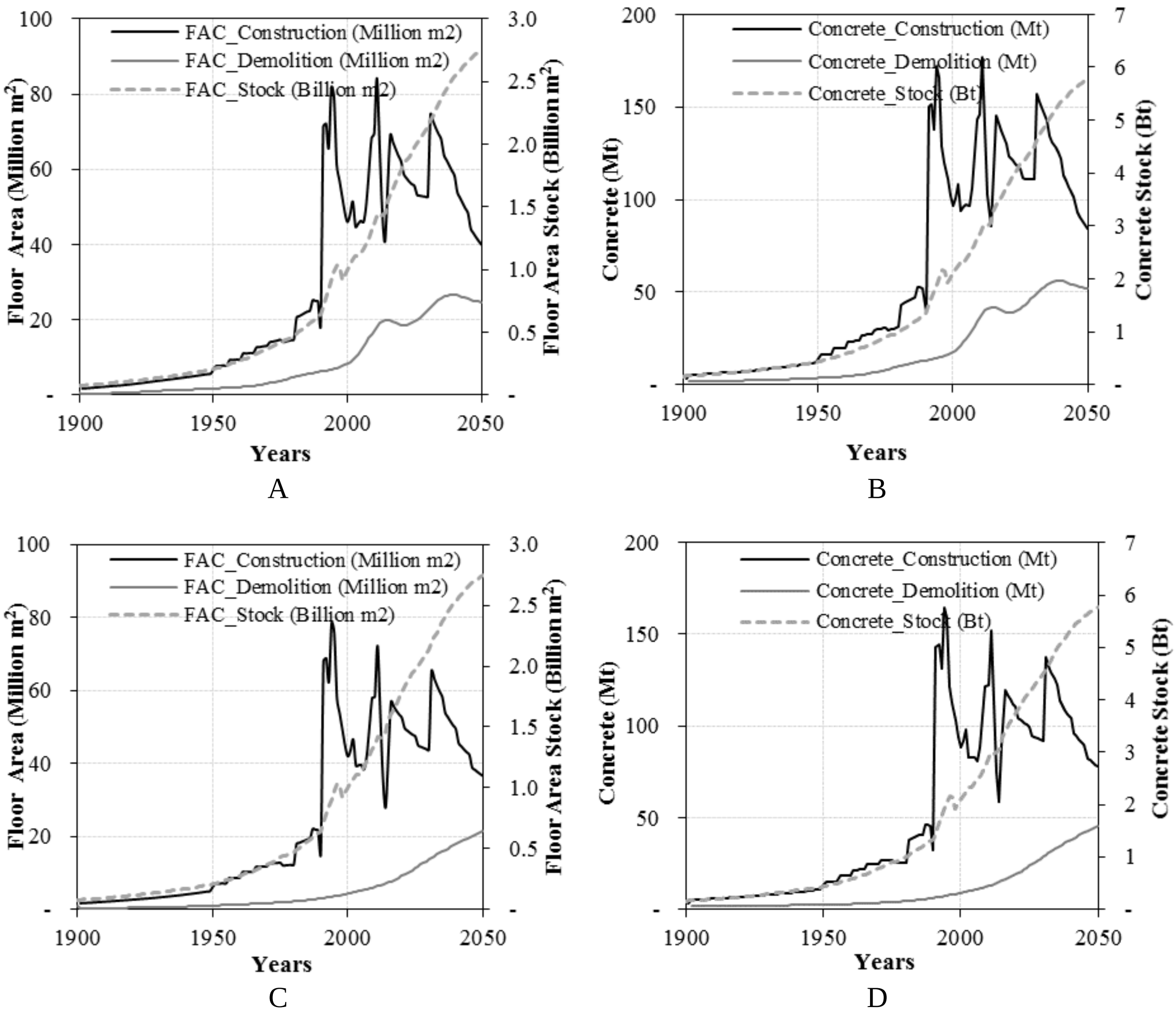


Figure 4-34 SDA results: FAC (m^2) in construction and demolition including concrete demand and waste (tonnes) for a housing sector in Thailand by different housing lifespan (25 and 50 year respectively) **Note**: construction and demolition including concrete demand and waste for a housing sector by different housing lifetime: 25 years (A and B) and 50 years (C and D)

4.3 Summary

4.3.1 Method Summary

Overarching methodological frameworks of this thesis consist of four main steps as (1) national cement production, (2) annual concrete stock, (3) future concrete stock (only housing sector) and (4) comparison of regions and countries. These frameworks used each step of calculations by two main methods: Material Flow Analysis: MFA for annual concrete stock including national cement calculations by the clinker calcination processes and Stock Dynamic Analysis: SDA in only the housing sector as the main concrete use in Thailand.

For MFA, this study used recorded data of clinker volume from governments and industries of Great Britain and Thailand in 2012 as the initial figures to calculate forward and backward with other referencing figures in order to comprehend the quantity of clinker components, CO_2

emission and trading clinker. Then, domestic clinker outcomes of both countries were added with additives and cement trading quantity to give domestic cement used in 2012. Eventually, these clinker and cement outcomes were combined with data of the annual concrete aggregates (both primary and recycled concrete aggregates for Great Britain and only primary aggregates for Thailand) from the aggregate markets for the construction industries as the annual concrete stocks in 2012. These stocks of two national case studies were separated into each construction sector to illustrate types of national concrete requirements more clearly.

Currently, primary aggregate use for the concrete industry is the most part (36%) in Great Britain. Therefore, Great Britain has considerable emphasis on recycled aggregate activities. Achieving the highest rate (29%) of recycled aggregate recovery in 2012 and fulfilling of C&D waste management targets make Great Britain suitable to show as a good case study among the EU. This calculation part can provide the potential of recycled aggregate operations following the EU aspects of the hard-inert waste management espectially concrete waste in Great Britain.

As the housing sector is the main construction sector in Thailand it is appropriate to start interrogating future problems in this sector to develop policy and taxation. This part also includes other important factors of Thailand comparing to Great Britain such as lower renovation activities, shorter housing lifespan and poorer housing quality. Supported by the increase in GDP, this thesis used SDA to forecast future floor area in use and for demolition including future concrete demand for housing construction and predicted concrete waste. Finally, the last step is comparing all MFA and SDA outcomes with EU strategies and actions of Great Britain, along with implementation approaches of ASEAN countries representing by Thailand.

4.3.2 Results Summary

As widely known, concrete consumption relies on the national economy and well-being. This chapter, therefore, applied Material Flow Analysis (MFA) to identify an annual pattern of construction material flows by setting boundaries of space and time, together with data from national cement industries by calcination calculations. Then, Stock Dynamic Analysis (SDA) has been used to interrogate a national housing sector for understanding demand (floor area per capita: FAC) and supply (concrete in use: CU) for construction and demolition activities including the estimated amount of future concrete waste using national housing lifespan. These outcomes can be linked with national sustainability policy, taxation and strategy of Great

Britain and Thailand including for comparison with regional perspectives of the EU and ASEAN.

4.3.2.1 MFA Results

Cement and concrete industries in Great Britain and Thailand were selected to estimate flows in all steps for producing domestic concrete in 2012. This study also concerns flows of import and export of clinker and cement together with waste and emission from cement and concrete manufacturing and consumption. For the aggregate market, a whole system of primary and recycled/ secondary aggregate markets in Great Britain was investigated as a good case study in the EU. In Thailand, a part of the primary aggregate for only concrete was computed.

This study uses Great Britain ratios to estimate some Thai figures such as additives, cement for mortar and primary aggregate for the concrete industry. Furthermore, the MFA results used Sankey diagrams to emphasise the importance of:

- **Key mineral-based components**: These principal minerals (limestone, shale and aggregates) are essential for cement, aggregate, concrete and mortar as the construction materials. Because of a higher volume of domestic consumption and export, Thailand required the higher quantity of these mineral-based components than Great Britain by around 4-6 times in each case.
- **CKD**: Higher CKD waste volume makes the excess requirement for clinker minerals and fuels, and it causes higher CO_2 emission from both calcination and combustion stages. Therefore, CKD volume should be reduced as much as possible.
- **Alternative fuels**: They are an important function in the worldwide cement industry because they can be used to save conventional fuels and to reduce CO_2 emission.
- **Additives**: These materials should be paid attention to the future demand and supply by focusing on the utilization of waste as the first priority.
- **Clinking manufacturing processes**: The dry process requires lower heat and fuels and generates lower CO_2 emission than the wet process.
- **Patterns of import/export clinker and cement**: The pattern of less export of clinker and cement for Great Britain contrasts with clinker and cement being important export products in Thailand. The results showed that, in 2012, Thai exports of cementitious products are around two times the amount of annual cement used for concrete for the whole of Great Britain.

- **Patterns of domestic cement consumption**: Although the populations in both countries were almost equal in 2012, Thailand consumed 4.05 times more cement than Great Britain.
- **Primary and recycled aggregates**: Both primary and recycled aggregate are used in Great Britain in concrete and construction industries. Although Great Britain achieves the highest rate of recycled and secondary aggregates in the aggregate market (29% of input aggregates in 2012) among European countries, this study found that Great Britain used recycled aggregates below capacity. As seen, Great Britain still has more potential to increase the use of recycled aggregates, especially in the concrete industry.

  In contrast, Thailand uses only primary aggregates with no specifically recorded data for any aggregate use and has no recycled aggregates used for the concrete industry, due to the high volume of concrete waste and cheap price for primary aggregates without the aggregate levy in Thailand.
- **Waste chains**: Wastes during the manufacturing/operating of cement, concrete and construction should be a concern and reduced by the best practices of manufacturers and contractors in particular including other stakeholders.
- **Patterns of concrete use**: Thai annual increase of the concrete stock in 2012 was approximately 3.78 times (256.14 Mt) higher than Great Britain (67.73 Mt). Moreover, Great Britain construction used the highest volume of concrete and mortar for non-residential buildings, while the residential building was the main sector of the concrete and mortar use in Thailand.

4.3.2.2 SDA Results

This SDA part is linked with the MFA calculations. As known from the MFA results, the housing sector is the main construction type, mostly using concrete and mortar in Thailand. Although both national case studies have a similar amount of population currently, the space of FAC and quantity of concrete demand for construction including concrete waste after demolition were different due to their future population, floor area demand (relating to GDP trend as the direct relationship) and lifespan of both national housing.

As the main reason is a shorter lifetime of housing, Thailand presently requires more concrete for new housing construction. By 25 years of Thai housing lifespan, between 2020 and 2050, Thailand will have more future concrete waste that needs to be disposed of properly than Great Britain, which will have a similar volume at the 100 years of housing lifespan in 2100. For the longer lifespan scenario for Thailand (50 years), a large volume of concrete waste occurred later (after 2050).

Unlike Great Britain, Thailand still has no plan, policy and taxation that encourage more sustainable use of aggregates and other construction materials. Thus, to support these national housing issues presently, it is an appropriate time for Thailand to establish an integrated policy to cope with the increased requirement of floor area and concrete in construction, especially as the model predicts an enormous amount of future concrete waste after the demolition stage given the short lifespan of housing.

Chapter 5 Discussion

In accordance with the aim and objectives introduced in Chapter 1, this Chapter discusses the most important findings and key themes of the thesis, including further important and relevant aspects. Annual and future concrete stocks were introduced, applied and described using Material Flow Analysis (MFA, including use of calcination calculations to estimate raw materials) and Stock Dynamic Analysis (SDA) for Great Britain and Thailand in Chapters 2 to 4. Based on values and recommendations arising from these methodologies, the outcomes can be used to identify, compare, choose and establish suitable alternatives for national policy and taxation of construction materials in Thailand and potentially other ASEAN countries, learning from good practices of the EU and Great Britain as the step 4 comparison of regions and countries in Chapter 4 (4.1.1 Overarching Methodological Frameworks).

5.1 Sustainability in Policy and Taxation

As mentioned in the literature review, integrated policy and taxation based on EU implementation and strategy for its members are vital in Great Britain, in practice involving co-operation by all stakeholders, government, private and civil sectors. As a result, in the EU, Great Britain consumes the highest rate of recycled aggregates, comparing to its total aggregates, used for all purposes (The European Environment Agency, 2008; The Concrete Centre, 2009; MPA, 2013c) and achieves the target of C&D waste management (Monier *et al.*, 2011; Defra, 2015a).

A number of lessons can be learnt from Great Britain and the EU regulation that encourages Great Britain to reach its targets using the regulatory tools summarised in **Figure 3-10**. This acheivement is supported by (1) systematic recorded data, (2) integrated sustainability policies and regulations, (3) environmental taxes and (4) environmental funds. However, the early stages of this approach in Great Britain did involve problems relating to fly tipping and also abuse of the environmental funds, which were sometimes used fraudulently (Martin and Scott, 2003; Bartelings *et al.*, 2005). Such problems are likely to arise in other jurisdictions, and care must be taken to minimise them.

Thailand, with higher domestic consumption and higher export of cementitious materials (**Figure 2-42** and **Figure 2-45**), considers the concept of sustainability in terms of the Philosophy of Sufficiency Economy of His Majesty King Bhumibol Adulyadej, but only at a level of the national plan (National Economic and Social Development Board, 2011). There is less tangible implementation, a weak relationship among related organisations (**Figure 2-59**), out of date regulations (**Figure 2-58**) and inconsequential spending in government budgets for waste management, with less concern in C&D waste management (**Figure 2-60**) and no environmental taxes.

There is only limited interest in this topic as a research activity in some universities and private sector organisations in Thailand. These significant issues can lead to problems of construction material supply that affect Thai natural resources and waste management, more widely relating to regional perspectives of ASEAN countries, which seem more concerned currently only with national and regional economic development.

Thus, the EU and Great Britain's approach to construction materials, summarised in **Figure 3-10**, can be adjusted to support Thailand and other ASEAN countries for improving integrated national and regional perspectives in environmental policy and taxation, following the concept of sustainable development and the real requirement of the Thai king's philosophy.

5.2 National Cement Production

An initial objective of the thesis was to calculate the quantity of raw materials used by both national cement industries, based on calcination characteristics and some recorded data from Great Britain to estimate cementitious products, fuels and additives including CKD and CO_2 emissions. Like other developing countries, Thailand requires more clinker and cement for domestic uses, together with trading products for ASEAN counties in particular (**Figure 2-42** and **Figure 2-45**). Although the Thai cement industry is expanding its investments and markets in other Asian countries (e.g. Vietnam, Cambodia, Laos), the cement export volume using Thai natural resources is still high. Therefore, the Thai government should consider this situation and introduce more supportive measures to control the use of Thai natural resources by the cement industry, as these are non-renewable.

In 2012, one interesting finding for the Thai cement industry (**Figure 4-12**) was that the trading volume of cementitious products (clinker and cement) was two times higher than the domestic cement required for the concrete industry in Great Britain (**Figure 4-11**). Because of its higher requirement for cementitious materials for domestic consumption and export, Thailand consumed around 4-6 times greater amounts of clinker and cement, with correspondingly higher use of natural resources (and generation of wastes) such as the main mineral raw materials (limestone and shale), additives, conventional and alternative fuels. Also, Thailand produced nearly 6 times more CKD and CO_2 emissions than Great Britain.

Because of global concern about climate change, the EU Emissions Trading System (EU ETS), implemented in 2005, aims to reduce greenhouse gas emissions from electricity generation and heavy industry, including combustion plants such as cement. This system pushes the UK government forward to consider both business and environmental targets for continuing UK industrial production and at the same time reducing CO_2 emission, using low carbon technologies (Parliamentary Office of Science and Technology, 2012).

For new practices in UK cement production, MPA (2016b) states that a novel low carbon cement (1) can embody less energy than traditional Portland cement, including those that contain additional inorganic/mineral constituents; (2) can be manufactured using a novel process that ideally utilises waste-derived fuels and raw materials and (3) can be expected to reduce both waste and emissions, such as CO_2 in particular. In addition, the Parliamentary Office of Science and Technology (2012) suggested that there are three options for CO_2 reduction in cement manufacturing by (1) making less clinker, (3) using a different reaction or (3) capturing/storing the CO_2.

New cement to reduce energy and CO_2 emitted from cement manufacture can be developed by adjusting cement recipes and yet maintaining the same quality of cement. New trends of global cement production can affect results from the calcination calculation in particular for limestone and shale, because 60% of cement emissions come directly from the chemical reaction of raw minerals (**Figure 2-2**; Parliamentary Office of Science and Technology (2012)). Therefore, the development of new types of low carbon cement, with lower mined material inputs, can disturb the MFA results generated in this study, regarding the estimation of the quantity of particular raw minerals (limestone and shale), fuels (both conservative and alternative), additives from wastes and emissions (CKD and CO_2).

5.3 Annual Concrete Stocks by Material Flow Analysis

This part of the study aims to quantify annual concrete use in construction in both nations (2012), following the study of Müller (2006) who considered the timber and minerals cycle of the Dutch construction industry. Annual concrete stocks were estimated using MFA to combine figures from national cement industries with recorded volumes from manufacturing and government data such as all aggregates used for concrete, other concrete components and waste. In addition, this study used the proportion of aggregates and cement for concrete manufacturing in Great Britain to calculate Thai figures due to the lack of recorded data for virgin aggregates. Furthermore, other missing figures needed for MFA for the Thai concrete industry were also calculated using proportions based on Great Britain data, such as additives and waste occurring during delivery and construction.

From the MFA results (**Figure 4-11** and **Figure 4-12**), the most obvious finding to compare from the analysis is the difference in the flow of cement, aggregates and concrete used in Great Britain and Thailand. In 2012, Thailand used more concrete for its construction activities than Great Britain by nearly four times, although the two countries had similar population, and Great Britain had two times higher population density than Thailand. Importantly, a weak point of the concrete outcomes is that popular types of concrete used in both countries are different. Great Britain mostly uses precast and ready-mixed concrete in which all components are controlled by manufacturing recipes and standards. Thailand uses this manufactured concrete only in cities, and mostly applies site-mixed concrete particularly in rural areas, which means that Thai concrete components and properties can be varied by contractors.

Residential building was the main construction type in Thailand with fewer renovation activities, measured by permitted floor area (<10%, **Figure 2-52**, National Statistical Office (2013a)). In contrast, the repair and maintenance value of the residential sector in Great Britain was higher, at around 47-64% (**Figure 2-31**, ONS (2008a); (2009a); (2010a); (2011c); (2012b); (2013b) and (2014b)). This is the main reason that made the demand of annual concrete used for the housing construction in Great Britain (37.01%, 25.07 Mt) to be lower than Thailand (51.51%, 131.94 Mt), and most of the concrete consumption in Great Britain was for non-residential building (44.07%, 29.85 Mt).

However, this thesis had to use proportions of national construction types to separate and to understand the annual concrete contribution into each construction sector as seen in **Appendix C**. The observed difference between Great Britain and Thailand that needs attention is the reporting formats of construction. Thailand reports new and modified construction using ‘permitted floor area in use’ (National Statistical Office, 2013a), and in contrast the value of buildings, with proportions of different types of new residential completion, is used in Great Britain (ONS, 2013b; DCLG, 2014).

Presently, Great Britain returns some recycled aggregates to use in concrete manufacture, following improved standards from the British Standards Institution (BSI, e.g. (1) BS EN 206:2013 (BSI, 2013a), (2) PD CEN/TR 16563:2013 (BSI, 2013d), (3) PD CEN/TR 16912:2016 (BSI, 2016) and (4) PD 6682-1:2009+A1:2013 (BSI, 2013c). To convince its contractors and users to use these recycled materials, Great Britain has the Mineral Products Association (MPA) as one example of a private partnership involving all manufacturers of heavy construction materials. Great Britain has established some related organisations, supported by the environmental taxes, such as the Waste & Resources Action Programme (WRAP), to encourage and enable businesses and consumers to achieve more efficiency in materials use and in recycling. It apparently seems that all related organisations of construction materials in Great Britain behave more cooperatively to comply with their obligations, following the national and regional defined targets.

In contrast, Thailand uses only virgin aggregates for concrete manufacturing without any evidence of recycled aggregate use due to the cheaper price (with no Aggregate Levy) for virgin aggregates, unlike Great Britain. Thailand also has no important criteria to start its policy and taxation properly for construction materials in terms of natural resources and waste management, such as a recording system, a permit system, national organisations, a public–private partnership and C&D waste management regarding a recycled concrete aggregate system and environmental taxes. Like Thailand, other ASEAN countries still have no supporting policy and taxation and no cooperation among the region. These natural resource and environmental issues should be considered together with the economic cooperation of the ASEAN community under the sustainability concept.

Virgin aggregates used in the concrete industry are one of the main components of the aggregate market in Great Britain (36.14%, MPA (2013c) and ONS (2014d)), and the government attempts to reduce the use of virgin aggregates in this manufacturing sector using their replacement by suitable proportions of recycled aggregates. Because of the close link between the integrated policy and environmental taxes (Landfill Tax and Aggregate Levy) under the EU action and strategy, Great Britain can achieve the highest rate of reused aggregates among the EU aggregate markets and the EU target of recycled activities of C&D waste management (The European Environment Agency, 2008; The Concrete Centre, 2009; Monier *et al.*, 2011; MPA, 2013c; Defra, 2015a).

Virgin aggregates can be replaced, to some extent, by controlled recycled aggregates in concrete. Therefore, Great Britain has agreed to reduce the use of virgin aggregates and set the target to increase the proportion of recycled and secondary aggregates to 25% of total aggregates in precast concrete by 2012, compared with 2008 (The European Environment Agency, 2008; The Concrete Centre, 2009; MPA, 2013c). However, The Concrete Centre (2013) reported that only 21.3% of aggregates used in 2012 were recycled or secondary origin for precast concrete. This lower use, comparing to its probable capacity (MPA, 2013b; MPA, 2013c; The Concrete Centre, 2013) and several important supports as above described, is the main reason leading some researchers to argue that although recycled and secondary aggregate use has more potential to increase, the present use of these alternative materials is hard to increase further in Great Britain (Thompson *et al.*, 2008; Mankelow *et al.*, 2010; Brown *et al.*, 2011).

5.4 Future Concrete Stocks by Stock Dynamic Analysis

As widely known, global population will increase continuously. UN (2015a) reported that the Great Britain and Thai populations are growing, and the Thai population will have a future reduced trend. Following the studies of World Bank (2015b,c), 80% of Great Britain's population already lives in an urban community. In contrast, Thai rural areas have steadily reduced in population due to rapid urbanisation. This reason pushes Thailand to require more fundamental elements for accommodating a fast expansion of its built-up communities, such as a rapidly increasing number of Thai households (**Figure 4-19**) with higher demand on construction materials such as cement (**Figure 3-2**), comparing to Great Britain.

As stated in **Figure 3-3** of the literature review, to understand both national housing sectors a strong relationship between GDP per capita and floor area in use can be confirmed by SDA results. Moreover, details of SDA findings for housing construction include prediction of floor area in use and in demolition, including future concrete demand and waste after the end of the housing lifespan. Concrete is a principle material for global construction, steadily growing for housing construction in particular. With other supporting criteria, a national growth in population, economy and urbanisation, requires effective national policy and regulation of construction materials and other associated factors such as higher housing quality, more renovation activity and longer housing lifespan.

Global GDP and extraction of construction materials have direct correlation. This situation also occurs in Thailand, as higher GDP pushes more domestic extraction of construction minerals as shown in **Figure 4-21**. To compare in more depth details of this relationship between developed and developing countries in cement consumption using the UK and Thai GDP, this study found a strong association between a lower income per person with a fast rate of GDP growth in Thailand, leading to higher expansion of personal cement consumption (around two times) than Great Britain with its higher personal incomes (**Figure 3-2**, **Figure 4-22**, **Figure 4-23** and **Figure 4-27**).

Then, demand of virgin and recycled aggregates is compared with GDP and environmental taxes from Great Britain's experience. As seen, after the enforcement of the Aggregate Levy in the UK (2002), use of virgin aggregates has clearly decreased, but the trend of recycled and secondary aggregates in Great Britain still follows the fluctuation of GDP of the UK construction sector and total UK GDP (**Figure 4-28**).

For European and Asian perspectives (**Figure 4-24**, **Figure 4-25** and **Figure 4-26**), higher GDP per capita relates to an increase in the personal floor area in the housing sectors. This financial measure also activates higher demand for construction activities and materials. Having higher personal financial status is also one of the reasons that changes a multi-family to be a single family with few members, and requires more residences to support this changing lifestyle in both regions. As seen in **Figure 4-30** and **Figure 4-31**, Great Britain and Thailand also follow the same situations of their regions.

The ENTRANZE Project (2008b) showed that for EU dwellings, according to construction date, housing in this region has a very long lifetime (**Figure 4-17**), and the UK has the oldest housing with associated high renovation activities (ONS, 2012b). Some evidence indicated that the UK residential building has low figures for new housing (7%) built after 2000 (The Chartered Institute of Building, 2013). Half of UK buildings have a lifespan more than 50 years, and a fifth are older than 100 years (the ENTRANZE Project, 2008c). This thesis used three scenarios of housing lifespan based on this and a study of Norway 's Dwelling Stock (Sartori *et al.*, 2008): 75, 100 and 125 years for Great Britain.

Lacking information relating to housing lifespan in Thailand, this study used GDP per capita of Asian countries to find a suitable analogy and then selected Chinese housing lifespan (25 and 50 years) to represent Thai housing characteristics as per capita GDP is similar presently (Hu *et al.*, 2010c; World Bank, 2015b). Because of shorter lifespan and lower renovation activities in the residential building sector, Thailand requires more concrete for new housing construction and will produce more future concrete waste after demolition of the old houses in due course.

For other factors used for SDA calculation for Great Britain and Thailand, this thesis used both national recorded data and results of 'what-if analysis' to predict future trends (low, medium and high) for national housing sectors such as persons per dwelling and floor area per capita. Then, 2.1 t/m^2 as a figure of concrete density was used following the Dutch (Müller, 2006) and Chinese (Hu *et al.*, 2010c) studies.

As shown in **Figure 4-33** and **Figure 4-34**, the future time periods of SDA calculations in both countries are different. This means the study can produce clear trends of its results until 2050 in Thailand (like the study of Hu *et al.* (2010c)) and 2100 for Great Britain. The key output from these SDA graphs is the production of concrete waste. Depending on the lifespan scenarios of each country, concrete waste in Great Britain will rise slowly to 30-70 Mt annually, by 2100. Thailand will generate concrete waste at similar levels to Great Britain (around 40-50 Mt annually), but by 2050. Moreover, due to shorter lifespan of the housing sector, Thailand will require more future concrete, made from the mining of natural resources as main raw materials. **Figure 5-1** shows that Thailand will demand 9-16 Mt cement and 67-118 Mt for virgin aggregates for the future housing construction (2020-2050).

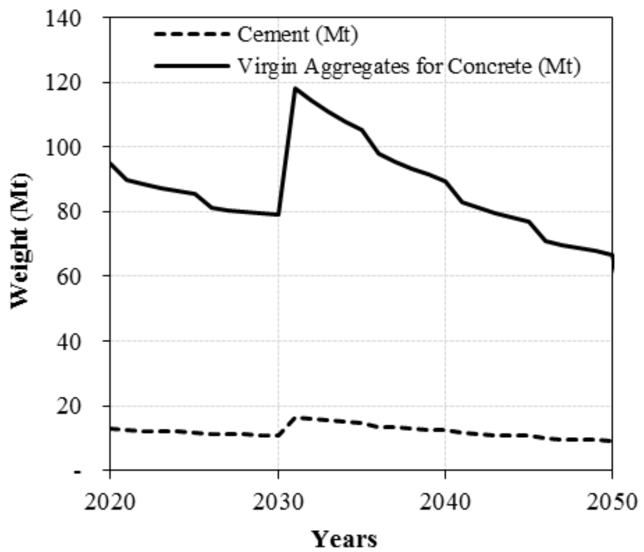


Figure 5-1 Future requirement of construction materials for housing sector in Thailand
Sources: Author

Although Sartori *et al.* (2008) stated that non-smooth curves, difficult for interpretation, may be meaningless for predicting long-term behaviour, this thesis tried to adjust graphs as little as possible. The SDA results, with fluctuating trends of the future concrete demand, can illustrate the increasing duration of concrete requirement and the smooth curve of concrete waste as the main outputs needed to support decision making for policy and taxation in Thailand. Having longer time than Thailand to cope with the similar volume of predicted concrete waste, Great Britain has already prepared policy and taxation to handle this problem, supported by the EU implementation, and achieves its targets. Therefore, Thailand and other countries should pay more attention to the policy and taxation for supporting its natural resources and environment in all relating sectors, especially the government sector.

5.5 Relationship between Annual and Future Concrete Stock

The relationship between annual and future concrete stock from MFA and SDA results in terms of concrete demand and waste is compared and described as follows.

5.5.1 Concrete Demand

The results of annual concrete stock by MFA (**Figure 4-11**) and future concrete stock using SDA (**Figure 4-33**), regarding the quantity of concrete demand for only housing construction in Great Britain (2012), are quite different (a higher figure in SDA than the MFA result). The reliable variables in the SDA calculation are: (1) population from UN statistics (an increasing trend, **Figure 4-15**) and (2) floor area per capita by what if analysis (low, medium and high) from the historical regression of the recorded data and GDP per capita (PPP, 2011, US$) from the World Bank (**Figure 4-30**). Therefore, the difference in concrete demand of the two methodologies in Great Britain might come from a longer housing lifespan than expected in three main scenarios (75, 100 and 125 years). This concrete demand is mostly affected by other significant criteria such as higher renovation activities and better housing quality to cope with the unpredictable weather in Great Britain.

Because of no data of floor area per capita for the SDA calculation, Thailand needs to use Chinese floor area per person as GDP per capita is similar when comparing all Asian GDP data (**Figure 4-18**). This study also used the UN statistics for Thai future population (an increasing trend then turning to decrease, **Figure 4-15**) with future floor area per capita from Chinese data comparing to Thai GDP per capita (PPP, 2011, US$) from the World Bank. As shown in **Figure 4-12** and **Figure 4-34**, Thai concrete demands from both methodological outcomes in 2012 are quite similar and SDA confirms that Thai housing lifespan (25 and 50 years) is shorter than Great Britain as expected.

All in all, SDA methodology can predict concrete demand for a housing sector and it might be more suitable for short lifetime scenarios with fewer renovation activities like Thailand. However, for Great Britain, there are some important criteria, probably disturbing the concrete demand in the SDA calculation, which should be considered and should have some future researches such as a longer housing lifespan, high renovation activities and better housing quality.

5.5.2 Concrete Waste

For concrete waste, Thailand has no recorded data to compare the methodological reliability of MFA and SDA results. Thus, this thesis used only the quantity of hard-inert waste of all building types in CD&E waste management and recycled aggregate activities (off-site operation) from MFA results in Great Britain (66 Mt, 2012, **Figure 4-10**) to compare with the predicted volume of concrete waste from the housing sector using SDA (18-22 Mt, 2012, **Figure 4-33**). Therefore, the SDA results for concrete waste in Great Britain are quite reasonable, comparing to MFA results that used real recorded data for calculations.

5.6 Options for Construction and Demolition Waste (C&D Waste) Policy for Thailand and other ASEAN Countries

The analyses carried out in this thesis demonstrate that it is possible to enhance the sustainable management of non-renewable raw materials used in construction, and at the same time to improve the management of waste from demolition and construction through the implementation of policy, as exemplified by Great Britain. This has been achieved through changes to taxation that have taken place over many years, supported by collection of relevant statistics. To introduce a similar policy in Thailand (and other ASEAN countries) will require a staged approach and adequate time.

To help design a suitable policy for construction and demolition waste management in Thailand, this thesis compares three main options:

- **Option 1**: No C&D waste policy,
- **Option 2**: C&D waste policy with a central budget to support only C&D waste management (adapting current policy),
- **Option 3**: Integrated C&D waste policy with a taxation system and incentive (in the early stage) to support both natural resource and C&D waste management (creating a new policy).

Presently, Thailand uses a huge amount of natural resources for construction and has no policy to support C&D waste management (the first option). The results of MFA and SDA (**Figure 4-12** and **Figure 4-34**), explain that Thailand has a high volume of C&D waste (mainly concrete waste) that is generated annually and this will increase in volume in the future, reaching 40-50 Mt in 2050. Moreover, Thailand still has serious problems of waste management such as lack of budget, equipment and technical expertise for establishing and improving new/old waste sites, and unsanitary landfill sites. There is a particular problem with demolition waste. Following recovery of metals and other easily recyclable or valuable material, in rural areas such waste normally goes to unofficial landfill or fly tipping, and in only some urban areas does it go to an official landfill.

Therefore, to prevent many more problems of waste management in the future, Thailand would benefit from an integrated policy to control and to manage C&D waste including to limit the use of natural resources as primary aggregates in particular. The first option, no policy, will not resolve a problem that SDA has shown will arise in future. There will be increased pressure on existing landfills, and more problems with unlicenced disposal in rural areas.

The second option is based on current policy that does not consider management of C&D waste. Current policy in Thailand is based on a waste system that addresses municipal solid waste, infectious waste, industrial waste and household hazardous waste, but not C&D waste. Due to the limits of budget from the central government, local municipalities have insufficient money to fully support a full range of waste management operations. Thus, given the huge amount of all waste types, it is hard to distribute only the central budget to address problems relating to C&D wastes, and there is no incentive to do so. However, a benefit from this and the first option might be that Thailand has no need to change any operations, and so ‘business as usual’ requires least change.

The last option is similar to the implementation in Great Britain and the EU of a system of taxation of primary aggregate use combined with a C&D waste management system (recycling activities and landfill tax). The integrated C&D waste policy combines a system of environmental taxation that can represent savings in the central budget and provides an early incentive to change behaviour. As in Great Britain, the aggregate levy is easier to introduce as a new system for the whole of Thailand, compared to landfill tax which is more complex. Careful selection of a small number of suitable municipal areas to operate on a pilot scale is an important step for the implementation of a new landfill tax and C&D waste management (espectially recycled concrete waste) protocol in Thailand.

If Option 3 is adopted, Thailand has the opportunity to operate the natural resources and waste management system better than is achieved using only the central budget (Option 2). Other ASEAN countries could use the same approach. Option 3 is discussed in more detail below.

5.7 Policy and Taxation Implications Appropriate for Thailand and ASEAN Countries (Option 3)

In this section, consideration is given to the development of a strategic plan to introduce policy intended to improve the use of non-renewable raw materials for construction, and the management of wastes arising from construction and demolition, in the interests of sustainable development. The development of new policy in Thailand is complex, because of the diversity of government departments that need to be involved. After proposal of a possible plan, the associated benefits are discussed, focusing on tax income as well as reductions in mining and waste.

Huesemann (2003) stated that a sufficiency culture in modern societies is a prerequisite for sustainable development. This relates directly to the Philosophy of Sufficiency Economy of the Thai king. Thailand presently focuses on national economic growth led by business, with less concerns on the environment and natural resources. It could be argued that Great Britain has a higher concern for sustainability in construction as it has less export of clinker and cement, which preserves natural resources for future domestic consumption, and it recycles concrete aggregates from C&D waste to reuse in concrete manufacturing and other construction activities. Importantly, the EU leads the implementation and regulation of sustainable development policies and Great Britain has integrated policies (e.g. The strategy for sustainable construction (BIS, 2016) and Mainstreaming Sustainable Development: The Government's Vision and What This Means in Practice (Defra, 2011)) and achieved targets (e.g. recycled aggregate uses (The European Environment Agency, 2008; The Concrete Centre, 2009; MPA, 2013c) and recycled C&D waste (Monier *et al.*, 2011; Defra, 2015a)).

As concrete is an essential component for construction in Thailand, the management of its associated wastes should be high priority by for example promoting recycling or the reuse of concrete wastes. The investigated results of MFA showed that the housing sector is the main construction type in Thailand using the most concrete annually. Thus, the SDA in this study concerns only the housing sector. Although Thailand has a similar population size presently and will have lower population in the future compared with Great Britain, SDA outcomes predicted that Thailand will need to cope with similar amounts of future concrete waste faster than Great Britain (in around 50 years), due to the shorter lifespan of residential buildings and less renovation activity. Importantly, Thailand still has no integrated policy to cope with hard-inert C&D waste, espectially concrete waste, in contrast to Great Britain.

Thailand is a leading cement manufacturer, consumer and exporter in ASEAN. Thus, problems faced in Thailand are also ASEAN problems, and concern sustainable use of construction materials within this region. From EU experience and the perspective of Symonds Group Ltd. et al (1999), the regulatory tools and detailed guidance of natural resources and waste management controlled/ published from the EU can convince EU members to follow willingly (e.g. (1) the Waste Framework Directive 2006/12/EC, revised by Directive 2008/98/EC (European Parliament, 2008) and (2) the best available techniques (BAT) conclusions under Directive 2010/75/EU (The Official Journal of the European Union, 2013)). If these tools can be set up for the ASEAN community in the future, ASEAN countries can provide adequate safeguards against abuse and avoidance of their natural resources and waste management.

5.7.1 Integrated Policy

It is necessary for Thailand to understand clearly real situations, problems, laws and regulations of construction materials, including main supporting organisations and their duties, and to handle natural resources and waste management in the early stage of the policy orientation. Following **Figure 3-10**, a summary of Great Britain operations under the EU implementations is an important guideline for Thailand. It is important that systems exist to monitor the amounts of materials that are affected by any policy, so that the success of the policy can be judged. Thus, the first step in any policy to improve management of natural resources and waste management is the physical identification and collection of records by type, source and volume of the amounts of material that are governed by the policy. This includes the annual consumption of virgin minerals (as collected in Great Britain by BGS) and requires a waste classification system (not only for C&D waste, but also for all waste types) similar to the EWC. The management of raw materials and wastes relating to construction and demolition involves many stakeholders. Thailand requires joined-up implementation involving all stakeholders; government, private and civil sectors, to create integrated policies in sustainability following the same goals, with appropriate incentives in the early stage of policy implementation. It also includes the creation of public-private partnerships that can reduce the investment obligation of the public sector.

Apart from financial support by environmental taxes (which will be clearly described in the next section), other main keys to promote greater and alternative applications of recycled aggregates in Thailand firstly should be government incentives and education of the public about the associated environmental benefits (Garber *et al.*, 2011). Other supports, such as standards like British Standards and technical development are needed to encourage use of recycled concrete aggregate, are also essential for Thai construction, and could be facilitated through the private and government-funded organisations similar to the MPA and WRAP, receiving financial supports from the environmental funds.

From the Great Britain case study, an outline integrated policy appropriate for Thailand and other ASEAN countries to support construction materials and waste in short, medium and long terms, can be seen in **Figure 5-2**. In this there are three phases:

- **Short term (1-3 years)** or **preparation phase**: this step is for (1) co-operation in the preparation of the relevant authorities (2) improvement and compliance the updating laws, regulations and standards and (3) participation among the private, public and civil sectors. This stage involves setting up an appropriate legislative framework.
- **Medium term (3-10 years)** or **operation phase**: this is the implementation to establish all involved systems with the cooperation of all sectors. Importantly, it involves establishment of a system for data collection relating to mineral production and waste generation. In this stage, members of the ASEAN community responsible for national resources and waste management should collaborate to develop (1) a waste classification system (via inter-governmental relationships) and (2) appropriate public education and communication (social relationships).
- **Long term (more than 10 years)** or **investigation and improvement phase**: this phase is for the investigation and improvement by setting strategy and targets to optimise operations from proper recorded data with all stakeholders involved. This stage involves operation of taxes and monitoring to determine the success of the policy.

Figure 5-2 summarises the process of policy development. This can be adjusted through cooperation by all ASEAN members, like the EU implementation, to avoid various problems in laws and regulations in each ASEAN country, or it can be prescribed for Thailand only.

Short Term (1-3 Years)	**Medium Term** (3-10 Years)	**Long Term** (More than 10 Years)
▪ Memorandum of cooperation among related agencies ▪ Identifying main duties of each related agency ▪ Studies in appropriate laws and practices before setting up suitable environmental systems ▪ Possibility study of public-private partnerships ▪ Public education for associated environmental benefits	▪ Waste classification System ▪ Environmental permitting system ▪ Report systems of natural resources and environment ▪ Systems of environmental taxes and funds ▪ Technical development for environmental management ▪ Public and private partnership ▪ Public education for associated environmental benefits	▪ Setting and adjusting possible strategies and targets following data from report systems of natural resources and environment ▪ Operating environmental taxes and funds ▪ Public and private partnership ▪ Public education for associated environmental benefits

Operated by Thailand or ASEAN for its members

Figure 5-2 Outlines of the integrated policy appropriate for Thailand and other ASEAN countries in short, medium and long terms
Sources: Author

To implement the steps shown in **Figure 5-2**, it is important to understand the government structure in Thailand, and how it relates to the commercial sector and the general public. For clarity, the involvement of different ministries and supporting organisations are summarised in tables that relate to each of the stages shown in **Figure 5-2**.

Figure 5-1 summarises the short term actions and identifies the bodies responsible for achieving them. It requires cooperation between ministries, and close liaison with supporting organisations, some of which represent industry, to establish a legal framework that facilitates sustainable use of natural resources required for construction. In this (and the following two tables), acronyms are used for simplicity, as listed below:

Thai Government Orgainsations

- Ministry of Agriculture and Cooperatives (MAC)
- Ministry of Commerce (MC)
- Ministry of Energy (ME)
- Ministry of Education (MEd)
- Ministry of Finance (MF)
- Ministry of Interior (MI)
- Ministry of Information and Communication Technology (MICT)
- Ministry of Industry (MIn)
- Ministry of Natural Resources and Environment (MNRE)
- Ministry of Transport (MT)
- Office of the Permanent Secretary (OPS)

Thai Institutes and Business Sectors

- The Council of Engineers of Thailand (CE)
- The Consulting Engineer Association of Thailand (CEA)
- Construction material associations (CMAs)

Table 5-1 Short term actions (Years 1-3)

<table>
<tr><th>No.</th><th>Actions</th><th>Main Organisations</th><th>Supporting Organisations</th></tr>
<tr><td>1.</td><td>Memorandum:
To make the agreement among stakeholders to facilitate change. Without a memorandum, the integrated policy appropriate for C&D waste by several organisations might be unstable.
• Memorandum of cooperation among related agencies
• Identifying main duties of each related agency</td><td>1. MAC
2. MC
3. MEd
4. ME
5. MF
6. MIn
7. MICT
8. MI
9. MNRE
10. MT
11. OPS</td><td>1. CMAs
2. CEA
3. CE</td></tr>
<tr><td colspan="4">OPS to lead a working group with representatives from each ministry and the supporting organisations to draft and sign a Memorandum of Cooperation.</td></tr>
<tr><td>2.</td><td>Law and regulation improvement:
Due to out of date law and regulation relating to natural resources and waste management (as seen in Figure 2-58), Thailand needs to improve them as soon as possible.
• Improving new institutional laws and regulations</td><td>1. MAC
2. MC
3. MEd
4. ME
5. MF
6. MIn
7. MICT
8. MI
9. MNRE
10. MT
11. OPS</td><td>1. CMAs
2. CEA
3. CE</td></tr>
<tr><td colspan="4">MNRE, supported by MIn, to lead on the drafting of laws based on those that exist in Great Britain, in consultation with other ministries listed above, and calling on Supporting Organisations for input.</td></tr>
<tr><td>3.</td><td>Standard improvement:
Because of no Thai standards for construction (Table 2-9) and Thailand follows international construction standards (US and UK standards). Therefore, Thailand should have
• Performance-based design and focus on initial cost
• Standardized codes
• Identifying gap between research and implementation
• Motivation to use sustainable materials</td><td>1. MC
2. ME
3. MF
4. MID
5. MIn
6. MNRE</td><td>1. CMAs
2. CEA
3. CE</td></tr>
<tr><td colspan="4">MIn supported by MI to lead on the drafting of standards for the reuse of aggregate and concrete-based materials arising from demolition.</td></tr>
<tr><td>4.</td><td>Public-private partnerships:
This activity use for setting up the public-private partnerships to encourage private investment and to save government budget by some activities such as
• Investment in research and increase market share
• Market for sustainable products
• Corporate social responsibility (CSR)</td><td>1. MC
2. MF
3. MIn
4. MI
5. CMAs</td><td>1. ME
2. MNRE</td></tr>
<tr><td colspan="4">MF supported by MIn, to lead on changing the law to enable public and private partnerships to exist, to encourage cooperation and generate budget savings.</td></tr>
<tr><td>5.</td><td>Public education:
Thailand should give more education about natural resources and waste management for the youth and people including stakeholders.
• Enhance of knowledge on sustainability and additional value to the youth and people including stakeholders</td><td>1. MEd
2. MI
3. CMAs</td><td>1. ME
2. MNRE</td></tr>
<tr><td colspan="4">MEd to lead, working closely with MI, to develop the curriculum so that it covers resources and waste appropriately.</td></tr>
</table>

Sources: Author

The second stage in implementing this policy is to establish systems for the collection of data relating to mineral production and use, and the amounts of waste generated following demolition and other construction activities. It is relatively easy to consider introduction of reporting systems for aggregate production using recorded royalty licences, as this involves a limited number of mines/quarries and a small number of products. In contrast, collection of data for waste depends on the development of a classification system able to deal with the diversity of waste streams and sources. The key parties involved in Stage 2 are summarised in **Table 5-2**. As this stage yields specific outcomes, it becomes appropriate to open dialogue with the ASEAN community to explore wider adoption.

Table 5-2 Medium term actions (Years 3-10)

<table>
<tr><th>No.</th><th>Actions</th><th>Main Organisations</th><th>Supporting Organisations</th></tr>
<tr><td>1.</td><td>Waste classification system:
Thailand should set up the same waste classification system for using as the standard code for the integrated C&D waste and other waste management.
• To develop the waste classification system that can apply for Thailand following EU and UK implementation and then will make it as a proposal for other ASEAN countries for future cooperation in the region for starting up the ASEAN system.</td><td>1. MI
2. MNRE
3. MIn</td><td>1. CMAs</td></tr>
<tr><td colspan="4">MNRE to lead, supported by MIn.</td></tr>
<tr><td>2.</td><td>Environmental permitting system:
The permitting system can be used to control all operations of natural resources and waste management.
• To develop the environmental permitting system</td><td>1. MI
2. MNRE
3. MIn</td><td>1. CMAs</td></tr>
<tr><td colspan="4">MNRE to lead, supported by MIn.</td></tr>
<tr><td>3.</td><td>Taxation system:
This system can give the financial support for the natural resources and waste management including related researches with no financial requirement from central budget.
• To develop the environmental taxation system and fund</td><td>1. MF</td><td>1. MNRE
2. MIn
3. MI
4. CMAs</td></tr>
<tr><td colspan="4">MF to lead, setting up a Thai equivalent to WRAP</td></tr>
<tr><td>4.</td><td>Reporting system:
The systemic report is required for understanding situation and setting up targets.
• To develop the environmental reporting system</td><td>1. MICT
2. MI
3. CMAs</td><td>1. MNRE
2. Min</td></tr>
<tr><td colspan="4">MICT, working with MI, to set up reporting system in consultation with key users especially the MNRE</td></tr>
<tr><td>5.</td><td>Technical development:
Thailand has no experience in C&D waste management especially recycled concrete aggregates. Technical development can
• Reduce cost of new technologies
• Improve higher level of technology and local technology</td><td>1. MIn
2. CMAs</td><td>1. ME
2. MNRE</td></tr>
<tr><td colspan="4">MIn to lead, working closely with MNRE, to develop the curriculum so that it covers resources and waste appropriately</td></tr>
<tr><td>6.</td><td>Public-private partnerships:
To continue private investment and to save government budget by some activities such as
• Investment in research and increase market share
• Market for sustainable products
• Corporate social responsibility (CSR)</td><td>1. MC
2. MF
3. MIn
4. MI
5. CMAs</td><td>1. ME
2. MNRE</td></tr>
<tr><td colspan="4">As in Table 5-1, continued activity to maintain momentum and communications</td></tr>
<tr><td>7.</td><td>Public education and communication:
To continue giving more education about natural resources and waste management for the youth, people and stakeholders.
• Enhance of knowledge on sustainability and additional value to the youth and people including stakeholders
• To open dialogue with the ASEAN community</td><td>1. MEd
2. MI
3. CMAs</td><td>1. ME
2. MNRE</td></tr>
<tr><td colspan="4">As in Table 5-1, continued activity to maintain momentum and communications. At this stage, open discussions to inform ASEAN of Thai policy changes and to explore wider adoption.</td></tr>
</table>

Sources: Author

The third stage in developing policy is to use the systems set up in Stages 1 and 2 nationally, to monitor improvements, establish targets, and to manage the tax income and associated spend through environmental programmes. The requirements to do this are summarised in **Table 5-3**.

Table 5-3 Long term actions (Year 10 onwards)

No.	Actions	Main Organisations	Supporting Organisations
1.	**Reporting system:** To report situation for setting up targets. • To report data to the environmental reporting system	1. MICT 2. MI 3. CMAs	1. MNRE 2. MIn
MI to lead in the use of the reporting system. This is the Minsitry responsible for collection of data and reporting to government and the public.			
2.	**Operating system:** Using recorded data from the reporting system, all stockholders can operate all systems with improved targets • To set and adjust possible strategies and targets following data from report systems of natural resources and environment • To operate environmental taxes and funds	1. MC 2. MF 3. MIn 4. MICT 5. MI 6. MNRE	1. CMAs
MNRE, supported by MIn, to lead on the operation of the policy through appropriate targets and use of environmental taxes and funds.			
3.	**Public-private partnerships:** To continue private investment and to save government budget by some activities such as • Investment in research and increase market share • Market for sustainable products • Corporate social responsibility (CSR)	1. MC 2. MF 3. MIn 4. MI 5. CMAs	1. ME 2. MNRE
MF supported by MIn, to lead on encouragement of partneships to promote mutually beneficial activities, including the development of new processes, activities and products that originate from research.			
4.	**Public education:** To continue giving more education about natural resources and waste management for the youth and people including stakeholders. • Enhance of knowledge on sustainability and additional value to the youth and people including stakeholders	1. MEd 2. MI 3. CMAs	1. ME 2. MNRE
ME to lead, working closely with MI, to develop the curriculum so that it covers resources and waste appropriately.			

Sources: Author

Table 5-1 to **Table 5-3** summarise the steps needed to develop a working policy, in a timescale of more than 10 years. Because of the scale of work involved to implement such a national policy, it is necessary to consider a pilot on a smaller scale to test the key parts of the policy in practice. Similarly, it is important that the policy is reviewed to identify possible weaknesses. To demonstrate progress, it is recommended that there is an annual review of the process, starting in Year 5. It may be necessary to restrict this to a pilot study in C&D waste management, for example addressing the needs of Bangkok and Thailand's city municipalities first, rather than the whole country.

The pilot study would focus on the waste reporting and operating systems identified in **Table 5-2**. This stage involves setting up a waste classification system, a waste permitting system and a system for reporting. A pilot trial should be carried out as soon as these three systems are established, so that they can be revised if necessary before wider adoption. Such a pilot would be carried out in Bangkok and the 29 municipalities. Once the three systems are robust and accepted by stakeholders, the waste taxation system (which provides an early incentive, once verified to show that it avoids poor C&D waste management in the pilot municipalities so that nearby rural areas are protected), can be introduced in the middle phase. In contrast, a tax on primary aggregate production could be introduced much earlier, for the whole country. Such a tax has scope for changing behaviour, and its success can only be measured once production reporting systems are in place.

5.7.2 Taxation Benefits

Financial support from environmental taxes, such as Landfill Tax, Aggregates Levy, and revenue distribution by a government-funded agency or a non-profit private company operating in Great Britain, can be adjusted to reduce the requirement of a central budget in Thailand. Following environmental taxes in Great Britain, this part uses present rates of Great Britain's Landfill Tax and Aggregates Levy (**Figure 3-11**) to calculate the possible taxation benefits for Thailand as annual and long-term taxation benefits.

5.7.2.1 Annual Taxation Benefits

To illustrate the annual value of environmental taxes, the MFA results provide estimates of aggregate use that would be subject to the Aggregate Levy. In Great Britain (2012), 54 Mt of primary aggregate were used to make concrete, yielding £107 million through the levy. 5 Mt of recycled aggregate were used, saving £13 million on Landfill Tax (in addition to saved disposal and environmental costs), and reducing payment through the Aggregate Levy of £10 million. Thailand used (2012) almost 225 Mt of aggregate for the concrete manufacturing; a levy like that of Great Britain would yield to the government the equivalent of £450 million. If developed as in the Great Britain, a combination of Aggregate Levy and Landfill Tax that encouraged the use of recycled aggregates could yield savings equivalent to £100 million.

5.7.2.2 Long-Term Taxation Benefits

This projection used 50 years of lifetime distribution from SDA results in future concrete stock of a Thai housing sector to predict the long-term taxation benefits in case of setting present rates of Aggregate Levy and Landfill Tax like Great Britain. It uses percent of dry concrete components from MPA (2013a) to illustrate the quantity of all types of virgin aggregates (85.95%) and to predict the possibility of recycled aggregates from volume of concrete waste. The WBCSD (2009b) reported that the European recycling rate for concrete waste was limited to 30% as recycled aggregates. So, 70% concrete waste needs to be disposed of properly as shown in **Figure 5-3A**.

Between 2020 and 2050 (**Figure 5-3A** and **B**), Thailand will probably use around 67-118 Mt virgin aggregates for a housing sector. If systems of environmental taxation and recycled aggregates can be established in 2020 with the same rates and capacity as Great Britain and the EU, Thailand can recycle 6-14 Mt aggregates and the remaining concrete waste requiring disposal is 14-32 Mt. For financial receipts in 2050, Thailand can collect cumulative payment from an Aggregate Levy of £5.4 billion and £2.7 billion for Landfill Tax, including a levy exemption from reusing recycled aggregates of around £2 billion. To sum up, these tax receipts can be used for supporting environmental funds, including for saving a government budget to conserve the natural resources and environment.

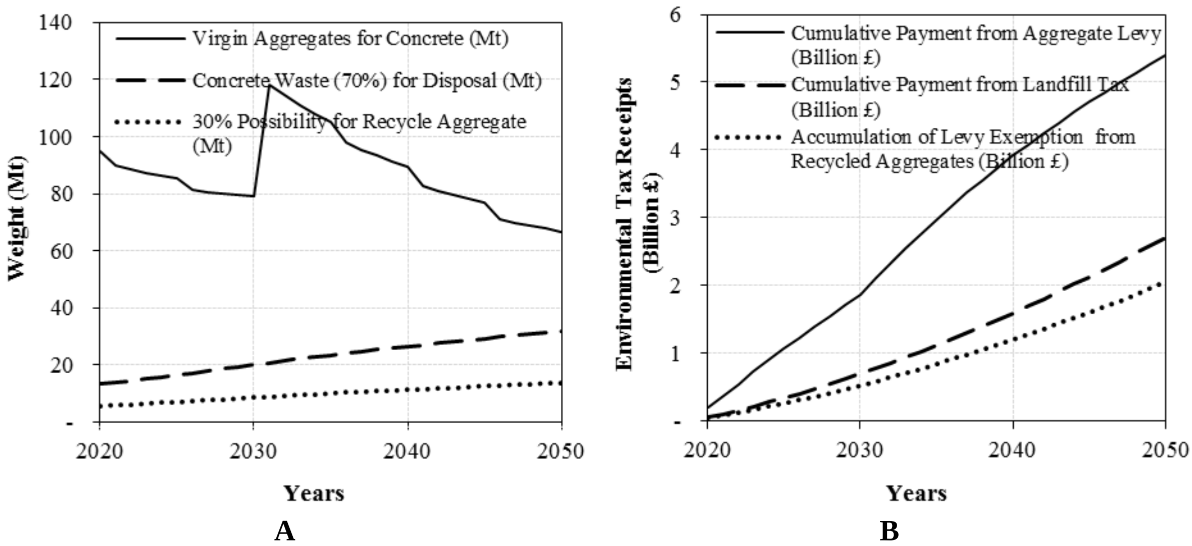


Figure 5-3 Estimation of quantity of virgin aggregates used for concrete and concrete waste for disposal and recycled aggregates in Thailand following an environmental tax system in Great Britain (A) and cumulative tax receipts from Aggregate Levy and Landfill Tax including accumulation of no charge from recycled aggregates in Aggregate Levy (B)
Source: Author based on SDA results and implementations of environmental taxes in Great Britain

5.8 Practical Implications of Policy and Taxation Implications for Thailand

For policy and taxation practice, an Aggregate Levy for the virgin aggregates can be established with its rules applicable to the whole of Thailand. Nevertheless, it is difficult to establish the recycled aggregate system and the operations of Landfill Tax for the entire country currently. The main reasons come from limitations of the central budget for a starting period and appropriate conditions of the target areas, potential for recycled aggregates and waste management such as responsible officials and suitable areas for recycling and disposal. For other supporting criteria of recycled aggregates and landfill management, technologies for the recycled aggregates and appropriate disposal sites of hard-inert waste are required.

Following the administrative summary of Thailand (**Table A - 2**), Bangkok and 29 city municipalities (**Figure 5-4)**, close to urban areas presently, are the first priority for organising the policy and taxation implications, following **Figure 5-2**. These municipalities have more housing construction activities with other supporting criteria as discussed above. Like Great Britain's experience in the first stage of policy orientation, Thailand has to improve related laws and regulations for preventing illegal dumping in the rural areas (including for storing of waste) and utilising environment taxes effectively. Then, after operating successfully in the first priority areas, town and sub-district municipalities will be considered to be the next operation as the second and third priority respectively.

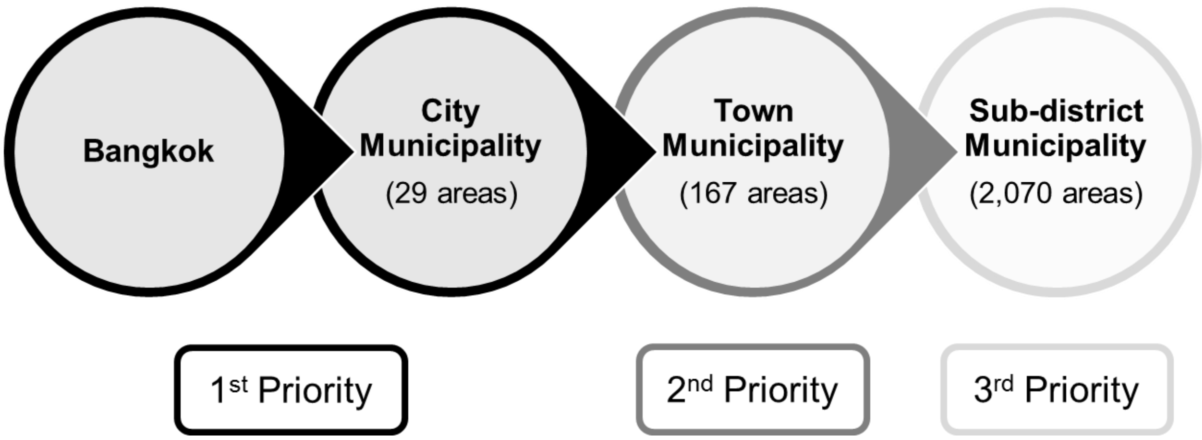


Figure 5-4 The priority of the recycled aggregate system and Landfill Tax implementation in Thailand
Sources: Author

5.8.1 Technologies for the Recycled Aggregates System

To recycle concrete waste to be reused as aggregates with suitable quality for reconstruction, the recycling system needs to be supported with more engineering techniques. In addition, Thailand still requires suitable engineering techniques for the recycled aggregate system to improve the quality of its operation, and Thai techniques should be considered to reduce import costs of the recycled equipment. As seen in **Figure 2-13**, there are two main recycling systems: (1) off-site plant and (2) on-site or mobile plant.

5.8.1.1 Off-Site Plant

Off-site plant can be constructed and operated as a central site in or near the urban area to support demolition activities for recycling concrete aggregates, following a generalised flow diagram for the aggregates recycling operation in **Figure 2-14**. The recycling activities of coarse and fine recycled concrete aggregates from Thompsons of Prudhoe at Springwell Quarry, Gateshead, Newcastle upon Tyne (**Figure 2-15**) can indicate that the site should be built nearby the community to reduce transportation cost and to be close to customers. Moreover, the system needs to have some important equipment such as crushers, magnetic separator, and screeners.

5.8.1.2 On-Site or Mobile Plant

On-site or mobile plant has similar equipment like the off-site plant, but it can be moved to operate anywhere. Therefore, this system should have a compact size with more concerns on noise and dust as it is used in urban areas. Such equipment is often limited to crushing, and so separation can be less efficient than at an off-site plant.

5.8.2 Disposal Sites of Hard-Inert Waste in Thailand

Thailand uses concrete as the main construction material so C&D waste after demolition activities is mostly from concrete as well. For present C&D waste management, some recyclable materials can be reused and the management of the remaining or hard-inert waste, particularly concrete waste, depends on contractors and building owners and includes activities such as fill and landscaping, as well as dumping. Thai waste classification in urban areas in **Figure 2-60** and the study of PCD *et al.* (2007) illustrate that illegal disposal is the main problem with concrete waste, with no aggregate recycling activities, and landfill is mostly used for municipal waste in Thailand.

5.8.2.1 Bangkok Metropolitan

Bangkok Metropolitan operates only municipal waste collection from household to three transfer stations and then sends it to landfill in Chachoengsao and Nakhon Pathom provinces by commissioning with two private companies due to a lack of suitable areas for waste management in Bangkok. In the future, if Thailand can establish the policy and taxation to support C&D waste management and a recycled aggregate system, the remaining part of this waste after recycling needs to be disposed of properly by landfill, located outside Bangkok like municipal waste.

This study suggests that concrete waste in Bangkok should be managed partly by recycling old concrete aggregates on-site using mobile plant and to consume these materials within the construction sites or nearby areas. These activities can avoid expensive transportation and waste disposal costs for the hard-inert waste, especially remaining concrete waste, by co-disposal in the private landfill located outside Bangkok.

5.8.2.2 City Municipalities

Thailand has 29 city municipalities that mostly have their own waste management systems (only Lampang City Municipality needs to send its municipal waste to nearby landfill sites) with their own budgets for waste collection and operation. Importantly, these municipalities still require more supporting money from the central government (the Environmental Quality Management Plan at the provincial level or the Environmental Fund) for construction of new landfill sites such as area and construction costs. For concrete waste, city municipalities can adjust both the mobile plants for use in construction sites and off-site plants as the central systems of recycled aggregates in their landfills, somewhere near the landfills or in other suitable areas. Then, the remaining C&D waste can be co-disposed of household waste in their landfill.

5.9 Research Restrictions

The research carried out in this study has a number of limitations:

- Results from both national cement industries using the calcination calculations may be affected by the development of novel cements by the global cement manufacturing industry that are designed to reduce energy and carbon losses from the chemical reaction of raw cement minerals in particular.

- Due to the lack of Thai recorded data, this thesis used some proportions for Great Britain data to calculate Thai figures. Importantly, Great Britain mostly uses precast and ready-mixed concrete in which all components are controlled by manufacturing recipes and standards. In contrast, Thailand consumes mostly site-mixed concrete particularly in local areas, which means that Thai concrete components may be varied by contractors.
- The reporting formats of national construction are different between Great Britain and Thailand. Thailand reports by permitted floor area in use and value of buildings with the proportion of new residential completion in terms of value is used for Great Britain.
- There are many unanswered questions about concrete used for all types of construction for several criteria. Therefore, the SDA has the limitation that it has been used to calculate the future concrete stock for only the housing sector.
- Stocks of construction materials from the previous years (before 2012) may disturb the reliability of this research in the MFA part.
- Dislocation may come from recorded data of each agency and manufacturer that use the different times to report their data.

Despite these limitations, it is clear that policy plays an important role in improving the sustainable management of construction materials. Weaknesses in the data do not invalidate the conclusions drawn from the MFA or SDA. However, future development of policy based on this work needs to take them into account, and to ensure that where possible they are addressed.

5.10 Future Research

Suggestions for future research that builds on what is presented in this thesis include:

- There should be a study of the consequences for construction material requirements in Great Britain of long lifespan and more maintenance activity, and construction quality, in the housing sector.
- Because of different compositions of household waste between Great Britain and Thailand, the co-disposal of household and inert waste should be investigated, including as a feasibility study, to suggest operation guidelines and engineering technical requirements and considering public private partnership.
- With old laws and regulation in environmental issues, Thailand should have more research on the new environmental laws and taxes.

- Relating to a short lifespan of the building and low building quality in Thailand, a study of the suitability on demolition of different types of building for recycled concrete aggregates should be performed.
- To understand the best choice for natural resources and waste management, a comparison between recycled concrete aggregates and primary aggregates in the new concrete following the sustainability concepts should be considered.
- Due to different national characteristics of the renovation activity between both countries, a study of Thai behaviour in the use of residential building should be investigated.
- Because of the lack of data for MFA calculations presently, a study of the Thai national cement industry should be applied using the real data from the cement factories.
- To understand the Thai residential sector more, a study of lifespan and floor area in use for all building types especially for residential building in Thailand should be investigated. This will be used for other researches in terms of financial, material and energy flows by Material Flow Methodologies (MFMs).
- With an unclear system of recycled concrete aggregates in Thailand, a study of recycled concrete aggregates with its proper system and technique should be studied.
- A study of the suitable prediction of future trends for SDA calculations in case of floor area in use and persons per dwelling should be developed.

5.11 Summary

The discussion chapter uses results of the national cement industries, annual concrete stocks (MFA) and future concrete stocks (SDA) in both case studies to compare with benefits of the policy and taxation implementations in Great Britain and the EU, based on the concept of sustainability. It can be shown that if Thailand can follow the appropriate operations of policy and taxation of Great Britain, separating into the short, medium and long terms in the priority areas, Thailand will also generate more opportunities, including savings in government budget, and can use the financial supports from these policies and taxation to conserve natural resources and to maintain or improve environmental quality.

However, the operation of policy and taxation cannot be established for the whole country promptly due to certain restrictions, such as insufficient experienced workers and limited initial budget. This thesis proposes to start operations from Bangkok and the 29 municipalities as the first priority areas, having more potential. If the performance is satisfactory, then the target areas can expand to other priority municipalities. Moreover, Thailand needs to develop supporting technologies for the recycled aggregates system and to control illegal dumping in remote areas, and to collect and utilise the environmental taxes effectively. As there are similar national problems, these practices can be also adjusted for other ASEAN countries..

Chapter 6 Conclusion

C&D waste is the highest quantity of waste generated in Great Britain annually, followed by municipal waste. Following the EU implementations and strategy, Great Britain operates a waste management system that covers all types of waste. The system also includes environmental taxes to control the increase of waste and to support activities of waste management.

In contrast, municipal waste management in Thailand has not yet achieved its goal and full management in all areas. As expected, the amount of Thai C&D waste will rise continuously, along with incomplete solid waste management. Shortly, Thailand will have severe problems from this approach to waste management, including a budget shortfall for supporting the waste management, combined with the enormous amount of waste generated, issues such as more illegal dumping, and a lack of suitable areas for landfill and recycling.

To comprehend the future problems clearly for Thai policy and taxation reflecting the overall problems of the ASEAN region, this thesis focuses on C&D waste, particularly concrete waste, with the main reasons as follows:

(1) Concrete demolition waste is important to consider because of the quantities involved.

(2) It is possible to model the creation of concrete from its components (cement and aggregates) and its ultimate fate on demolition for the nation using MFA.

(3) The amounts of concrete demand and waste in the housing sector arising in the future can be modelled using SDA.

(4) Study of policy and its execution in Great Britain shows the potential benefits to Thailand of improving the management of concrete waste.

6.1 National Cement Industries and Annual Concrete Stocks

Great Britain exports little clinker and cement while Thailand exports a large fraction of its products from natural resources. The MFA results demonstrate that Thailand does need to adjust its construction materials, which holds true especially considering that the volume of Thai cementitious export was double the quantity of the domestic cement used for the concrete industry in Great Britain. Although the population in both countries is quite similar, Thailand consumed 3.8 times more domestic concrete and mortar (256.14 Mt) than Great Britain (67.73 Mt) in 2012. In addition, Great Britain construction used the highest volume of concrete and mortar for the non-residential building while residential building with a short lifespan and very low renovation activities was the main construction sector of the concrete and mortar used in Thailand.

Great Britain has recorded data about primary and recycled aggregate used for each construction activity. Virgin aggregate used for the concrete industry is the main utilisation that Great Britain has focused on recently to reduce and to replace by suitable proportions of recycled aggregates. In 2012, the promotion of recycled and secondary aggregates for all construction activities accounts for 29% of input aggregates using a policy package and a multi-level approach from the Aggregates Levy and Landfill Tax which create strong incentives to support the aggregate industry and waste management following the EU implementation and strategy.

Although Great Britain achieves the highest rate of recycled and secondary aggregates in the aggregate market among the EU presently, this study found that Great Britain used recycled aggregates below capacity, and this country has more potential to increase the use of recycled aggregates in both precast and ready-mixed concrete. In contrast, Thailand has no recorded data for any aggregate use. It also has no recycled aggregates used for the concrete industry, and this is evident from the high volume of concrete waste and cheaper price for primary aggregates without the aggregate levy or other environmental taxes.

MFA techniques provide a quantitative description of the construction and demolition sector that informs policy development. They require records of material uses at all stages of the processes, augmented by informed calculations based on technical constraints. A relatively robust MFA can be achieved for both Great Britain and Thailand, but the comparative and quantitative analyses of natural resources used and waste management in construction materials are inhibited by a lack of recorded data in Thailand.

6.2 Future Concrete Stocks

The future concrete stocks of Great Britain and Thailand have different criteria for residential building due to their national background such as demographic and economic characteristics. As seen from SDA results, Great Britain requires natural materials for construction activities lower than Thailand. This situation also occurs in terms of the regional demand, as the ASEAN countries (developing countries mostly) with a fast growth in economy and population with changing lifestyle have more new construction from rapid urbanisation and require more construction materials than the EU countries (more developed countries), which have longer lifespan of housing building and more renovation activities, as well as higher construction quality.

Shorter lifetime of housing sector and low activity in housing renovation push Thailand to demand more concrete as the main construction material using its natural resources (such as cement minerals and aggregates) for providing adequate supply and keeping up with the fast development of the country. Using SDA to investigate the past, present and future situations of the housing sector, in around 50 years Thailand will cope with a similar amount of concrete waste as Great Britain and require more concrete produced from natural resources.

6.3 Policy and Taxation

As seen, although Great Britain consumes lower volumes of cement and concrete than Thailand, Great Britain has a waste management system covering all wastes and natural resource conservation has limited resources to use only for domestic consumption, within a framework of clear policies and targets from the EU. Thus, it is time that Thailand should turn more attention to natural resources as non-renewable materials, and to waste management, according to the polluter pays principle and the Thai king's Philosophy of Sufficiency Economy.

Integrated policies in Great Britain, driven by EU regulation, have led to changes in behaviour that reduce disposal to landfill and encourage the use of secondary aggregates in construction. 29% of total aggregate use (all sectors) in Great Britain is reused or recycled, and there is scope for increased use of these materials in concrete. In contrast, there is no recorded reuse or recycling of aggregates in Thailand.

Like other developing countries presently, Thailand focuses mainly on national economic growth and business aspects with fewer concerns on the environment and natural resources. It could be argued that Great Britain has higher concerns for sustainability as it has (1) less export of clinker and cement, which preserves raw materials from natural resources for future domestic consumption, (2) recycled aggregates from C&D waste to reuse in concrete manufacturing and other construction activities and (3) integrated policies including the environmental taxes and achieved targets to support sustainable development. These practices are inseparably supported by the EU strategies targeted for all EU members.

Without starting classification criteria for the individual wastes as listed in the EWC, the first step in waste management in Thailand is limited by the physical difficulties of identifying waste types and sources. Therefore, Thailand needs to apply a classification system to record systematic data like the EU implementation of all kinds of waste, not only for C&D waste. It is most necessary for Thailand to understand clearly the real situations and problems of construction materials and waste management, and to handle waste in the early stage of the policy orientation.

Moreover, Thailand requires joined-up implementation involving all stakeholders relating to construction materials and industries from the government, private sector and community to create integrated sustainability policies with the same goals. This is because concrete is an essential component of construction in Thailand presently. After the end of building lifespan, the predicted vast amount of concrete waste is too difficult to manage due to the lack of an integrated sustainability policy and regulation including the environment taxes like those of Great Britain. Financial support and control from environmental taxes (e.g. Landfill Tax, Aggregates Levy) can generate tax revenue that conserves a central government budget.

Furthermore, the costs of recycled aggregates have increased because of more complicated processes and technologies to generate products with properties similar to the virgin aggregates. This important issue makes recycled aggregates less attractive for contractors. Thus, the key to promote the greater and alternative applications of recycled aggregates in Thailand at the beginning stage should be the government incentives and education of public environmental benefits for stakeholders.

The other support that is required is a set of reliable standards for recycled aggregate concrete like the British Standards from British Standards Institution (BSI), which are essential for Thai construction. The main private sector for construction materials should consider setting up bodies like the MPA, and the government should consider establishing a research centre funded by environmental tax like WRAP. These tools can accordingly be adjusted for Thailand following the king’s philosophy for natural resources and waste management in practice.

As known, Thailand is one of the ASEAN countries and the leading cement manufacturer, consumer and exporter in ASEAN. The Thai problems as described above are also ASEAN problems that can be regarded as the main issues of construction materials in this region. To be a strong trading group for future bargaining, ASEAN requires adequate safeguards against abuse and avoidance of natural resources and waste management.

Thus, from EU experiences, the policy and regulatory tools of natural resources and waste management enforced by EU members can be set up for the future ASEAN. Great Britain's experiences also suggest that the eventual development of policy similar to Great Briain would yield an equivalent but greater benefit. Similar benefits may apply more widely in ASEAN countries, with similar patterns of resource use associated with urban and infrastructure development.

6.4 Summary

All the above conclusions show that appropriate policies and taxation are vital to the future of waste management in Thailand, especially concerning concrete waste from construction and demolition. In addition to these operations as mentioned, they also support the exploitation of natural resources as non-renewable resources to improve the stability of Thailand in the future.

Therefore, to comply with the philosophy of the Sufficiency Economy of His Majesty King Bhumibol Adulyadej literally, the implementation and strategy for concrete waste management like the EU and Great Britain following the concept of sustainability should be established in Thailand in practice. Moreover, the conservation of natural resources and proper waste management are also necessary to other ASEAN countries which are about to be united with attention to economic development coupled with the environmental development of this region.

References

Alsop, P.A. (2014) *Cement Plant Operations Handbook for Dry Process Plants*. Sixth Edition edn. Tradeship Publications Ltd.

Altuncu, D. and Kasapseçkin, M.A. (2011) Bologna. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-84255200414&partnerID=40&md5=3a56edf10c6f30391ddc6d6a75b2afd4 (Accessed: 15 September 2011 through 16 September 2011).

Andrews, J.F., Davis, J. and Loskamp, T. (2012) *Construction & Building Materials*. HSBC.

Aranda Usón, A., López-Sabirón, A.M., Ferreira, G. and Llera Sastresa, E. (2013) 'Uses of alternative fuels and raw materials in the cement industry as sustainable waste management options', *Renewable and Sustainable Energy Reviews*, 23(0), pp. 242-260.

Aroche, F. (2009) '1932 -1938: Wassily Leontief's Early Papers: Besides the Input Output Model', *17th International Input Output Conference* São Paulo, Brazil 13 - 17 July 2009 Available at: http://www.iioa.org/conferences/17th/abstracts/29.pdf.

Assies, J.A. (1998) 'A Risk-Based Approach to Life-Cycle Impact Assessment', *Journal of Hazardous Materials*, 61(1–3), pp. 23-29.

Azapagica, A. and Cliftb, R. (1999) 'Allocation of Environmental Burdens in Multiple-Function Systems', *Journal of Cleaner Production*, 7(2), pp. 101-119.

Bank of Thailand (2015a) *Indicators of Private Investment*. Bangkok, Thailand.

Bank of Thailand (2015b) *Product Prices of Major Industries*. Bangkok, Thailand.

Bank of Thailand (2015c) *Thailand's Macro Economic Indicators* Bangkok, Thailand. [Online]. Available at: http://www2.bot.or.th/statistics/ReportPage.aspx?reportID=409&language=eng (Accessed: 23 March 2015).

Bank of Thailand (2015d) *Thailand's Macro Economic Indicators* [Online]. Available at: http://www2.bot.or.th/statistics/ReportPage.aspx?reportID=409&language=eng (Accessed: 23 March 2015).

Bartelings, H., van Beukering, P.J.H., Kuik, O.J., Linderhof, V.G.M., Oosterhuis, F.H., Brander, L.M. and Wagtendonk, A.J. (2005) 'Effectiveness of landfill taxation'.

Begum, R.A., Siwar, C., Pereira, J.J. and Jaafar, A.H. (2006) 'A Benefit–Cost Analysis on the Economic Feasibility of Construction Waste Minimisation: The Case of Malaysia', *Resources, Conservation and Recycling*, 48(1), pp. 86-98.

Behrens, A., Giljum, S., Kovanda, J. and Niza, S. (2007) 'The material basis of the global economy: Worldwide patterns of natural resource extraction and their implications for sustainable resource use policies', *Ecological Economics*, 64(2), pp. 444-453.

References

Benhelal, E., Zahedi, G., Shamsaei, E. and Bahadori, A. (2013) 'Global Strategies and Potentials to Curb CO2 Emissions in Cement Industry', *Journal of Cleaner Production*, 51(0), pp. 142-161.

Bergsdal, H., Bohne, R.A. and Brattebø, H. (2007a) 'Projection of Construction and Demolition Waste in Norway', *Journal of Industrial Ecology*, 11(3), pp. 27-39.

Bergsdal, H., Brattebø, H., Bohne, R.A. and Müller, D.B. (2007b) 'Dynamic Material Flow Analysis for Norway's Dwelling Stock', *Building Research & Information*, 35(5), pp. 557-570.

Berlin, J. (2002) 'Environmental Life Cycle Assessment (LCA) of Swedish Semi-Hard Cheese', *International Dairy Journal*, 12(11), pp. 939-953.

Berndt, M.L. (2015) 'Influence of concrete mix design on CO2 emissions for large wind turbine foundations', *Renewable Energy*, 83, pp. 608-614.

BGS (2003) *United Kingdom Minerals Yearbook 2002*. Amersham, Buckinghamshire, United Kingdom: Halstan & Co.Ltd.

BGS (2004) *United Kingdom Minerals Yearbook 2003*. Amersham, Buckinghamshire, United Kingdom: Halstan & Co.Ltd, .

BGS (2005) *United Kingdom Minerals Yearbook 2004*. Amersham, Buckinghamshire, United Kingdom: Halstan & Co.Ltd, .

BGS (2006) *United Kingdom Minerals Yearbook 2005*. Amersham, Buckinghamshire, United Kingdom: Halstan & Co.Ltd, .

BGS (2007) *United Kingdom Minerals Yearbook 2006*. Amersham, Buckinghamshire, United Kingdom: Halstan & Co.Ltd, .

BGS (2008a) *Aggregate Resource Alternatives: Options for Future Aggregate Minerals Supply in England*. Nottingham.

BGS (2008b) *United Kingdom Minerals Yearbook 2007*. Amersham, Buckinghamshire, United Kingdom: Halstan & Co.Ltd, .

BGS (2009) *United Kingdom Minerals Yearbook 2008*.

BGS (2010) *United Kingdom Minerals Yearbook 2009*.

BGS (2011) *United Kingdom Minerals Yearbook 2010*.

BGS (2012) *United Kingdom Minerals Yearbook 2011*.

BGS (2013) *United Kingdom Minerals Yearbook 2012*.

BGS (2014a) *European Mineral Statistics 2008-2012: A Product of the World Mineral Statistics Database*.

BGS (2014b) *Mineral Planning Factsheet: Cement*.

BGS (2014c) *United Kingdom Minerals Yearbook 2013*.

BIS (2016) *The Strategy for Sustainable Construction*. Available at: http://webarchive.nationalarchives.gov.uk/+/www.bis.gov.uk/policies/business-sectors/construction/sustainable-construction/strategy-for-sustainable-construction (Accessed: 24 August 2016).

Björklund, A. (2012) 'Life Cycle Assessment as an Analytical Tool in Strategic Environmental Assessment. Lessons Learned from a Case Study on Municipal Energy Planning in Sweden', *Environmental Impact Assessment Review*, 32(1), pp. 82-87.

Boardman, B., Darby, S., Killip, G., Hinnells, M., Jardine, C.N., Palmer, J. and Sinden, G. (2005) '40% House'.

Bogue, R.H. (1947) *The Chemistry of Portland Cement*. New York: Reinhold Publ. Corporation.

Böhmer, S., Moser, G., Neubauer, C., Peltoniemi, M., Schachermayer, E., Tesar, M., Walter, B. and Winter, B. (2008) *Aggregates Case Study*. Vienna: The Institute for Prospective Technological Studies.

Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., Lazarus, E., Morales, J.C., Wackernagel, M. and Galli, A. (2013) 'Accounting for Demand and Supply of the Biosphere's Regenerative Capacity: The National Footprint Accounts' Underlying Methodology and Framework', *Ecological Indicators*, 24(January 2013), pp. 518-533.

Boston Consulting Group (2013) *Cembureau 2012 Activity Report—The Cement Sector: A Strategic Contributor to Europe's Future*. Brussels, Belgium: CEMBUREAU The European Cement Association CEMBUREAU-European Cement Association.

Bouman, M., Heijungs, R., van der Voet, E., van den Bergh, J.C.J.M. and Huppes, G. (2000) 'Material Flows and Economic Models: An Analytical Comparison of SFA, LCA and Partial Equilibrium Models', *Ecological Economics*, 32(2), pp. 195-216.

Briggs, H., Townsend, R. and Wilson, J. (1982) 'An Input-Output Analysis of Maine's Fisheries', *Marine Fisheries Review*, 44(1).

British Ready-Mixed Concrete Association (2012) 'Ready-Mixed Concrete an Essential Sustainable Construction Material - Locally Available'.

British Ready-Mixed Concrete Association (2014) *Ready-Mixed Concrete Resource Efficiency Action Plan February 2014*.

British Standards Institution (2013) *BSI Standards Publication: Aggregates for Concrete (BS EN 12620:2013)*. BSI Standards Limited 2013.

Broin, E.Ó. (2007) *Energy Demands of European Buildings: A Mapping of Available Data, Indicators and Models*. Chalmers University of Technology.

Brown, T., McEvoy, F. and Ward, J. (2011) 'Aggregates in England—Economic Contribution and Environmental Cost of Indigenous Supply', *Resources Policy*, 36(4), pp. 295-303.

References

BSI (2013a) *BS EN 206:2013 Concrete Specification, Performance, Production and Conformity*.

BSI (2013b) *BS EN 12620:2013 Aggregates for concrete*. BSI.

BSI (2013c) *PD 6682-1:2009+A1:2013 Aggregates. Aggregates for Concrete. Guidance on the Use of BS EN 12620* BSI.

BSI (2013d) *PD CEN/TR 16563:2013. Principles of the Equivalent Durability Procedure*.

BSI (2016) *PD CEN/TR 16912:2016 Guidelines for a Procedure to Support the European Standardization of Cements*

Building Research Establishment (2002) *The Green Guide to Specification: An Environmental Profiling System for Building Materials and Components*. Blackwell Publishing.

Building Research Establishment (2008) *Wastage Rate Report*. Garston, UK.

Bureau of Registration Administration (2015) *Statistics of Thai Population and Number of Houses*

Bye, G.C. (1999) *Portland Cement Composition, Production and Properties*. Thomas Telford Limited.

Cencic, O. and Rechberger, H. (2008a) 'Material Flow Analysis with Software STAN ', *Environmental Informatics and Industrial Ecology*.

Cencic, O. and Rechberger, H. (2008b) 'Material Flow Analysis with Software STAN ', *J. Environ. Eng. Manage.*, 18(1)(3-7 (2008)), pp. 1-7.

Chee, Y.L. (2012) *The Rio Declaration on Environment and Development: An Assessment*. Third World Network.

Chisholm, D., Kirby, A., Hambling, J., Barnard, D., Lowe, J., Park, S., Scott, A. and Slaughter, G. (2011) *Best Practice Guide for the Use of Recycled Aggregates in New Concrete* The Cement & Concrete Association of New Zealand.

Christ, C.F. (1955) *A Review of Input-Output Analysis*. Princeton University Press. Available at: http://www.nber.org/chapters/c2866.

Cleary, J. (2009) 'Life Cycle Assessments of Municipal Solid Waste Management Systems: A Comparative Analysis of Selected Peer-Reviewed Literature', *Environment International*, 35(8), pp. 1256-1266.

Communitatis Europeae Lex (2016) *European Union Legislation Database*. Available at: http://europa.eu/eu-law/index_en.htm (Accessed: 18 February 2016).

Competitiveness Development Office (2013) *Thailand Cement Industry*. [Online]. Available at: http://www.cm.nesdb.go.th/ (Accessed: 10 April 2013).

Conneely, D., Gibbs, M.J. and Soyka, P. (2001) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*.

Corbett, C.J., Montes-Sancho, M.J. and Kirsch, D.A. (2004) 'The Financial Impact of ISO 9000 Certification in the US: An Empirical Analysis '.

Croft, N.H. (2012) *ISO 9001:2015 and Beyond - Preparing for the Next 25 Years of Quality Management Standards*. Available at: http://www.iso.org/iso/home/news_index/news_archive/news.htm?refid=Ref1633 (Accessed: 24 October 2013).

Čuček, L., Klemeš, J.J. and Kravanja, Z. (2012) 'A Review of Footprint Analysis Tools for Monitoring Impacts on Sustainability', *Journal of Cleaner Production*, 34(0), pp. 9-20.

Cuéllar-Franca, R.M. and Azapagic, A. (2012) 'Environmental impacts of the UK residential sector: Life cycle assessment of houses', *Building and Environment*, 54, pp. 86-99.

Curry, R.L., ,Jr, and Sura, K. (2007) 'Human Resource Development (HRD) Theory and Thailand's Sufficiency Economy Concept and Its" OTOP" Program', *Journal of third world studies*, 24(2), p. 85.

Davidovits, J. (1994) 'Global Warming Impact on the Cement and Aggregates Industries', *World Resource Review*, 6(2), pp. 263-278.

DCLG (2006) *Planning for Sustainable Waste Management: Companion Guide to Planning Policy Statement 10*. DCLG Publications.

DCLG (2007) *Survey of Arisings and Use of Alternatives to Primary Aggregates in England, 2005 Construction, Demolition and Excavation Waste*. London: Capita Symonds Ltd,.

DCLG (2010) *Statistical Release: Household Projections, 2008 to 2033, England*.

DCLG (2012) *National Planning Policy Framework*. [Online]. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/6077/2116950.pdf (Accessed: 4 August 2015).

DCLG (2013) *English housing survey*.

DCLG (2014) *House Building: December Quarter 2013, England*. London, DCLG.

DCLG (2015a) *2010 to 2015 government policy: building regulation*.

DCLG (2015b) *Household Projections for England and Local Authority Districts*. [Online]. Available at: https://www.gov.uk/government/statistical-data-sets/live-tables-on-household-projections.

Defra (2011) *Mainstreaming Sustainable Development: The Government's Vision and What This Means in Practice*. [Online]. Available at: http://webarchive.nationalarchives.gov.uk/20110223093550/http://sd.defra.gov.uk/documents/mainstreaming-sustainable-development.pdf (Accessed: 14 August 2015).

Defra (2012a) *Construction, Demolition and Excavation Waste Generation Estimate: England, 2008-2010*.

Defra (2012b) *Methodology for Estimating Annual Waste Generation from the Construction, Demolition and Excavation (CD&E) Sectors in England*.

References

Defra (2013) *London 2012 Olympic and Paralympic Games: The Legacy: Sustainable Procurement for Construction Projects*.

Defra (2015a) *Digest of Waste and Resource Statistics – 2015 Edition*. London.

Defra (2015b) *UK Statistics on Waste – 2010 to 2012*. York.

Delmas, M. (2002) 'The Diffusion of Environmental Management Standards in Europe and in the United States: An Institutional Perspective', *Policy Sciences*, 35(1), pp. 91-119.

Demyanyk, Y. and Van Hemert, O. (2011) 'Understanding the Subprime Mortgage Crisis', *Review of Financial Studies*, 24(6), pp. 1848-1880.

Department for Business Innovation and Skills (2012) *UK Trade Performance Across Markets and Sectors*.

Department for Business Innovation and Skills (2013) *UK Construction: An Economic Analysis of the Sector*

Department of Local Administration (2013) *Work Plan (2014-2017)*. Bangkok, Thailand.

Department of Mineral Resources (2008a) *Guidelines for Management of Cement Resources*.

Department of Mineral Resources (2008b) *A Project for the Management of Mineral Resources for the Cement Industry.* Bangkok.

Department of Primary Industries and Mines (2003) *Cement used and Types of Finished Concrete in 2003*.

Department of Primary Industries and Mines (2014) *Database of Quarries and Quarrying*. Available at: http://www.dpim.go.th/datacenter.

Department of Provincial Administration (2015) *Thai Population*.

Department of Trade and Industry (1998) *Rethinking Construction*.

DePauw, C. and Vyncke, J. (1996) 'European C&D recyclers—Developing new standards for aggregate use: C&D Debris Recycling', pp. 12-13.

Di Maio, F., Rem, P., Lofti, S., Serranti, S., Bonifazi, G., Hu, M., N., B.V., Skouras, E., Cucchietti, F. and Vázquez, M. (2012) *Cement and Clean Aggregates from CDW: The C2CA Project*. The European Commission.

Domone, P. and Illston, j. (2010) *Construction Materials: Their Nature and Behaviour*. 4th edn. USA: Spon Press.

Don't Incinerate Steering Committee (DISC) (2010) *Waste: Reduce Reuse Recycle Rethink*.

Ecofys, Fraunhofer Institute for Systems and Innovation Research and Öko-Institut (2009) *Methodology for the Free Allocation of Emission Allowances in the EU ETS post 2012: Sector Report for the Cement Industry*.

Economic and Social Statistics Bureau (2009) *The Major Conclusion of Construction Industry 2009*.

ECOTEC Research and Consulting et al (2001) *Study on the Economic and Environmental Implications of the Use of Environmental Taxes and Charges in the European Union and its Member States*.

Environment Agency (2011) *How to Comply with Your Environmental Permit*. Bristol, UK: Environment Agency.

Environment Agency, Scottish Environment Protection Agency (SEPA), Natural Resources Wales/ Cyfoeth Naturiol Cymru and Northern Ireland Environment Agency (NIEA) (2015) *Guidance on the Classification and Assessment of Waste (1st Edition 2015) Technical Guidance WM3*.

Environmental Impact Evaluation Bureau (2014) *A Database System for Environmental Impact Assessment*. Available at: http://eia.onep.go.th/pro-info-4.php (Accessed: 13 November 2014).

EPA (2002) *European Waste Catalogue and Hazardous Waste List*. [Online]. Available at: http://www.nwcpo.ie/forms/EWC_code_book.pdf (Accessed: 18 January 2015).

EPA (2008) *Lifecycle Construction Resource Guide*.

Ercin, A.E. and Hoekstra, A.Y. (2012a) *Carbon and Water Footprints Concepts, Methodologies and Policy Responses*. The United Nations Educational, Scientific and Cultural Organization. Available at: http://unesdoc.unesco.org/images/0021/002171/217181E.pdf.

Ercin, A.E. and Hoekstra, A.Y. (2012b) *Carbon and Water Footprints: Concepts, Methodologies and Policy Responses*. the United Nations Educational, Scientific and Cultural Organization.

Etxeberria, M., Vázquez, E., Marí, A. and Barra, M. (2007) 'Influence of Amount of Recycled Coarse Aggregates and Production Process on Properties of Recycled Aggregate Concrete', *Cement and Concrete Research*, 37(5), pp. 735-742.

European Commission (2010) *Communication from the Commission Europe 2020: A European Strategy for Smart, Sustainable and Inclusive growth*.

European Communities (1999) *EU Focus on Waste Management*. Directorate-General Environment, Nuclear Safety and Civil Protection.

European Parliament (2008) *Directive 2008/98/CE of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives*.

European Ready Mixed Concrete Organization (2013) *Read-Mixed Concrete Industry Statistics Year 2012*. Brussels, Belgium.

Eurostat (2001) *Economy-Wide Material Flow Accounts and Derived Indicators. A Methodological Guide*. Statistical Office of the European Union,.

Eurostat (2008a) *68th Meeting of the Statistical Programme Committee*. Luxembourg. [Online]. Available at: http://epp.eurostat.ec.europa.eu/portal/page/portal/environmental_accounts/documents/ESEA_REVISION_2008_0.pdf.

Eurostat (2008b) *Eurostat Manual of Supply, Use and Input-Output Tables*. Office for Official Publications of the European Communities.

Eurostat (2009) *Economy Wide Material Flow Accounts: Compilation Guidelines for Reporting to the 2009 Eurostat Questionnaire*. European Statistical Office. Available at: http://epp.eurostat.ec.europa.eu/portal/page/portal/environmental_accounts/documents/Eurostat%20MFA%20compilation%20guide%20for%202009%20reporting.pdf.

Eurostat (2015a) *Average Household Size* (Accessed: 7 October).

Eurostat (2015b) *Average Number of Persons per Household*.

Eurostat (2015c) *Waste Statistics* Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics (Accessed: 27 June 2015).

Ewing, B., Moore, D., Goldfinger, S., Oursler, A., Reed, A. and Wackernage, l. (2010) *Ecological Footprint Atlas 2010*. Available at: http://www.footprintnetwork.org/images/uploads/Ecological_Footprint_Atlas_2010.pdf.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. and Suh, S. (2009) 'Recent developments in Life Cycle Assessment', *Journal of Environmental Management*, 91(1), pp. 1-21.

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H. and Weisz, H. (2011) 'Methodology and Indicators of Economy-wide Material Flow Accounting', *Journal of Industrial Ecology*, 15(6), pp. 855-876.

Fischer, C., Werge, M. and Reichel, A. (2009) *EU as a Recycling Society Present Recycling Levels of Municipal Waste and Construction & Demolition Waste in the EU*. Copenhagen, Denmark: European Topic Centre on Resource and Waste Management,.

Fishman, T., Schandl, H. and Tanikawa, H. (2015) 'The socio-economic drivers of material stock accumulation in Japan's prefectures', *Ecological Economics*, 113, pp. 76-84.

Fishman, T., Schandl, H. and Tanikawa, H. (2016) 'Stochastic Analysis and Forecasts of the Patterns of Speed, Acceleration, and Levels of Material Stock Accumulation in Society', *Environmental Science & Technology*.

Fishman, T., Schandl, H., Tanikawa, H., Walker, P. and Krausmann, F. (2014) 'Accounting for the Material Stock of Nations', *Journal of Industrial Ecology*, 18(3), pp. 407-420.

Flath, D. (2002) *The Japanese Distribution Sector in Economic Perspective: the Large Store Law and Retail Density*.

Frosch, R.A. and Gallopoulos, N.E. (1989) 'Strategies for Manufacturing: Waste from One Industrial Process Can Serve as the Raw Materials for Another, Thereby Reducing the Impact of Industry on the Environment', *Scientific American*, 261(3), pp. 144-152.

Gagne, L. (2011) 'Environmental Accounting ', *CMA/CGA/FMI Workshop*. Victoria, 1-2 March , 2011. Available at: http://www.fmi.ca/media/old/March_1_-__2_Lynda_Gagne_Environmental_Accounting.pdf.

Gale, R.J.P. and Stokoe, P.K. (2001) *Environmental Cost Accounting and Business Strategy* Kluwer Academic Publishers. Available at: http://www.ecological-economics.org/pages/environmental_cost_accounting.pdf.

Galli, A., Wiedmann, T., Ercin, E., Knoblauch, D., Ewing, B. and Giljum, S. (2011) *Integrating Ecological, Carbon and Water Footprint: Defining the 'Footprint Family' and its Application in Tracking Human Pressure on the Planet*. Available at: http://www.oneplaneteconomynetwork.org/resources/programme-documents/WP8_Integrating_Ecological_Carbon_Water_Footprint.pdf.

Garber, S., Rasmussen, R., Cackler, T., Taylor, P., Harrington, D., Fick, G., Snyder, M., Van Dam, T. and Lobo, C. (2011) *A Technology Deployment Plan for the Use of Recycled Concrete Aggregates in Concrete Paving Mixtures*.

Garfield, E. (1986) 'Wassily Leontief: Pioneer of Input-Output Analysis', *Essays of an Information Scientist*, 9, pp. 3-12.

Giljum, S. and Hubacek, K. (2004) 'Alternative Approaches of Physical Input–Output Analysis to Estimate Primary Material Inputs of Production and Consumption Activities', *Economic Systems Research*, 16(3), pp. 301-310.

Glauser, D. (2007) *Material Flow of Waste from Construction and Demolition Sites in Bangkok*. University of Applied Sciences Northwestern Switzerland.

Global Construction Perspectives and Oxford Economics (2013) *Global Construction 2025*.

Glöser, S., Tercero, L., Soulier, M. and Faulstich, M. (2013) 'Using Dynamic Stock & Flow Models for Global and Regional Material and Substance Flow Analysis in the Field of Industrial Ecology:The Example of a Global Copper Flow Model', *The 31st International Conference of the System Dynamics Society*. Cambridge, Massachusetts USA.

González, A., Sala, J.M., Flores, I. and López, L.M. (2003) 'Application of Thermoeconomics to the Allocation of Environmental Loads in the Life Cycle Assessment of Cogeneration Plants', *Energy*, 28(6), pp. 557-574.

Grenon, G., Martha, J., Turner, M. and Hamilton, B.A. (2008) *How Big is Your Carbon Footprint? Before You Can Build an Energy-Efficient Supply Chain, You Need to Understand Your Company's Carbon Emissions*. Booz & Company Inc.

Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T. and Rydberg, T. (2010) 'Life Cycle Assessment: Past, Present, and Future', *Environmental Science & Technology*, 45(1), pp. 90-96.

Haes, U.d., Vijverberg, A.J., Deistler, M., Baccini, P., Brunner, P.H., Lahner, T. and Lohm, U. (n.d.) *Materials Accounting as a Tool for Decision Making in Environmental Policy (Mac Tempo)*. [Online]. Available at: http://cordis.europa.eu/documents/documentlibrary/51667541EN6.pdf.

Halpern-Givens, E. (2010a) *Evaluating the Economic Impact of Improvements in Freight Infrastructure: An Input-Output Approach*. University of Illinois at Chicago.

Halpern-Givens, E. (2010b) *Evaluating the Economic Impact of Improvements in Freight Infrastructure: An Input-Output Approach*. University of Illinois at Chicago.

HelgiLibrary (2015) *Housing Stocks (sqm per Person) for All Countries*. Available at: http://www.helgilibrary.com/indicators/index/housing-stocks-sqm-per-person/albania (Accessed: 11 October).

Henry, M. and Kato, Y. (2012) 'Understanding the Regional Context of Sustainable Concrete in Asia: Case studies in Thailand and Korea', *Resources, Conservation and Recycling*, 69, pp. 122-129.

Hinterberger, F., Giljum, S. and Hammer, M. (2003) 'Material Flow Accounting and Analysis (MFA): A Valuable Tool for Analyses of Society-Nature Interrelationships'.

Hirner, H. (2012) 'Greenhouse Gas Emissions - ISO 14067 to Enable Worldwide Comparability of Carbon Footprint Data'.

Hiromi Ariyaratne, W.K., Melaaen, M.C. and Tokheim, L.-A. (2013) 'The Effect of Alternative Fuel Combustion in the Cement Kiln Main Burner on Production Capacity and Improvement with Oxygen Enrichment', *World Academy of Science, Engineering and Technology*, 7.

HM Revenue & Customs (2011) *UK Export and Import in 2011: Top Products and Trading Partners* Available at: https://docs.google.com/spreadsheet/ccc?key=0AgdO92JOXxAOdFJycldPNWJCT3g3VER4UlN5dVo2Z3c#gid=5 (Accessed: 6 February 2015).

HM Revenue & Customs (2015a) *Excise Notice AGL1: Aggregates Levy*.

HM Revenue & Customs (2015b) *Overseas Trade Statistics*. [Online]. Available at: https://www.uktradeinfo.com/Statistics/BuildYourOwnTables/Pages/Table.aspx (Accessed: 6 February 2015).

HM Revenue & Customs (2015c) *Reform of the Landfill Communities Fund*.

HM Revenue & Customs (2016) *Excise Notice LFT1: a general guide to Landfill Tax*.

Hoekstra, A.Y. (2008) *Water Neutral: Reducing and Offsetting the Impacts of Water Footprints*. UNESCO-IHE Institute for Water Education. Available at: http://doc.utwente.nl/77202/1/Report28-WaterNeutral.pdf.

Hora, M. (2007) *Construction and Demolition Waste in Developing Countries*

Hou, W., Tian, X. and Tanikawa, H. (2015) 'Greening China's Wastewater Treatment Infrastructure in the Face of Rapid Development: Analysis Based on Material Stock and Flow through 2050', *Journal of Industrial Ecology*, 19(1), pp. 129-140.

House of Commons (1974) *Control of Pollution Act 1974 (Chapter 40)*. London: Her Majesty's Stationery Office

House of Commons (2002) *The Role of Defra: Tenth Report of Session 2001-02*. London: The Stationery Office Limited.

HQ Air Force Center for Environment Excellence (2006) *Construction and Demolition Waste Management Pocket Guide*.

Hu, M., Bergsdal, H., van der Voet, E., Huppes, G. and Müller, D.B. (2010a) 'Dynamics of Urban and Rural Housing Stocks in China', *Building Research & Information*, 38(3), pp. 301-317.

Hu, M., Pauliuk, S., Wang, T., Huppes, G., van der Voet, E. and Müller, D.B. (2010b) 'Iron and Steel in Chinese Residential Buildings: A Dynamic Analysis', *Resources, Conservation and Recycling*, 54(9), pp. 591-600.

Hu, M., Van Der Voet, E. and Huppes, G. (2010c) 'Dynamic Material Flow Analysis for Strategic Construction and Demolition Waste Management in Beijing', *Journal of Industrial Ecology*, 14(3), pp. 440-456.

Huang, C.-L., Vause, J., Ma, H.-W. and Yu, C.-P. (2012) 'Using Material/Substance Flow Analysis to Support Sustainable Development Assessment: A Literature Review and Outlook', *Resources, Conservation and Recycling*, 68(0), pp. 104-116.

Huang, Y.A., Lenzen, M., Weber, C.L., Murray, J. and Matthews, H.S. (2009) 'The Role of Input Output Analysis for The Screening of Corporate Carbon Footprints', *Economic Systems Research*, 21(3), pp. 217-242.

Huesemann, M. (2003) 'The limits of technological solutions to sustainable development', *Clean Technologies and Environmental Policy*, 5(1), pp. 21-34.

IMF (2015) *World Economic Outlook: Uneven Growth Short- and Long-Term Factors*. Washington, DC, USA.

Information and Communication Technology Centre (2013a) *The export products of Thailand from 1992 to 2013*. [Online]. Available at: http://www2.ops3.moc.go.th/ (Accessed: 15 April 2013).

Information and Communication Technology Centre (2013b) *The import products of Thailand from 1992 to 2013*. [Online]. Available at: http://www2.ops3.moc.go.th/.

Information Technology Centre (2006a) *Mineral Consumption of Thailand 2003 - 2005*.

Information Technology Centre (2006b) *Mineral Production of Thailand 2003 - 2005*.

Information Technology Centre (2009a) *Mineral Consumption of Thailand 2006 - 2008*.

Information Technology Centre (2009b) *Mineral Production of Thailand 2006 - 2008*.

Information Technology Centre (2012a) *Mineral Consumption of Thailand 2009 - 2011*.

Information Technology Centre (2012b) *Mineral Production of Thailand 2009 - 2011*.

Information Technology Centre (2014a) *Mineral Consumption of Thailand 2012 - 2013*.

Information Technology Centre (2014b) *Mineral Production of Thailand 2012 - 2013*.

Institute of Management Accountants (1996) *Tools and Techniques of Environmental Accounting for Business Decisions*. Institute of Management Accountants. Available at: http://www.imanet.org/PDFs/Public/Research/SMA/Tools%20and%20Techniques%20of%20Environmental.pdf.

International Cement Review (2013) *Global Cement Report*.

International Energy Agency (2007) *Energy Use in the New Millennium, Trends in IEA Countries*.

Jasch, C. (2009) *Environmental and Material Flow Cost Accounting*. Springer Science + Business Media B.V.

Kääntee, U., Zevenhoven, R., Backman, R. and Hupa, M. (2004) 'Cement manufacturing using alternative fuels and the advantages of process modelling', *Fuel Processing Technology*, 85(4), pp. 293-301.

Kaddatz, K.T., Rasul, M.G. and Rahman, A. (2013) 'Alternative Fuels for use in Cement Kilns: Process Impact Modelling', *Procedia Engineering*, 56(0), pp. 413-420.

Khoman, T. (1992) *ASEAN Conception and Evolution in the ASEAN Reader*. Available at: http://www.asean.org/news/item/asean-conception-and-evolution-by-thanat-khoman (Accessed: 15 November 2014).

Kofoworola, O. and Gheewala, S. (2008) 'Environmental Life Cycle Assessment of a Commercial Office Building in Thailand', *The International Journal of Life Cycle Assessment*, 13(6), pp. 498-511.

Kofoworola, O.F. and Gheewala, S.H. (2009a) 'Estimation of Construction Waste Generation and Management in Thailand', *Waste Management*, 29(2), pp. 731-738.

Kofoworola, O.F. and Gheewala, S.H. (2009b) 'Life Cycle Energy Assessment of a Typical Office Building in Thailand', *Energy and Buildings*, 41(10), pp. 1076-1083.

Kohler, N. and Hassler, U. (2002) 'The building stock as a research object', *Building Research & Information*, 30(4), pp. 226-236.

Kokubu, K., Campos, M.K.S., Furukawa, Y. and Tachikawa, H. (2009) *Material Flow Cost Accounting with ISO 14051*. ISO Management Systems.

Kokubu, K., Campos, M.K.S., Furukawa, Y. and Tachikawa, H. (2009) *Material Flow Cost Accounting with ISO 14051*. [Online]. Available at: http://www.google.co.th/url?sa=t&rct=j&q=&esrc=s&frm=1&source=web&cd=4&cad=rja&ved=0CE8QFjAD&url=http%3A%2F%2Fwww.iso.org%2Fiso%2Flivelinkgetfile-isocs%3FnodeId%3D15229294&ei=MKtqUqjVPOS40QW5k4DoBA&usg=AFQjCNGWab406jCYV5VPHp8gNGLMH3_Xig&sig2=chI4ejz0EHF7qoxa7CV4AQ&bvm=bv.55123115,d.d2k.

Kokubu, K. and Kitada, H. (2010) 'Conflicts and Solution Between Material Flow Cost Accounting and Conventional Management Thinking', *the 6th Asia-Pacific Interdisciplinary*

Perspectives on Accounting Research (APIRA) Conference. University of Sydney, 12-13 July 2010.

Kokubu, K. and Kitada, H. (2012) 'Material Flow Cost Accounting and Conventional Management Thinking: Introducing a New Environmental Management Accounting Tool into Companies', *the IPA Conference*

Kokubu, K. and Nakajima, M. (2004) 'Material Flow Cost Accounting in Japan: A New Trend of Environmental Management Accounting Practices', *the Fourth Asia Pacific Interdisciplinary Research in Accounting Conference*. Singapore, 4 - 6 July 2004

Kourmpanis, B., Papadopoulos, A., Moustakas, K., Stylianou, M., Haralambous, K.J. and Loizidou, M. (2008a) 'Preliminary study for the management of construction and demolition waste', *Waste Management & Research*, 26(3), pp. 267-275.

Kourmpanis, B., Papadopoulos, A., Moustakas, K., Stylianou, M., Haralambous, K.J. and Loizidou, M. (2008b) 'Preliminary Study for the Management of Construction and Demolition Waste', *Waste Management and Research*, 26(3), pp. 267-275.

KPMG Asia Pacific Tax Centre (2014) *The ASEAN Economic Community 2015*.

Kua, H.W. and Wong, C.L. (2012) 'Analysing the life cycle greenhouse gas emission and energy consumption of a multi-storied commercial building in Singapore from an extended system boundary perspective', *Energy and Buildings*, 51, pp. 6-14.

Kurdowski, W. (2014) *Cement and Concrete Chemistry* Dordrecht : Springer.

Kyd, J.G. (1952) *Scottish Population Statistics including Webster's Analysis of Population 1755*. T. and A. Constable Ltd.

Lafarge (2015) *The Primary Aggregate Market*. Available at: http://www.lafarge.in/wps/portal/in/3_B_2_A-All_about_Aggregates.

Lamas, W.d.Q., Palau, J.C.F. and Camargo, J.R.d. (2013) 'Waste materials co-processing in cement industry: Ecological efficiency of waste reuse', *Renewable and Sustainable Energy Reviews*, 19(0), pp. 200-207.

Lawson, N., Douglas, I., Garvin, S., McGrath, C., Manning, D. and Vetterlein, J. (2001) 'Recycling construction and demolition wastes – a UK perspective', *Environmental Management and Health*, 12(2), pp. 146-157.

Lea, F.M. (1971) *The Chemistry of Cement and Concrete*. New York: Chemical Publishing Company.

Lemieux, P., Stewart, E., Realff, M. and Mulholland, J.A. (2004) 'Emissions Study of Co-Firing Waste Carpet in a Rotary Kiln', *Journal of Environmental Management*, 70(1), pp. 27–33.

Li, D.Z., Chen, H.X., Hui, E.C.M., Zhang, J.B. and Li, Q.M. (2013) 'A Methodology for Estimating the Life-Cycle Carbon Efficiency of a Residential Building', *Building and Environment*, 59, pp. 448-455.

Limsuwan, E. (n.d.) *CBM-CI International Workshop*. Karachi, Pakistan. Available at: http://enpub.fulton.asu.edu/cement/cbm_CI/CBMI_Separate_Articles/Article%2022.pdf (Accessed: 15 September 2013).

Low, M.-S. (2005) *Material Flow Analysis of Concrete in the United States*. Massachusetts Institute of Technology

Lu, W. and Yuan, H. (2011) 'A Framework for Understanding Waste Management Studies in Construction', *Waste Management*, 31(6), pp. 1252-1260.

Maltitz, G.v. (2000) *The Impacts of the ISO 1400 Management System on Sustainable Forest Management in South Africa*. Division of Environment, Water and Forest Technology, CSIR. Available at: http://www.nda.agric.za/doaDev/sideMenu/ForestryWeb/webapp/ResourceCentre/Documents/Reports/scan21.pdf.

Mankelow, J.M., Bate , R., Bide, T., Mitchell, C., Linley, K., Hannis, S. and Cameron, D. (2010) 'Aggregate Resource alternatives: Future Options for Meeting Aggregate Minerals Supply from Outside National Parks and Areas of Outstanding Natural Beauty', *The 15th Extractive Industry Geology Conference*. EIG Conferences Ltd, pp. 28-34.

Manning, D.A.C. (1995) *Introduction to Industrial Minerals* London Chapman & Hall

Manowong, E. (2012) 'Investigating Factors Influencing Construction Waste Management Efforts in Developing Countries: An Experience from Thailand', *Waste Management & Research*, 30(1), pp. 56-71.

Marcellus-Zamora, K.A., Gallagher, P.M., Spatari, S. and Tanikawa, H. (2015) 'Estimating Materials Stocked by Land-Use Type in Historic Urban Buildings Using Spatio-Temporal Analytical Tools', *Journal of Industrial Ecology*, pp. n/a-n/a.

Market Research Reports (2013) *The Global Construction Aggregates Market - Key Trends and Opportunities to 2017*.

Martin, A. and Scott, I.A.N. (2003) 'The Effectiveness of the UK Landfill Tax', *Journal of Environmental Planning and Management*, 46(5), pp. 673-689.

Massa, I., Keane, J. and Kennan, J. (2012) *The Euro Zone Crisis and Developing Countries*. Overseas Development Institute.

Matthews, E., Amann, C., Bringezu, S., Fischer-Kowalski, M., Huetller, W., Kleijn, R., Moriguchi, Y., Ottke, C., Rodenburg, E., Rogich, D., Schandl, H., Schuetz, H., van der Voet, E. and Weisz, H. (2000) *The Weight of Nations. Material Outflows from Industrial Economies.* Washington: World Resources Institute,.

Mattoon, S. (2013) *Hong Kong Ecological Footprint Report 2013*. Kong, W.H. [Online]. Available at: http://www.footprintnetwork.org/images/article_uploads/hong_kong_ecological_footprint_report_2013.pdf.

McLaughlin, S. (1998) *An Introduction to Environmental Accounting as a Business Management Tool: Key Concepts and Terms*. The Green Bottom Line: Environmental Accounting for Management: Current Practic.

Miettinen, P. and Hämäläinen, R.P. (1997) 'How to Benefit from Decision Analysis in Environmental Life Cycle Assessment (LCA)', *European Journal of Operational Research*, 102(2), pp. 279-294.

Ministry of Infrastructure of the Italian Republic (2006) *Housing Statistics in the European Union 2005/2006*.

Ministry of Natural Resources and Environment (2006) *Notification of Ministry of Natural Resources and Environment: Wastes Used as Alternative Fuels or as Raw Materials in Cement Manufacturing*.

Ministry of the Interior and Kingdom Relations (2010) *Housing Statistics in the European Union 2010*.

Mitchell, C.J. (2012) 'Aggregate carbon demand: the hunt for low carbon aggregate', *Mroueh UM, Eskola P, Laine-Ylijoki Extractive Industry Geology, Portsmouth, UK*.

Moll, S., Vrgoc, M., Watson, D., Femia, A., Pedersen, O.G. and Villanueva, A. (2006) *Environmental Input-Output Analyses Based on NAMEA Data: A Comparative European Study on Environmental Presures Arising from Consumption and Production Patterns*. Højbro Plads 4, DK-1200 Copenhagen K European Topic Centre on Resource and Waste Management.

Monahan, J. and Powell, J.C. (2011) 'An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework', *Energy and Buildings*, 43(1), pp. 179-188.

Monier, V., Mudgal, S., Hestin, M., Trarieux, M. and Mimi, S. (2011) *Service Contract on Management of Construction and Demolition Waste – SR1*. Paris, France: European Commission (DG ENV),.

Moore, D.J., Tilton, J.E. and Shields, D.J. (1996) 'Economic growth and the demand for construction materials', *Resources Policy*, 22(3), pp. 197-205.

Mortar Industry Association (2013) *Brick and Block Production*.

MPA (2009) *Press Releases* (Accessed: 13 November 2014).

MPA (2011) *MPA Aggregates Information Sheet*. [Online]. Available at: http://www.mineralproducts.org/documents/Information_Sheet_Recycled_Aggregates_WRAP_QP.pdf.

MPA (2013a) *Concrete Industry Guidance Document on Sustainability Performance Indicators*. London, UK, MPA.

MPA (2013b) *Concrete Industry Sustainability Performance Report*. MPA The Concrete Centre, on behalf of the Sustainable Concrete Forum.

MPA (2013c) *Engagement and Delivery : A Continuing Commitment: Summary Sustainable Development Report 2013*. London, UK, MPA.

MPA (2013d) *The UK Cement Industry Aims to Reduce Greenhouse Gases by 81% by 2050*. MPA Cement. [Online]. Available at: http://www.mineralproducts.org/documents/MPA_Cement_2050_Strategy.pdf.

MPA (2014a) *Location of MPA Members* [Online]. Available at: http://cement.mineralproducts.org/cement/manufacture/location_of_mpa_members_cement_plants.php.

MPA (2014b) *The Mineral Products Industry at a Glance-Key Facts*

MPA (2014c) *MPA Cement Sustainable Development Report 2013: Building a Sustainable UK Cement Industry*.

MPA (2015a) *Annual Cement Channel of Sale 2003-2014*. [Online]. Available at: http://cement.mineralproducts.org/documents/annual-cement-channel-of-sale.pdf.

MPA (2015b) *Annual Cement Regional Sales 2003-2014*. [Online]. Available at: http://cement.mineralproducts.org/documents/annual-cement-regional-sales.pdf.

MPA (2015c) *Annual Cementitious 2001-2014*. [Online]. Available at: http://cement.mineralproducts.org/documents/annual-cementitious.pdf.

MPA (2016a) *Aggregates Levy*. Available at: http://www.bmapa.org/issues/aggregates_levy.php (Accessed: 24 August 2016).

MPA (2016b) *MPA Cement Fact Sheet 12: Novel Cements: Low Energy, Low Carbon Cements*.

Müller, D.B. (2006) 'Stock Dynamics for Forecasting Material Flows—Case Study for Housing in the Netherlands', *Ecological Economics*, 59(1), pp. 142-156.

Muller, N. and Harnisch, J. (2008) *A Blueprint for a Climate Friendly Cement Industry*. Nurnberg, Germany: Ecofys Germany GmbH on behalf of WWF International.

Nakamura, S. and Kondo, Y. (2009) *Waste Input-Output Analysis Concepts and Application to Industrial Ecology*. Dordrecht : Springer.

National Economic and Social Development Board (2011) *The Eleventh National Economic and Social Development Plan (2012-2016)*. Bangkok, Thailand.

National Ready Mixed Concrete Association (2012) *Concrete CO2 Fact Sheet* (2PCO2). 900 Spring Street, Silver Spring, MD 20910. [Online]. Available at: www.nrmca.org (Accessed: 4 April 2013).

National Records of Scotland (2013) *2011 Census: First Results on Population and Household Estimates for Scotland - Release 1B.*

National Statistical Office (2004) *The Preliminary Results of the Survey Construction Industry in 2004*. [Online]. Available at: http://service.nso.go.th/nso/nsopublish/themes/industry.html (Accessed: 15 April 2013).

National Statistical Office (2005) *The 2004 Construction Area*. Bangkok, Thailand. [Online]. Available at: http://service.nso.go.th/nso/nsopublish/themes/industry.html (Accessed: 15 April 2013).

National Statistical Office (2006) *The 2005 Construction Area*. Bangkok, Thailand.

National Statistical Office (2007) *The 2006 Construction Area*. Bangkok, Thailand.

National Statistical Office (2008) *The 2007 Construction Area*. Bangkok, Thailand.

National statistical Office (2009a) *The 2008 Construction Area*. Bangkok, Thailand.

National Statistical Office (2009b) *Survey of the Construction Industry in 2009*. [Online]. Available at: http://service.nso.go.th/nso/nsopublish/themes/industry.html (Accessed: 15 April 2013).

National statistical Office (2010) *The 2009 Construction Area*. Bangkok, Thailand.

National statistical Office (2011) *The 2010 Construction Area*. Bangkok, Thailand.

National statistical Office (2012a) *The 2011 Construction Area*. Bangkok Thailand.

National Statistical Office (2012b) *Processing of Construction Area 2000 - 2012*.

National Statistical Office (2013a) *The 2012 Construction Area*. Bangkok Thailand.

National Statistical Office (2013b) *Survey Report for Working Situation of Thai Population (February 2013)*.

National statistical Office (2014) *The 2013 Construction Area*. Bangkok Thailand.

Neno, C., Brito, J.d. and Veiga, R. (2013) 'Using Fine Recycled Concrete Aggregate for Mortar Production', *Materials Research*.

Nitivattananon, V. and Borongan, G. (2007) Chennai, India, 5 - 7 September 2007.

OECD (2000) 'Special Session on Material Flow Accounting', *OECD Working Group on Environmental Information and Outlooks (WGEIO)*, . Paris. Available at: http://www.oecd.org/env/indicators-modelling-outlooks/4425421.pdf.

OECD (2001) 'Sustainable Development: Critical issues'.

OECD (2011) 'Resource Productivity in the G8 and the OECD: A Report in the Framework of the Kobe 3R Action Plan'.

OECD (2013) *OECD Economic Surveys China*.

Office of Environmental Fund (2011) *Master Plan for Environmental Fund 2012-2016*.

Office of Industrial Economics (2001) *Summary of Industrial Economic Situation 2001 and 2002 trend*. Bangkok, Thailand.

Office of Industrial Economics (2002) *Summary of Industrial Economic Situation 2002 and 2003 trend*. Bangkok, Thailand.

References

Office of Industrial Economics (2003) *Summary of Industrial Economic Situation 2003 and 2004 trend*. Bangkok, Thailand.

Office of Industrial Economics (2004) *Summary of Industrial Economic Situation 2004 and 2005 trend*. Bangkok, Thailand.

Office of Industrial Economics (2005) *Summary of Industrial Economic Situation 2005 and 2006 trend*. Bangkok, Thailand.

Office of Industrial Economics (2006) *Summary of Industrial Economic Situation 2006 and 2007 trend*. Bangkok, Thailand.

Office of Industrial Economics (2007) *Summary of Industrial Economic Situation 2007 and 2008 trend*. Bangkok, Thailand.

Office of Industrial Economics (2008) *Summary of Industrial Economic Situation 2008 and 2009 trend*. Bangkok, Thailand.

Office of Industrial Economics (2009) *Summary of Industrial Economic Situation 2009 and 2010 trend*. Bangkok, Thailand.

Office of Industrial Economics (2010) *Summary of Industrial Economic Situation 2010 and 2011 trend*. Bangkok, Thailand.

Office of Industrial Economics (2011) *Summary of Industrial Economic Situation 2011 and 2012 trend*. Bangkok, Thailand.

Office of Industrial Economics (2012) *Summary of Industrial Economic Situation 2012 and 2013 trend*. Bangkok, Thailand.

Office of Industrial Economics (2013) *Summary of Industrial Economic Situation 2013 and 2014 trend*. Bangkok, Thailand.

Office of Industrial Economics (2014) *Summary of Industrial Economic Situation 2014 and 2015 trend*. Bangkok, Thailand.

Office of National Economic and Social Development Board (2015) *Quarterly Gross National Product Chain Volume Measures 1993-2014*. Bangkok, Thailand.

Office of the National Economic and Social Development Board (2007) *Sufficiency Economy Implications and Applications*. Sufficiency Economy Movement Sub-committee, Office of the National Economic and Social Development Board

Ogunlana, S.O., Promkuntong, K. and Jearkjirm, V. (1996) 'Construction Delays in a Fast-Growing Economy: Comparing Thailand with other Economies', *International Journal of Project Management*, 14(1), pp. 37-45.

Online Historical Population Reports (2012a) *Census of England and Wales 1921*.

Online Historical Population Reports (2012b) *General Tables: England and Wales 1931*.

Online Historical Population Reports (2012c) *Population Summary 1801-1821*.

ONS (2000) *Mineral Extraction in Great Britain 1999*.

ONS (2001) *Mineral Extraction in Great Britain 2000*.

ONS (2002) *Mineral Extraction in Great Britain 2001*.

ONS (2003) *Mineral Extraction in Great Britain 2002*.

ONS (2004) *Mineral Extraction in Great Britain 2003*.

ONS (2005) *Mineral Extraction in Great Britain 2004*.

ONS (2006) *Mineral Extraction in Great Britain 2005*.

ONS (2007) *Mineral Extraction in Great Britain 2006*.

ONS (2008a) *Construction Statistics Annual 2008*.

ONS (2008b) *Mineral Extraction in Great Britain 2007*.

ONS (2009a) *Construction Statistics Annual 2009*.

ONS (2009b) *Mineral Extraction in Great Britain 2008*.

ONS (2010a) *Construction Statistics Annual 2010*.

ONS (2010b) 'Import and Export Values in the UK '.

ONS (2010c) *Mineral Extraction in Great Britain 2009*.

ONS (2011a) *2011 Census - Population and Household Estimates for Wales*.

ONS (2011b) *The Administrative Geography Map of the UK*. [Online] Available at: http://www.ons.gov.uk/ons/guide-method/geography/beginner-s-guide/maps/index.html (Accessed: 16 January 2015).

ONS (2011c) *Construction Statistics Annual 2011*.

ONS (2011d) *Mineral Extraction in Great Britain 2010*.

ONS (2011e) *The Number of Each Type of Administrative Area in Each Part of the UK*. [Online]. Available at: http://www.ons.gov.uk/ons/guide-method/geography/frequently-asked-questions/topics-relating-to-our-work/number-of-administrative-areas-in-uk/index.html (Accessed: 26 January 2015).

ONS (2012a) *Annual Mid-year Population Estimates, 2011 and 2012*.

ONS (2012b) *Construction Statistics Annual 2012*.

ONS (2012c) *An Executive Summary, 2010-Based NPP Reference Volume*.

ONS (2012d) *Measuring National Well-being, Social Trends 42 - Population*.

ONS (2012e) *Mineral Extraction in Great Britain 2011*.

ONS (2013a) *Annual Business Survey, 2012 Provisional Results*.

ONS (2013b) *Construction Statistics Annual 2013* [Online]. Available at: http://www.ons.gov.uk/ons/publications/re-reference-tables.html?edition=tcm%3A77-324202.

ONS (2013c) *Detailed industry dataset 1990 - 2012 for GDP*. Available at: http://www.ons.gov.uk/ons/search/index.html?newquery=KKI3 (Accessed: 2 November).

ONS (2013d) *Population Estimates Summary for the UK, mid-2013*.

ONS (2014a) *Annual Mid-year Population*.

ONS (2014b) *Construction Statistics Annual 2014*.

ONS (2014c) *Households and Household Composition in England and Wales, 2001-11*.

ONS (2014d) *Mineral Extraction in Great Britain 2012*.

ONS (2015a) *Output in the Construction Industry: August 2013*.

ONS (2015b) *Preliminary Estimate of GDP* [Online]. Available at: http://www.ons.gov.uk/ons/datasets-and-tables/data-selector.html?cdid=ABMI&dataset=pgdp&table-id=A2 (Accessed: 29 January 2015).

ONS (2015c) *Publication Tables UK Trade, January 2015, Trade in Goods and Services*. [Online]. Available at: http://www.ons.gov.uk/ons/publications/re-reference-tables.html?edition=tcm%3A77-371562 (Accessed: 4 May 2015).

ONS (2015d) *The UK and its Countries: Facts and Figures*. [Online]. Available at: http://www.ons.gov.uk/ons/guide-method/geography/beginner-s-guide/administrative/the-countries-of-the-uk/index.html (Accessed: 16 January 2015).

Osmani, M., Glass, J. and Price, A.D.F. (2008) 'Architects' Perspectives on Construction Waste Reduction by Design', *Waste Management*, 28(7), pp. 1147-1158.

Ozcebe, S., H. Crowley, Baker H., Spence, R. and Foulser-Piggott, R. (2014) *Census Data Collection and Harmonisation for Europe*.

Palmer, J. and Cooper, I. (2013) *United Kingdom Housing Energy Fact File 2013*. Department of Energy and Climate Change.

Park, J.-a., Hong, S.-j., Kim, I., Lee, J.-y. and Hur, T. (2011) 'Dynamic Material Flow Analysis of Steel Resources in Korea', *Resources, Conservation and Recycling*, 55(4), pp. 456-462.

Parliamentary Office of Science and Technology (2012) *Low Carbon Technologies for Energy-Intensive Industries*.

PCD, Mahidol University and German Technical Cooperation (2007) *Studied Report of Construction Waste Management in Thailand*

PCD. (2015) *The draft National Waste Management Act.* Bangkok, Thailand.

Petavratrzi, E. and Barton, J. (2007) *Characterisation of Mineral Wastes, Resources and Processing Technologies – Integrated Waste Management for the Production of Construction Material*

Poon, C.S., Yu, A.T.W. and Jaillon, L. (2004) 'Reducing Building Waste at Construction Sites in Hong Kong', *Construction Management and Economics*, 22(5), pp. 461-470.

PricewaterhouseCoopers LLP (PWC) (2015) *The World in 2050: Will the Shift in Global Economic Power Continue?*

Private Sector & Development (2011) 'Cement Confronting Ecological Responsibility and Economic Imperatives', *Private Sector & Development Proparco's Magazine*(10).

Python Group Mining Specialists (2010) *Ready Mixed Concrete Processes*. Available at: http://www.pythongroup.ca/mining-news/article/id/58.

Quazi, H.A., Khoo, Y.-K., Tan, C.-M. and Wong, P.-S. (2001) 'Motivation for ISO 14000 Certification: Development of a Predictive Model', *Omega*, 29(6), pp. 525-542.

Radunsky, K. (2012) 'Carbon Footprint Of Products – ISO 14067', *IV Seminario Internacional CEPAL sobre la Huella de Carbona*. Santiago, Chile, 11-12 October 2012. Available at: http://www.cepal.org/comercio/tpl/contenidos/Carbon_footprint_Radunsky.pdf.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.P., Suh, S., Weidema, B.P. and Pennington, D.W. (2004) 'Life Cycle Assessment: Part 1: Framework, Goal and Scope Definition, Inventory Analysis, and Applications', *Environment International*, 30(5), pp. 701-720.

Rector R (2007) *How Poor are America's Poor? Examining the 'Plague' of Poverty in America*. Washington DC: The Heritage Foundation.

Renforth, P., Washbourne, C.-L., Taylder, J. and Manning, D.A.C. (2011) 'Silicate Production and Availability for Mineral Carbonation', *Environmental Science and Technology*, 45 (6), pp. 2035–2041.

Research and Development of System Form and Structure Sector (2012) *The Number of Local Administrations in Thailand*. [Online]. Available at: http://www.dla.go.th/work/abt/index.jsp.

Rhodes, C. (2015) 'Construction Industry: Statistics and Policy', 01432, *www.parliament.uk/commons-library* [Online] (Accessed: 7 September 2015).

Rogich, D.G. and Matos, G.R. (2008) *The global flows of metals and minerals: U.S. Geological Survey* [Online]. Available at: http://pubs.usgs.gov/of/2008/1355/.

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N. and Shiina, T. (2009) 'A Review Of Life Cycle Assessment (LCA) on Some Food Products', *Journal of Food Engineering*, 90(1), pp. 1-10.

Sandberg, N.H., Bergsdal, H. and Brattebø, H. (2010) 'Historical Energy Analysis of the Norwegian Dwelling Stock', *Building Research & Information*, 39(1), pp. 1-15.

Sandberg, N.H. and Brattebø, H. (2012) 'Analysis of Energy and Carbon Flows in the Future Norwegian Dwelling Stock', *Building Research & Information*, 40(2), pp. 123-139.

Sandberg, N.H., Sartori, I. and Brattebø, H. (2014a) 'Sensitivity Analysis in Long-Term Dynamic Building Stock Modeling—Exploring the Importance of Uncertainty of Input Parameters in Norwegian Segmented Dwelling Stock Model', *Energy and Buildings*, 85, pp. 136–144.

Sandberg, N.H., Sartori, I. and Brattebø, H. (2014b) 'Using a dynamic segmented model to examine future renovation activities in the Norwegian dwelling stock', *Energy and Buildings*, 82, pp. 287-295.

Sandberg, N.H., Sartori, I., Heidrich, O., Dawson, R., Dascalaki, E., Dimitriou, S., Vimmr, T., Filippidou, F., Stegnar, G., Šijanec Zavrl, M. and Brattebø, H. (2016) 'Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU', *Energy and Buildings*.

Sartori, I., Bergsdal, H., vard, Muller, D., Bratteb and Helge (2008) 'Towards Modelling of Construction, Renovation and Demolition Activities: Norway's Dwelling Stock, 1900-2100', *Building Research and Information*, 36(5), pp. 412-425.

Saunders, A. (2015) 'The cement industries of southeast Asia', *Global Cement Magazine* April 2015.

SCG Cement Public Co. Ltd. (2014) *Company Profile*. Available at: http://www.scg.co.th/en/01corporate_profile/ (Accessed: 13 November 2014).

Schepelmann, P. (n.d.) 'Lifecycle Assessment (LCA)'.

Schmidt, A., Hache, B., Herold, F. and Götze, U. (n.d.) 'Material Flow Cost Accounting with Umberto'.

Schneider, M., Romer, M., Tschudin, M. and Bolio, H. (2011) 'Sustainable Cement Production—Present and Future', *Cement and Concrete Research*, 41(7), pp. 642-650.

Schorcht, F., Kourti, I., MariaScalet, B., Roudier, S. and DelgadoSancho, L. (2013) *Best Available Techniques Reference Document for the Production of Cement, Lime and Magnesium Oxide*. European Union.

Scientific Applications International Corporation (SAIC) (2006) *Life Cycle Assessment: Principles and Practice*. National Risk Management Research Laboratory.

Scottish Building Standards Agency (2007) *Design Life of Buildings: A Scoping Study*. Glasgow, the UK: Building Research Establishment (BRE).

Seely, A. (2011) *Aggregates Levy*.

Shi, J. and Xu, Y. (2006) 'Estimation and forecasting of concrete debris amount in China', *Resources, Conservation and Recycling*, 49(2), pp. 147-158.

Shima, H., Tateyashiki, H., Matsuhashi, R. and Yoshida, Y. (2005) 'An Advanced Concrete Recycling Technology and its Applicability Assessment through Input-Output Analysis', *Journal of Advanced Concrete Technology*, 3(1), pp. 53-67.

Simmonds, C. (2010) *Management Board Environmental Targets*. [Online]. Available at: http://www.parliament.uk/documents/commons-commission/Commons-Management-Board/MB2010/02-Feb10/MB2010.P.18_Environmental_Targets.pdf (Accessed: 26 January 2015).

Sjunnesson, J. (2005) *Life Cycle Assessment of Concrete*. Master thesis. Lund University.

Söderholm, P. (2011) 'Taxing Virgin Natural Resources: Lessons from Aggregates Taxation in Europe', *Resources, Conservation and Recycling*, 55(11), pp. 911-922.

Sofios, S., Arabatzis, G. and Christopoulou, O. (2005) 'Input Output Analysis: The Case of Western Thessaly', *Discussion Paper Series*, 11(8), pp. 129 - 140.

Song, C.H. (2005) 'Whole Life and Highgrade Qualitystick to the Implement Housing Performance Certification', *Housing Scienc*, 290(8), pp. 287–302.

Statista (2015a) 'United Kingdom (UK) HMRC Aggregates Levy Receipts from Fiscal Year 2002/2003 to Fiscal Year 2013/2014 (in Million GBP)'.

Statista (2015b) *United Kingdom (UK) HMRC Landfill Tax Receipts from Fiscal Year 2000/2001 to Fiscal Year 2013/2014 (in Million GBP)*.

Streicher-Porte, M., Bader, H.-P., Scheidegger, R. and Kytzia, S. (2007) 'Material Flow and Economic Analysis as a Suitable Tool for System Analysis under the Constraints of Poor Data Availability and Quality in Emerging Economies', *Clean Technologies and Environmental Policy*, 9(4), pp. 325-345.

Suh, S. (2005) 'Theory of Materials and Energy Flow Analysis in Ecology and Economics', *Ecological Modelling*, 189(3–4), pp. 251-269.

Suh, S. (2009) *Handbook of Input-Output Economics in Industrial Ecology*. Dordrecht ; London : Springer.

Supachalasai, S. and Pangkanon, P. (1996) *The Potentialities and Opportunities for Export and the Impacts of the ASEAN Free Trade Area for a Cement Industry*. Sectorial Economic Programme, Thailand Development Research Institute.

Suwanteep, K., Chavalparit, O. and Ongwandee, M. (n.d.) 'Evaluation of Carbon Footprint of Activated Sludge Wastewater Treatment System'.

Sygulla, R., Bierer, A. and Götze, U. (2011) 'Material Flow Cost Accounting – Proposals for Improving the Evaluation of Monetary Effects of Resource Saving Process Designs', *The 44th CIRP Conference on Manufacturing Systems*. Madison, Wisconsin, USA, 1-3 June 2011. Available at: www.tu-chemnitz.de/wirtschaft/bwl3/DownloadAllgemeinOffen/44thCIRP_MFCA.pdf.

Symonds Group Ltd. et al (1999) *Consulting Engineers and Planners and PRC Bouwcentrum. Report to DGXI: Construction and Demolition Management Practices and their Economic Impacts*. Brussels, Belgium: Symonds Group, .

Tallon, A. (2013) *Urban Regeneration in the UK*. Taylor and Francis. Available at: http://NCL.eblib.com/patron/FullRecord.aspx?p=1211691.

Tanikawa, H., Managi, S. and Lwin, C.M. (2014) 'Estimates of Lost Material Stock of Buildings and Roads Due to the Great East Japan Earthquake and Tsunami', *Journal of Industrial Ecology*, 18(3), pp. 421-431.

Taylor, H.F.W. (1997) *Cement Chemistry*. Thomas Telford Publishing.

TFCM (2014) *Background Information*. Available at: http://www.thaicma.or.th/ (Accessed: 13 November 2014).

TFCM (2015) *Cement Industry in Thailand*.

Thailand Concrete Association (2014) *Board and Purposes of Thailand Concrete Association* Available at: http://www.thaitca.or.th/index.php?option=com_content&view=category&layout=blog&id=34&Itemid=53 (Accessed: 13 November 2014).

The ASEAN Secretariat (2008) *ASEAN Economic Community Blueprint*. Public Affairs Office, The ASEAN Secretariat. Available at: http://www.asean.org/archive/5187-10.pdf.

The British Standards Institution (2013) *Aggregates for Concrete (BS EN 12620:2013)*.

The Cabinet Office (2011) 'Government Construction Strategy'.

The Cement & Concrete Institute (2009) 'Mortar Mixes for Masonry'. Midrand, South Africa.

The Chartered Institute of Building (2013) *Sustainable Construction and the Green Deal*.

The Concrete Centre (2009) *The Concrete Industry Sustainability Performance Report*.

The Concrete Centre (2010a) *Concrete Credentials: Sustainability: A Quick Reference Guide to the Sustainable and Performance Benefits of Concrete*.

The Concrete Centre (2010b) *The Concrete Industry Sustainability Performance Report: 2nd Report: 2008 Performance Data and Release of 2012 Performance Targets*. The Concrete Centre, part of the Mineral Products Association The Concrete Centre, p.o.t.M.P.A., on behalf of the Sustainable Concrete Forum.

The Concrete Centre (2012) *The Concrete Industry Sustainable Construction Strategy*.

The Concrete Centre (2013) 'Sustainability Matters 2013'.

The ENTRANZE Project (2008a) *Average floor area per capita* (Accessed: 6 October).

The ENTRANZE Project (2008b) *Dwellings according to construction date*. Available at: http://www.entranze.enerdata.eu/average-size-of-dwelling.html#/share-of-dwellings-built-before-1980-in-total-stock.html (Accessed: 5 October 2015).

the ENTRANZE Project (2008c) *Share of Dwellings Built After 2000 in Total Stock*. Available at: http://www.entranze.enerdata.eu/average-size-of-dwelling.html#/share-of-dwellings-built-after-2000-in-total-stock.html (Accessed: 5 October).

The European Cement Association (2007) *Activity Report 2006*.

The European Cement Association (2013) *The Role of Cement in the 2050 Low Carbon Economy*.

The European Environment Agency (2008) *Effectiveness of Environmental Taxes and Charges for Managing Sand, Gravel and Rock Extraction in Selected EU Countries*. Schultz Grafisk.

The European Parliament and the Council (2008) *The Raw Materials Initiative: Meeting Our Critical Needs for Growth and Jobs in Europe*. Brussels.

The House of Commons (2002) *Aggregates Levy: The Aggregates Levy (General) Regulations 2002*. London: Her Majesty's Stationery Office and Queen's Printer of Acts of Parliament.

The International Energy Agency (IEA) and Tsinghua University (2015) *Building Energy Use in China: Transforming Construction and Influencing Consumption to 2050*.

The International Organization for Standardization (2009) *Environmental Management the ISO 14000 Family of International Standards*. Available at: http://www.iso.org/iso/theiso14000family_2009.pdf.

The Ministry of Economy Trade and Industry (Japan) (2002) *Environmental Management Accounting (EMA) Workbook.* Available at: http://www.meti.go.jp/policy/eco_business/pdf/workbook.pdf.

The Ministry of Economy Trade and Industry (Japan) (2007) *Guide for Material Flow Cost Accounting (ver.1)* Available at: http://www.meti.go.jp/policy/eco_business/pdf/mfca%20guide20070822.pdf.

The Official Journal of the European Union (2013) 'The Best Available Techniques (BAT) Conclusions under Directive 2010/75/EU of the European Parliament and of the Council on Industrial Emissions for the Production of Cement, Lime and Magnesium Oxide'.

The Royal Thai Government (1979) *Building Control Act B.E. 2522 (1979)*.

The Sustainable Construction Task Group (2012) *A new Government Construction Clients Sustainability Action Plan 2012-2015*. Department of Finance and Personnel.

Thompson, A., Harris, K., Knapman, D., Marker, B., Poole, J. and Higgs, J. (2008) *Reasons for the Decline in Aggregate Reserves in England*. The Mineral Industry Research Organisation.

Tikul, N. and Srichandr, P. (2011) 'Assessment of Environmental Impact of Thai Housing', *Gazi University Journal of Science*, 24(3), pp. 585-591.

UEPG (2015) *European Aggregates Association: A Sustainable Industry for a Sustainable Europe: Annual Review 2013-2014*. Brussels, Belgium.

UN (1992) 'The Rio Declaration on Environment and Development (1992)', *The United Nations Conference on Environment and Development*,. Rio de Janeiro, 3 - 14 June 1992.

UN (2000) *The 10th Session UNCTAD Conference on Trade and Development*. Bangkok, Thailand, 12-19 February 2000.

UN (2004) *World Population to 2300*. New York, USA: Population Division, Department of Economic and Social Affairs.

UN (2012) *World Population Prospects: The 2012 Revision*. Available at: http://esa.un.org/unpd/wpp/index.htm (Accessed: 24 March 2015).

UN (2014) *World Economic Situation and Prospects 2014: Country Classification*. [Online]. Available at: http://www.un.org/en/development/desa/policy/wesp/wesp_current/2014wesp_country_classification.pdf (Accessed: 25 June 2015).

UN (2015a) 'Probabilistic Population Projections based on the World Population Prospects: The 2015 Revision' July 2015. 22 September 2015. Available at: http://esa.un.org/unpd/ppp/.

UN (2015b) *World Population Prospects: The 2015 Revision, Key Findings and Advance Tables* (Working Paper No. ESA/P/WP.241). New York, USA: Department of Economic and Social Affairs, Population Division.

UNEP (2013) *City-Level Decoupling Urban Resource Flows and The Governance of Infrastructure Transitions* (978-92-807-3298-6).

United Nations (2015) 'World Population Prospects: The 2012 Revision'. 24 March 2015. Population Estimates and Projections Section, Population Division, Department of Economic and Social Affairs Available at: http://esa.un.org/unpd/wpp/unpp/panel_population.htm.

United Nations Development Programme (ed.) (2007) *Thailand Human Development Report 2007: Sufficiency Economy and Human Development*. Bangkok, Thailand.

US.EPA (1993) *Cement Kiln Dust Waste: Volume II Methods and Findings*.

USDA (2015a) *Historical Gross Domestic Product Per Capita for Baseline Countries/Regions (in 2010 dollars) 1969-2014*. Available at: https://view.officeapps.live.com/op/view.aspx?src=http%3A%2F%2Fwww.ers.usda.gov%2Fdatafiles%2FInternational_Macroeconomic_Data%2FHistorical_Data_Files%2FHistoricalRealPerCapitaGDPValues.xls (Accessed: 29 October).

USDA (2015b) *Real Historical Gross Domestic Product (GDP) and Growth Rates of GDP for Baseline Countries/Regions (in Billions of 2010 Dollars) 1969-2014*. Available at: http://www.ers.usda.gov/data-products/international-macroeconomic-data-set.aspx (Accessed: 30 October).

Va´zquez, E. (2013) *Progress of Recycling in the Built Environment*. Springer.

Van Oss, H.G. (2005) *Background Facts and Issues Concerning Cement and Cement Data*. U.S.Department of the Interior and U.S.Geological Survey

Van Oss, H.G. and Padovani, A.C. (2002) 'Cement Manufacture and the Environment: Part I: Chemistry and Technology', *Journal of Industrial Ecology*, 6(1), pp. 89-105.

Van Oss, H.G. and Padovani, A.C. (2003) 'Cement Manufacture and the Environment Part II: Environmental Challenges and Opportunities', *Journal of Industrial Ecology*, 7(1), pp. 93-126.

Vantage Pipes (2015) *Precast Concrete Processes*. Available at: http://jameshardiepipes.com.au/our-process.

Viere, T., Möller, A. and Prox, M. (2011) 'A Material Flow Cost Accounting Approach to Improvement Assessment in LCA', *International Journal for Sustainable Innovations*, 1(1).

Wang, T., Tian, X., Hashimoto, S. and Tanikawa, H. (2015) 'Concrete transformation of buildings in China and implications for the steel cycle', *Resources, Conservation and Recycling*, 103, pp. 205-215.

Ward, K. (2012) *The World in 2050 from the Top 30 to the Top 100*. HSBC.

WBCSD (2009a) *Cement Industry Energy and CO2 Performance "Getting the Numbers Right"*.

WBCSD (2009b) *The Cement Sustainability Initiative: Recycling Concrete*.

WBCSD (2014) *The Cement Industry Creating Solutions for Safe, Resource-Efficient Waste Management*.

Weidema, B.P., Thrane, M., Christensen, P., Schmidt, J. and Løkke, S. (2008) 'Carbon Footprint a Catalyst for Life Cycle Assessment?', *Journal of Industrial Ecology*, 12.

West, J., Schandl, H. and UNEP (2010) 'CSIRO and UNEP Asia-Pacific Material Flows Online Database'. 12 February 2016. Available at: http://www.cse.csiro.au/forms/form-mf-start.aspx.

Wiedmann, T. (2010a) *Frequently Asked Questions about Input-Output Analysis*. Innovation Centre, Innovation Way, York Science Park, York, YO10 5DG, United Kingdom: Centre for Sustainability Accounting. [Online]. Available at: http://www.censa.org.uk/docs/CENSA_Special_Report_FAQ_IOA.pdf.

Wiedmann, T. (2010b) *Frequently Asked Questions about Input - Output Analysis*. Centre for Sustainability Accounting. Available at: http://www.censa.org.uk/docs/CENSA_Special_Report_FAQ_IOA.pdf.

Wiedmann, T. and Minx, J. (2008) *A Definition of 'Carbon Footprint'*. Nova Science Publishers. Available at: http://www.utm.my/co2footprintutm/files/2011/11/ISA-UK_Report_07-01_carbon_footprint.pdf.

Wilburn, D.R. and Goonan, T.G. (1998) *Aggregates from Natural and Recycled Sources Economic Assessments for Construction Applications—A Materials Flow Analysis*. U.S. Geological Survey.

Wilcox, K. (2007) *ISO 14001: An Analysis*. [Online]. Available at: http://irps.ucsd.edu/assets/020/8401.pdf.

Williams, A.S. (2009) *Life Cycle Analysis: A Step by Step Approach*. Illinois Sustainable Technology Center, Institute of Natural Resource Sustainability, University of Illinois at Urbana-Champaign.

Wilson, D.C., Parker, D., Cox, J., Strange, K., Willis, P., Blakey, N. and Raw, L. (2012) 'Business waste prevention: a review of the evidence', *Waste Management & Research*, 30(9 suppl), pp. 17-28.

Woodward, R. and Duffy, N. (2011) 'Cement and Concrete Flow Analysis in a Rapidly Expanding Economy: Ireland as a Case Study', *Resources, Conservation and Recycling*, 55(4), pp. 448-455.

World Bank (2008) *Global Purchasing Power Parities and Real Expenditures, 2005, International Comparison* (Accessed: 28 October).

World Bank (2012) *Getting to Green—A Sourcebook of Pollution Management Policy Tools for Growth and Competitiveness*.

World Bank (2015a) *GDP per capita (current 2011 US$)*. Available at: http://data.worldbank.org/indicator/NY.GDP.MKTP.CD (Accessed: 10 October).

World Bank (2015b) *Global Purchasing Power Parities and Real Expenditures, 2011, International Comparison*. Available at: http://data.worldbank.org/indicator/NY.GDP.PCAP.PP.KD?display=default (Accessed: 4 October 2015).

World Bank (2015c) *Purchasing Power Parities and the Real Size of World Economies*.

World Bank (2015d) *World Development Indicators (China)*. Available at: http://data.worldbank.org/ (Accessed: 11 October).

World Bank (2015e) *World Development Indicators (Thailand)*. Available at: http://data.worldbank.org/ (Accessed: 28 January 2015).

World Bank (2015f) *World Development Indicators (the UK)*. Available at: http://data.worldbank.org/ (Accessed: 28 January 2015).

World Business Council for Sustainable Development (2009) *Recycling Concrete*.

World Steel Association (2011) *Life Cycle Assessment Methodology Report*. Available at: http://www.worldsteel.org/dms/internetDocumentList/bookshop/LCA-Methodology-Report/document/LCA%20Methodology%20Report.pdf.

Worrell, E., Price, L., Martin, N., Hendriks, C. and Meida, L.O. (2001) 'Carbon Dioxide Emissions from the Global Cement Industry', *Annual Review of Energy and the Environment*, 26(1), pp. 303-329.

WRAP (2003) *Aggregates Programme for Scotland – Production of High Value Aggregates from Construction, Demolition and Excavation Waste*. Realm Construction's Scottish Programme.

WRAP (2007) *Performance Related Approach to Use of Recycled Aggregates*.

WRAP (2008) *Waste Reduction Potential of Precast Concrete Manufactured Offsite* (WAS 003-003).

WRAP (2010) *Construction, Demolition and Excavation Waste Arisings, Use and Disposal for England 2008*.

WRAP (2011) *The Efficient Use of Materials in Regeneration Projects Overview (Sections 1-4)*.

WRAP (2013) *Quality Protocol: Aggregates from Inert Waste: End of Waste Criteria for the Production of Aggregates from Inert Waste*.

WRAP (2015a) *More Information on Recycled and Secondary Aggregates*. Available at: http://aggregain.wrap.org.uk/more_information.html (Accessed: 8 February 2015).

WRAP (2015b) 'WRAP Vision'.

Yang, W. (2006) *Modeling the Evolution of the Chinese Building Stock in a Sustainable Perspective*. Tianjin University.

Yuan, H. (2013) 'Key Indicators for Assessing the Effectiveness of Waste Management in Construction Projects', *Ecological Indicators*, 24, pp. 476-484.

Yuan, H., Chini, A.R., Lu, Y. and Shen, L. (2012) 'A dynamic model for assessing the effects of management strategies on the reduction of construction and demolition waste', *Waste Management*, 32(3), pp. 521-531.

Yuan, H.P., Shen, L.Y., Hao, J.J.L. and Lu, W.S. (2011) 'A model for cost–benefit analysis of construction and demolition waste management throughout the waste chain', *Resources, Conservation and Recycling*, 55(6), pp. 604-612.

Yuan, Z., Bi, J. and Moriguichi, Y. (2006) 'The Circular Economy: A New Development Strategy in China', *Journal of Industrial Ecology*, 10(1-2), pp. 4-8.

Zhou, N., Masaru., N. and Weijun., G. (2008) *Current Status and Future Scenarios of Residential Building energy consumption in China*. The U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Appendix A: National Overviews

1 Great Britain

1.1 National Overview

1.1.1 Geographical and Administrative Summary

The United Kingdom (UK) is a sovereign state in Europe combining four nations – England, Scotland, Wales and Northern Ireland. The UK mainland consists of England, Scotland and Wales, called Great Britain. The UK is located on the north-western coast of the European mainland. The national government is at Westminster, with devolved administrations in Edinburgh, Cardiff and Belfast. A parliamentary democracy with a constitutional monarch is the government form in the UK. A queen or king is the head of state, and the head of government is a prime minister. Parliament members are represented using election from UK citizens. The number of each type of the UK administrative areas can be seen in **Table A - 1** and the UK administrative geography map is shown as **Figure A - 1**.

Table A - 1 The number of each type of the UK administrative areas

The United Kingdom (its countries)	Number
England	
Regions (former Government Office Regions)	9
Non-metropolitan (shire) counties	27
Non-metropolitan districts	201 (subdivisions of non-metropolitan counties)
Unitary authorities	56
Metropolitan districts	36 (subdivisions of the 6 former metropolitan counties)
London boroughs	32 (plus the City of London, which is a City Corporation)
Scotland	
Council areas	32
Wales	
Unitary authorities	22
Northern Ireland	
District Council areas	26

Source: Author based on ONS (2011e)

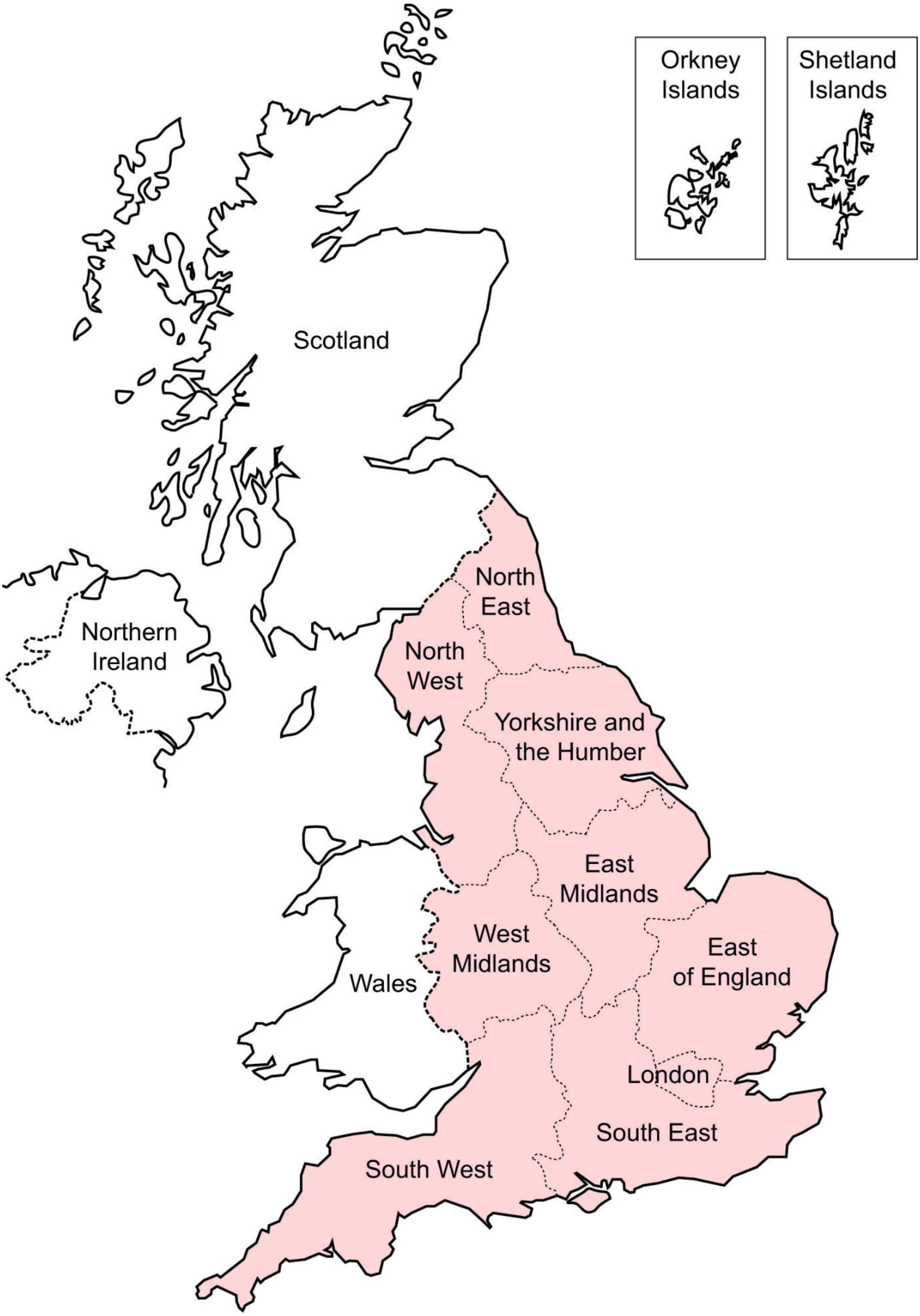
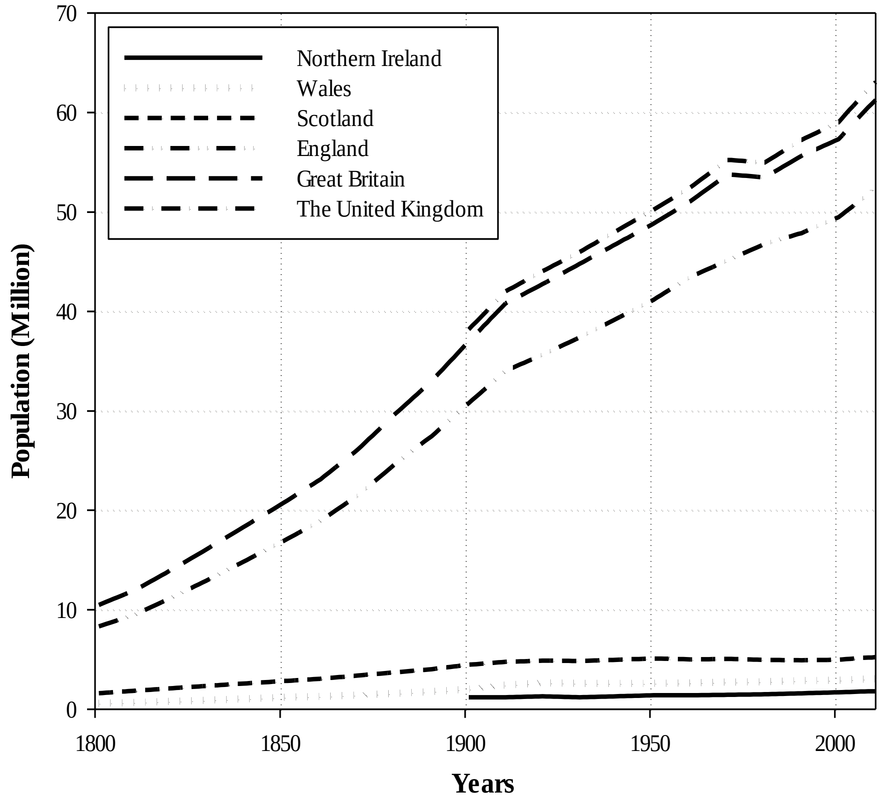


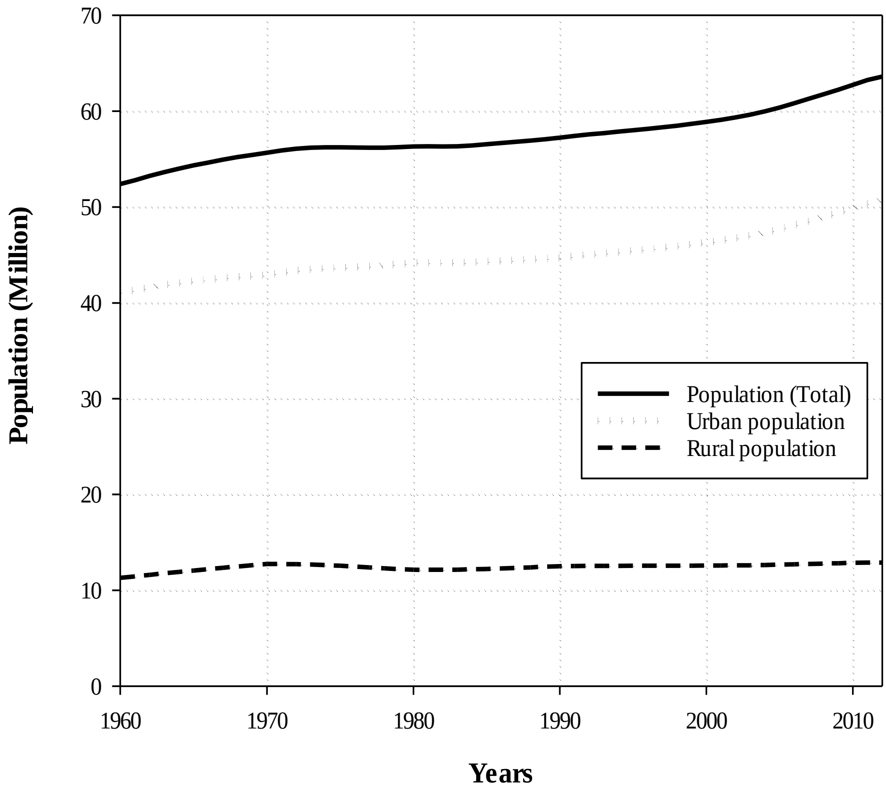
Figure A - 1 Administrative geography map of the UK
Source: Taken from ONS (2011b)

1.1.2 Demographic and Social Summary

The UK has a total area of 248,531.52 square kilometres (km^2) separated into England 132,937.69 km^2, Scotland 80,239.47 km^2, Wales 21,224.63 km^2 and Northern Ireland 14,129.72 km^2. Thus, 234,407.79 km^2 or 94.31% of the UK area is Great Britain territory. In mid-2012, it is estimated that the total UK population was 63.7 million people (ONS, 2015d): England 53.5, Scotland 5.3, Wales 3.1 and Northern Ireland 1.8 million inhabitants. Therefore, 61.9 million people or 97.17% of UK population lived in Great Britain. The trend of UK population from 1801 to 2011 increased steadily due mainly to the increase in the British populations, shown in **Figure A - 2** which also shown that 80% of the UK population has social and living conditions in urban communities (World Bank, 2015f).



A



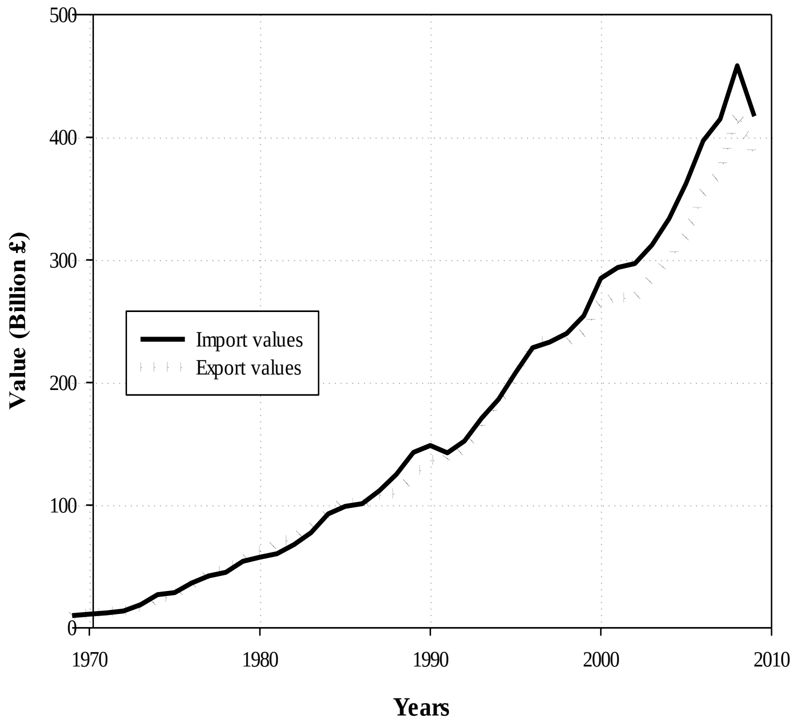
B

Figure A - 2 UK population (1801-2011, A) and UK urban and rural population (1960-2011, B)
Sources: A: Author based on Kyd (1952); National Records of Scotland (2013); Online Historical Population Reports (2012a), (2012b), (2012c); ONS (2011a), (2012c), (2012d)
B: Author based on World Bank (2015f)

1.1.3 Economic Summary

The UK is the sixth largest trader in the world, behind the United States (US), China, Germany, Japan and France (Department for Business Innovation and Skills, 2012). From 1969, the UK import and export trends were similar (**Figure A - 3**). However, since 1998, the UK had expenditure in excess of revenue, i.e. (1) a trade deficit for foreign trading, and (2) the import and export values decreased in 2008 as a consequence of the global financial crisis and the European sovereign debt crisis (Massa *et al.*, 2012). For import and export products, the principal UK goods are (1) cars, electrical and mechanical machinery, (2) medicinal and pharmaceutical products and (3) crude and refined oil (ONS, 2015c). Asia and North America as China, Japan, Hong Kong, South Korea and the US are the main foreign trading partners outside the European Union (non-EU). For EU commerce, Germany, France, Netherlands, Irish Republic, Norway, Italy, Spain and Belgium are the main UK trading countries. (HM Revenue & Customs, 2011; HM Revenue & Customs, 2015b; ONS, 2015c).

Using chained volume measures (ONS, 2015b), Gross Domestic Product (GDP) in the UK had continuously increased until 2008. Then, because of the 2008-2009 global financial crisis and the European sovereign debt crisis, UK GDP had dropped and then rose up again (**Figure A - 3**). **Figure A - 3** also shows the construction sector contributed around £72.6 billion or 7.66% in 2012, separated into (1) specialised construction activities £34.7 billion (47.80%) as electrical and plumbing installation, demolition and site preparation, plastering, painting and roofing, (2) construction of buildings £25.6 billion (35.26%) as commercial and residential and (3) civil engineering £12.3 billion (16.94%) as roads, tunnels, bridges and utilities (Department for Business Innovation and Skills, 2013; ONS, 2013a). Moreover, UK construction created around 2.04 million positions or about 6.4% of the total UK employment in 2012. Then, in 2014, there was an increasing trend in the UK construction sector which contributed £103 billion or 6.5% of the UK GDP and supported 2.1 million jobs for UK population or 6.3% of the total (Rhodes, 2015).



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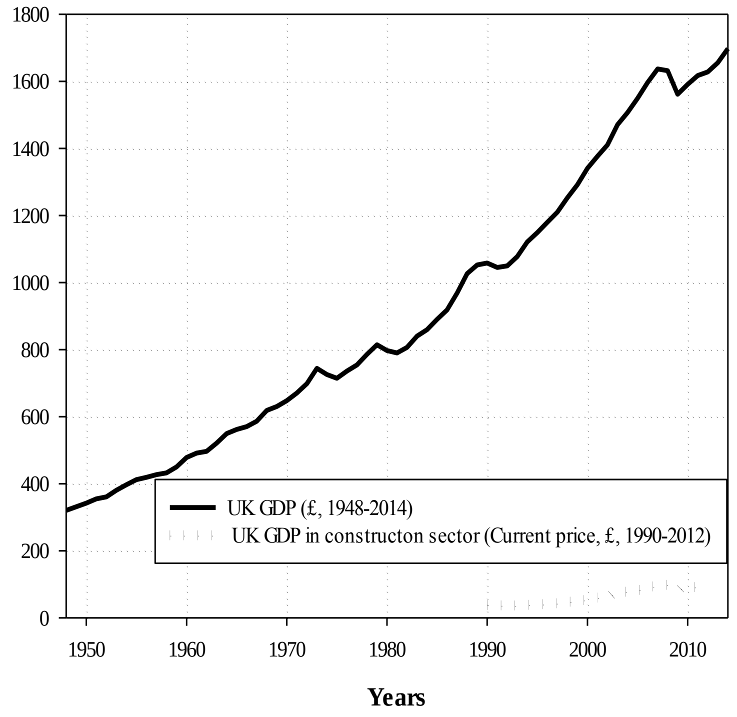


B

Figure A - 3 UK import and export values (A) and UK GDP including GDP in construction sector (B)
Source: A: Author based on ONS (2010b)
B: Author based on ONS (2013c) and ONS (2015b)

2 Thailand

2.1 National Overview

2.1.1 Geographical and Administrative Summary

Thailand, located in Southeast Asia, has national territory of approximately 513,000 square kilometres (km^2) or double that of Great Britain. The territory can be divided into six main regions: namely the North, Central, East, Northeast, West and South. According to administrative boundaries (**Figure A - 4**), Thailand has 76 provinces including the capital city Bangkok. Thai administrative levels can be identified into two main groups (Department of Local Administration, 2013): Special and General Local Administrations. The first group is under direct supervision of the Minister of Interior and has individual management to govern its controlled areas such as (1) its revenues, (2) own legislation under the national constitution and (3) local elections for its own administrators. The principal members of this group are only Bangkok and Pattaya City.

The second type of administation, General Local Administration exists across all provinces except Bangkok and Pattaya City, and can be separated into three main groups:

(1) The Provincial Administration Organisation is a decentralised organisation in each of 76 provinces, mainly responsible for provincial public services. These can support lower levels of administration including provincial coordination in order to avoid redundant tasks within their provinces.

(2) The Municipality which is separated into three sub-groups using population, prosperity, and area size, named City, Town and Sub-district Municipalities.

(3) The third is the biggest group and the smallest organisation especially in most remote areas, a Sub-district Administrative Organisation.

All groups of General Local Administration are governed using direct elections and work under auditing and counterbalancing of Local Administrative Councils. In summary, the missions of all administrative levels are to follow a decentralised policy from the central government by a chain of descending commands, depending on organisation sizes. Besides, most of the Thai local administration is small agencies in remote areas that are difficult to govern and to allocate adequate budget and officials. The number of local administrations in Thailand is shown in **Table A - 2**.

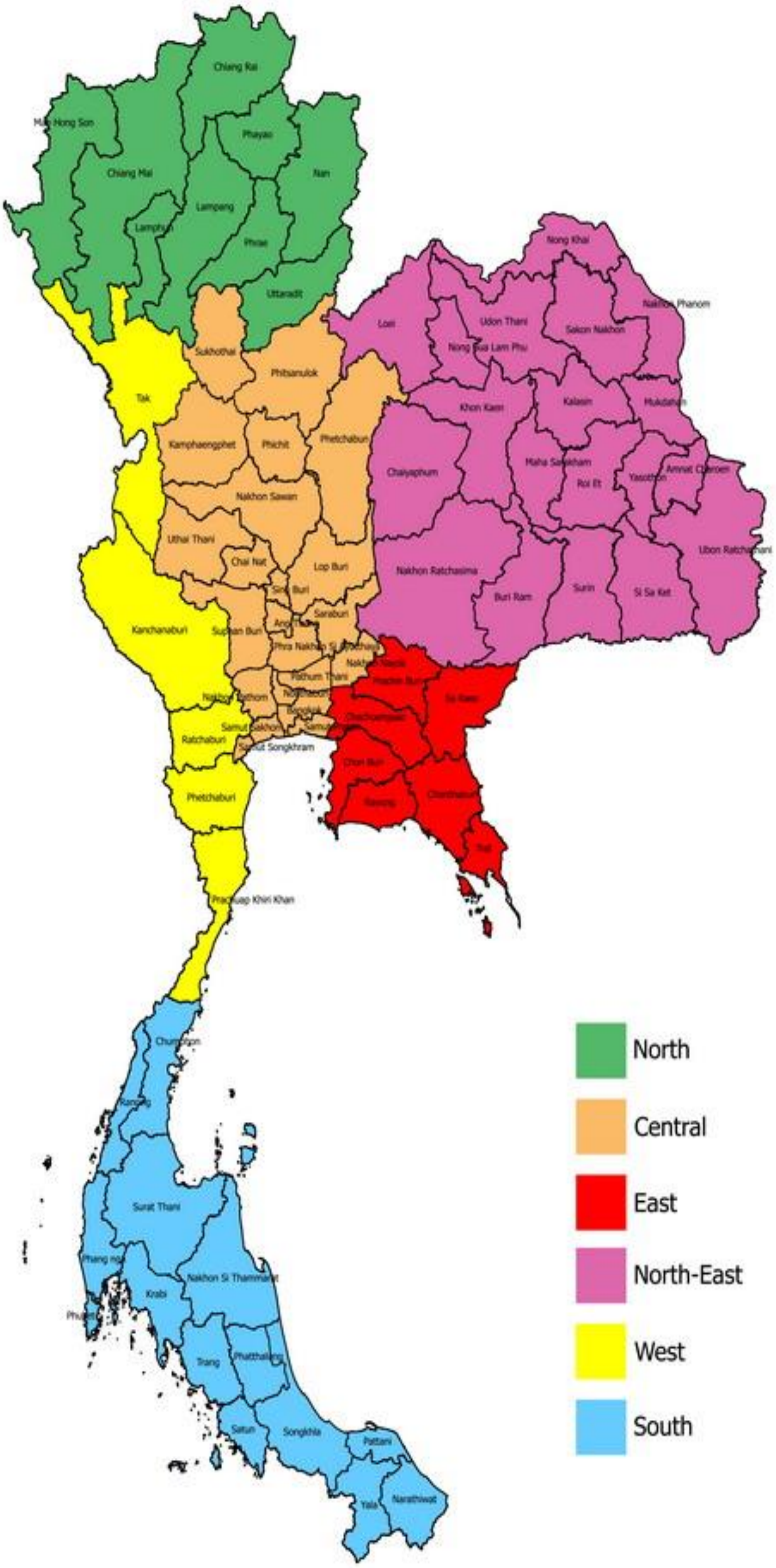


Figure A - 4 Political map of Thailand
Source: Taken from Department of Provincial Administration (2015)

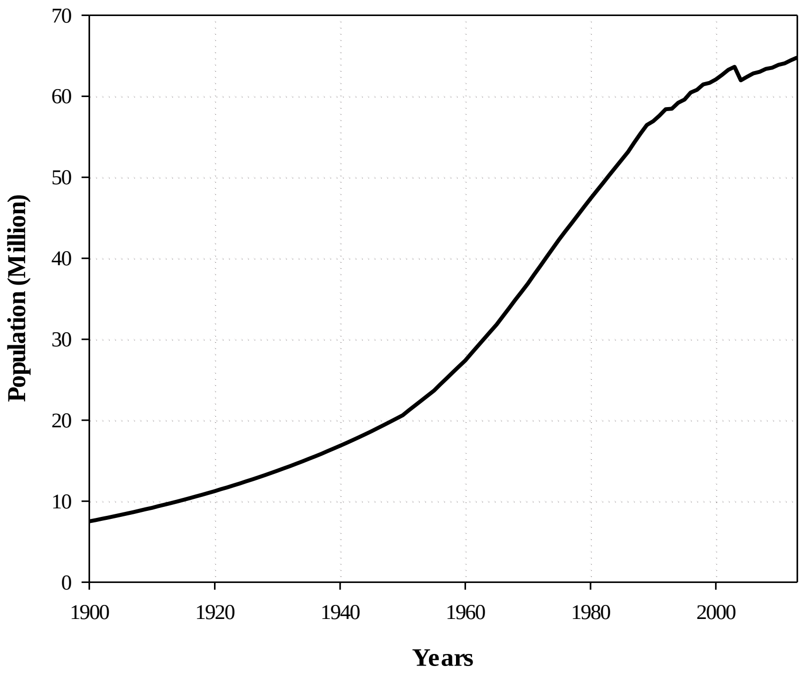
Table A - 2 Number of local administrations in Thailand

No.	**Administrative Levels** (1 October 2012)	**Number of Local Administrations**
1.	**Special Administration** (Bangkok and Pattaya City)	**2**
2.	**Provincial Administration Organization**	**76**
3.	**Municipality**	**2,266**
	City Municipality	29
	Town Municipality	167
	Sub-district Municipality	2,070
4.	**Sub-district Administrative Organization**	**5,509**
	Total	**7,853**

Source: Author based on Research and Development of System Form and Structure Sector (2012)

2.1.2 Demographic and Social Summary

As can be seen in **Figure A - 5**, the Thai population has gradually increased since 1900. In 2012, Thailand had 64.5 million people with a growth rate around 0.6%, quite similar to the Great Britain population. Living in rural areas is the main residence of the 65% Thai population and it tends to change gradually to be urban areas over time. Thus, the urban population has continuously increased. Furthermore, an important region having most people was the Northeast (34%) followed closely by the Central (31%). The other four regions, the South, North, East and West, had around 14, 9, 7 and 5% of the total population respectively. Separating Thai people by gender, Thailand had slightly more women (50.82%) than men (49.18%, **Figure A - 6**).



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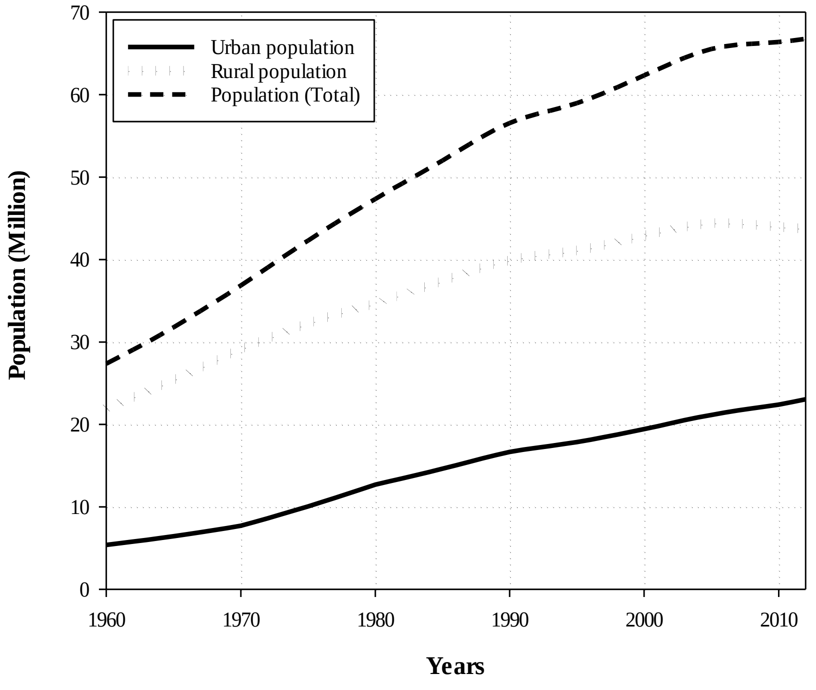

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Figure A - 5 Thai national populations (1900-2012, A) and Thai urban and rural population (B)
Sources: Author based on United Nations (2015), Department of Provincial Administration (2015) and World Bank (2015e)

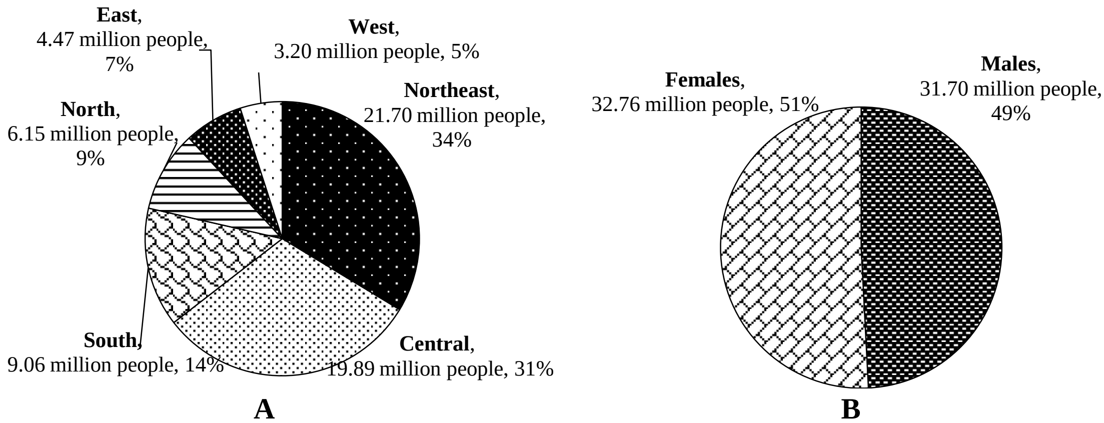


Figure A - 6 Percentage of Thai population in each region (A) and gender (B) in 2012
Source: Author based on Department of Provincial Administration (2015)

Formerly, the dominant occupation of Thai people was agriculturist. Then, modern industrial development has made the member of people in the agricultural sector decrease. This situation was reviewed by National Statistical Office (2013b), showing that only 14 million Thai people still worked in the agricultural sector. On the one hand, almost 25 million people worked in a non-agricultural sector and three million of those worked for construction businesses especially 1.5 million Northeast people. However, Bangkok which has the most buildings in Thailand (more than 80% of Bangkok buildings are new constructions), used most migrant labourers (Ogunlana *et al.*, 1996; National Statistical Office, 2004; 2009b). Thus, transitory migration for construction employment is one of the social problems in Thailand.

2.1.3 Economic Summary

Thailand has various appropriate determinants for cultivation such as proper agricultural areas, enough fresh water and warm weather. Although agricultural products are commonly made for domestic consumption and some surplus goods can be exported to several countries in the world, revenue from these sales is much lower than industrial products. As explicitly elucidated using a Thai standard of living in **Figure A - 7**, the Gross Domestic Product (GDP) attributed to the agricultural sector was annually less than 10 %, and was quite stable from 1990 to 2013. It is because the value of agricultural products is comparatively less than the industrial products. Hence, the market value of all officially recognized final goods and services produced in Thailand is dominated by the non-agricultural sector (Bank of Thailand, 2015d). In addition, Gross National Product (GNP) in the Thai construction sector was 3-6% of the Thai GDP (Office of National Economic and Social Development Board, 2015).

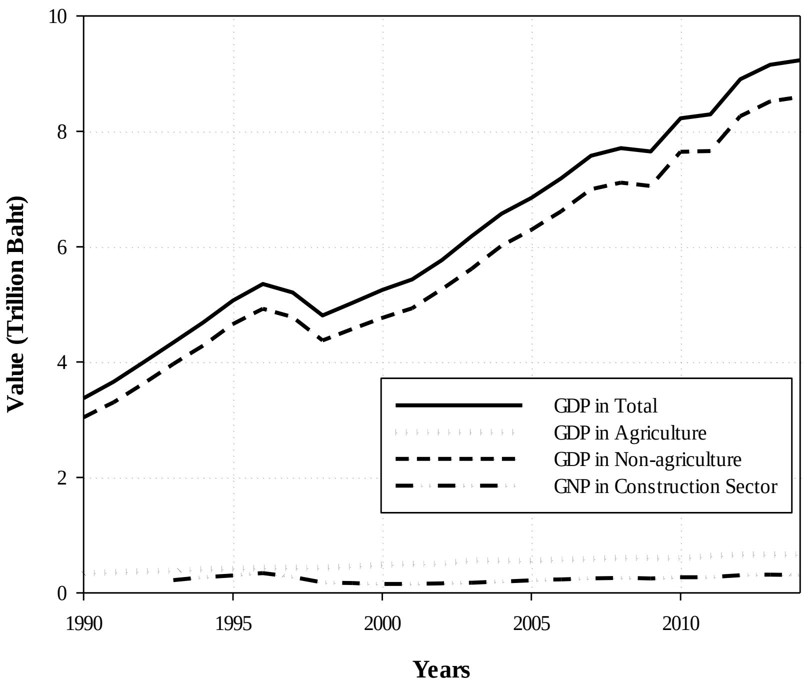
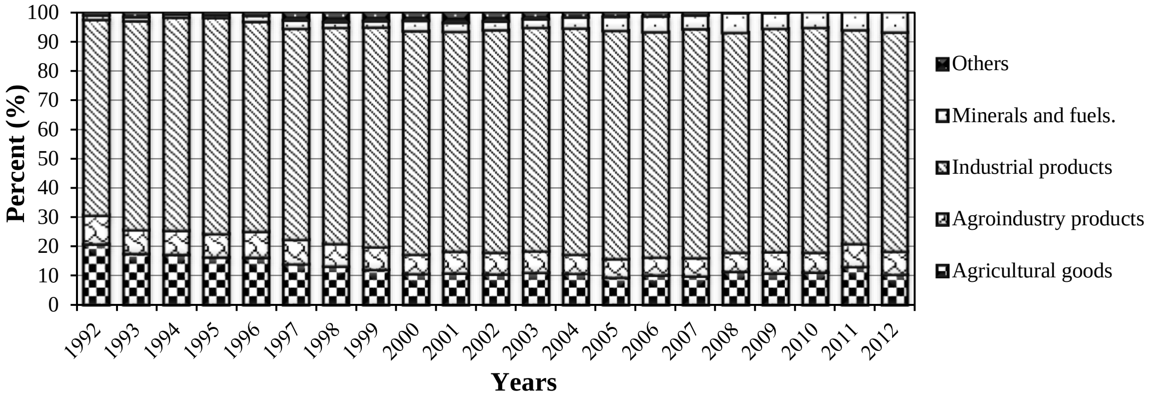


Figure A - 7 Thai GDP in Agriculture and Non-Agriculture including GNP in Construction Sector
Source: Author based on Bank of Thailand (2015d) and Office of National Economic and Social Development Board (2015)

To consider export figures published from 1992 to 2012 (**Figure A - 8**), a report from Thai industrial economists stated that Thailand exported products to several nations such as Asian countries (25%), China (12%), Japan (10%), European countries (10%) and the USA (10%). The export value was more than 70% from industry as the principal export products and less than 20% from agriculture and agroindustry products (Office of Industrial Economics, 2012; Information and Communication Technology Centre, 2013a). Moreover, Thailand needed to import 40% raw materials and 30% capital goods that were primary feed stocks of several Thai industries. One-third of these imports came from nearby Asian countries such as 20% Japan and 16% other Asian countries (Office of Industrial Economics, 2012). To summarise an economic overview using **Figure A - 9**, Thailand was previously faced with a trade deficit. Then, import and export trends had been converted since 1997 to a trade surplus with foreign trading partners due principally to increasing value of production from the industrial sector (Bank of Thailand, 2015d).



A

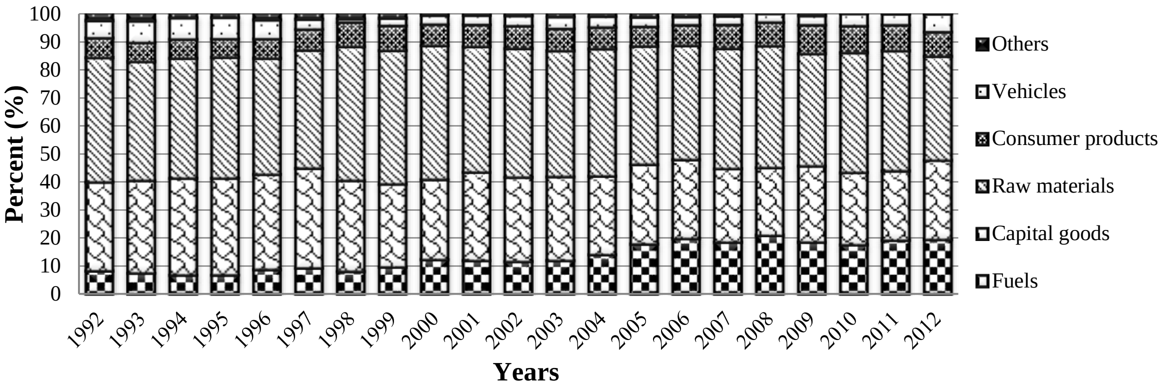


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Figure A - 8 Proportion of Thai export value (A) and import value (B)
Source: Author based on Information and Communication Technology Centre (2013a)

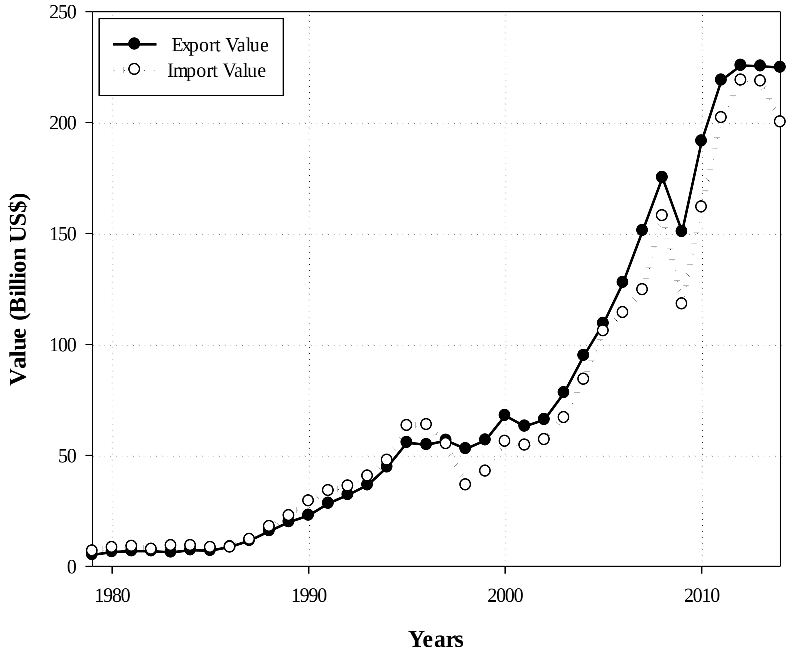

Figure A - 9 Value of Thai import and export goods and services
Source: Author based on Bank of Thailand (2015d)

Governmental evidence shows that one of the most important industrial products is cement, enabling Thailand to receive 21,018.92 million Baht (฿) or 420.38 million Pound Sterling (£, using ฿50 per £1) from exporting 6.19 million tonnes of clinker and 7 million tonnes of mixed cement to nearby countries in 2012 such as Vietnam, Cambodia, Myanmar, and Bangladesh (Office of Industrial Economics, 2012; Competitiveness Development Office, 2013). However, Thailand still needs to import a small amount of cement such as premium grade cement from Japan (only 16,364.55 tonnes in 2012, Office of Industrial Economics (2012); Information and Communication Technology Centre (2013b).

3 Summary

Double in size of population density, Great Britain is classified as a developed country, and the developing economy with upper middle income is defined for Thailand.

3.1 Great Britain

Great Britain has 94.31% and 97.17% of the UK area and UK population (2012) respectively. The population has steadily increased and urban societies dominate. Since 1998, the UK had excess expenditure as a trade deficit in foreign trading. In addition, both UK import and export values has been disturbed by a consequence of the global financial crisis and the European sovereign debt crisis. One of the whole UK industries relating to the growth of national GDP is the construction business, contributed around £72.6 billion or 7.66% of the UK GDP in the non-financial business economy in 2012.

3.2 Thailand

Thailand is a member of 10 countries in the Association of Southeast Asian Nations (ASEAN). Although Thailand has double the area of territory as Great Britain, both countries have quite similar number of population. For Thai living conditions, rural areas are presently the main residence, tending to gradually reduce over time to be more urban. The GDP from an agricultural sector is annually less than 10% as the main revenue comes from an industrial sector including from construction materials and business. Due to an increasing value of production from the industrial sector including cementitious products, this makes a trade surplus from foreign trading partners as a pattern of Thai import and export.

Appendix B: A Review of Methodological Advantages and Limitations

Table B - 1 A review of methodological advantages and limitations

No.	Methodologies	Advantages	Limitations
1.	Input Output Analysis (IOA)	• A linear programming model of IOA can include all data from input-output tables consisting of an entire production system and primary inputs (Eurostat, 2008b). • IOA can create estimates of changes in environmental impacts and a quantitative consumption/ income by measuring of economic activities (Briggs *et al.*, 1982). • IOA can analyse key contributors of supply chain impacts in products or services bought or used by an enterprise or a country (Wiedmann, 2010a). • Because of changing by an effective procurement policy, IOA can support organisational planning/ policies and set orders of magnitude following sustainable development on other economic variables for production and investment, capital and labour including requirements of energy and emissions in time (Eurostat, 2008b; Wiedmann, 2010b). • IOA provides an allocation of all impacts from product and supply chains to consuming sectors or groups of final products (Wiedmann, 2010a). • Because of requiring a minimum of data collection, IOA is an efficient method that saves time and money (Wiedmann, 2010a). • IOA is a unique tool as a general balance of an empirical analysis which can visualise reciprocity within all economic sectors precisely and thoroughly (Sofios *et al.*, 2005). • The usefulness of IOA is to trace direct and indirect activities which can be applied to use in CF and LCA (Wiedmann, 2010a). • IOA is used to allocate and evaluate the environmental and social impacts of production processes or consumption sections in Ecological Footprint and LCA studies (Huang *et al.*, 2009; Mattoon, 2013).	• IOA cannot replace cost and labour intensive tasks like Process Analysis (Wiedmann, 2010a). • Based on physical input–output tables regarding levels of the sectorial aggregation, IOA has some main problems such as very limited and restrictive data situation including the representation of different material groups (Giljum and Hubacek, 2004). • IOA need personal experience and rather strict cooperation of research activities to handle a study for the suitable framework (Christ, 1955). • Input-output tables are a summary of the countless individual activities (financial transactions) and for practical reasons so IOA can only show an impact of that industry or a group of product, not for a specific product type (Wiedmann, 2010a).

No.	Methodologies	Advantages	Limitations
2.	Life Cycle Assessment (LCA)	• LCA can improve accounting for existing internal environmental costs, recognise external environmental impacts, and evaluate all environmental burdens and opportunities (Institute of Management Accountants, 1996). • LCA can support the government for environmental information and policy regarding a performance of product, energy, transport, building and agriculture. For a private sector, LCA can support information, internal/external communication, and internal strategic decision including revealing investment potentials for clean technologies in a company (Viere *et al.*, 2011; Schepelmann, n.d.). • LCA can be used to avoid shifting environmental problems to another place (Scientific Applications International Corporation (SAIC), 2006).	• LCA has related to an internal decision making more than external information management (Viere *et al.*, 2011). • LCA represents only a part of environmental impacts and it does not consider the rebound, other social effects and economic topics but it can work with the economic methodology (Schepelmann, n.d.). • Allocation of environmental burdens in combined processes of the waste treatment is a problem of LCA (Azapagica and Cliftb, 1999; González *et al.*, 2003).
3.	Material Flow Analysis (MFA)	• MFA boundary can be defined (1) extraction of primary materials from the national environment and discharge of materials to the national environment and (2) political (administrative) borders that determine material flows to/from the rest of the world (imports and exports) excluding natural flows into/out of a geographical territory (Eurostat, 2001). • MFA is (1) to support systematic information and indicators for the assessment of sustainable development, (2) to analyses critical pathways, links and key substances of the environment and (3) to provide the relationship between material flows and processes of sustainable development (Huang *et al.*, 2012). • It can be used for effective policies of sustainable development and waste management regarding resources management (Woodward and Duffy, 2011).	• Due to converting into a graph, and handling with uncertain/ inconsistent/ contradictable data, MFA still has problems about laborious and prone errors as well as corresponding uncertainties (Cencic and Rechberger, 2008a).
4.	Material Flow Cost Accounting (MFCA)	• Using MFCA make researchers understand a specific partial accounting for improving a decision making of the economy and environment respecting to material and energy uses (Sygulla *et al.*, 2011). • MFCA can provide important information in material uses and losses in business and identify opportunities for improved performances and increased efficiency of its production processes and	• MFCA still has a problem in the practicing stage; it is because a new method and measurement effects require having more validation followed by an extensive expansion of technology (Kokubu and Kitada, 2012)

No.	Methodologies	Advantages	Limitations
		capital investment (The Ministry of Economy Trade and Industry (Japan), 2002; Kokubu *et al.*, 2009; Sygulla *et al.*, 2011). • Benefits of MFCA are increased profit, improving productivity efficiency, reducing cost (Internal benefits) and environmental impacts (External benefits) as well as linking to the economy and environment (Kokubu *et al.*, 2009). • MFCA makes a possible extension to a supply chain as well as social cost management and can by used in any organizational structures of developing and developed countries with regardless type, size, activity and location (Kokubu *et al.*, 2009). • MFCA is one of the major supporting tools of environmental management accounting (EMA) and emphasises on internal uses within an organization (The International Organization for Standardization, 2009). • MFCA can increase efficiency in processes of material and energy productivity instead of reducing the workforce, and waste treatment operations by reducing waste generation and material inputs (resources consumption) (The Ministry of Economy Trade and Industry (Japan), 2007). • The advantages of MFCA are (1) to identify problems for realising uncontrolled material losses and (2) to recognise the necessity for improvement (The Ministry of Economy Trade and Industry (Japan), 2007). • MFCA can support decisions within organisations, and can improve the coordination and communication regarding material and energy consumption (Schmidt *et al.*, n.d.). • It can link physical and monetary data by an enhanced quality and consistency of corporate information systems (Jasch, 2009).	• Because of new ideas of management, it may have some conflicts between MFCA and conventional management thinking (Kokubu and Kitada, 2010). • A big problem of MFCA results is to encourage the highest executives to focus on results of the completed analysis (Kokubu and Kitada, 2012).
5.	Carbon Footprint (CF)	• CF can identify carbon in processes as a preliminary screening in a product or service. Then, CF results can be used as a measurement for reducing pollutions and raising efficiency (Hirner, 2012). • CF is easy to calculate online and calculated value can be easily grasped (Weidema *et al.*, 2008).	• Because of its study in only GHGs, CF cannot track full human demands on the environment such as carbon concentration or climate change problems. Therefore, CF still requires assessing the environmental impacts of

No.	Methodologies	Advantages	Limitations
		• CF may have more potential to promote a consistent framework for the environmental assessment of products and services (Weidema *et al.*, 2008). • CF can be used to reduce greenhouse gas emissions and can mitigate global warming or climate change (Suwanteep *et al.*, n.d.). • CF results can prepare for impending legislation (Suwanteep *et al.*, n.d.). • CF results make workers understand the exposure level of carbon in operations and activities (Suwanteep *et al.*, n.d.).	a single product or process by integration of specific process data (hybridisation, Galli *et al.* (2011)).
6	Stock Dynamic Analysis (SDA)	• SDA results, stocks follow flows, can support environmental policy making (Müller, 2006). • SDA allows variation of different input data and parameters by defining probability functions and analysing various scenarios relating to censuses or surveys on population and housing conditions for forecasting stock and flows of the residential sector (Sartori *et al.*, 2008). • SDA concepts can also support other studies such as energy, building waste, building material flow and environmental impacts, domestic mass flow, reserves for resources, predicting building demand, empty buildings and brownfield sites (Kohler and Hassler, 2002).	• SDA still has uncertainty inherent in the definitions of those probability functions (Sartori *et al.*, 2008). • Due to the relevant parameters, SDA can use only for a residential sector, not for non-residential sector (Sartori *et al.*, 2008).

Appendix C: Great Britain and Thai Annual Concrete Stock in 2012

1 National Cement Production

1.1 Clinker Calculations

The starting figures for these calculations come from recorded data of total clinker produced in Great Britain and Thailand (2012). Clinker production involves minerals formed by 75% limestone, or other minerals such as cementstone, marble and chalk and 25% shale or other minerals such as clay and marl (Manning, 1995; Conneely *et al.*, 2001; Worrell *et al.*, 2001). Its manufacturing processes involve the quantity of cement kiln dust (CKD), fuels, fuel ash, domestic clinker and import/export clinker, and include CO_2 emission derived from (1) the main raw materials in the calcination reactions (around 44% and 10% of limestone and shale respectively) and (2) combustion of conventional and alternative fuels.

1.1.1 Backward Clinker Calculation

(1) Cement Kiln Dust (CKD)

From a study of Van Oss and Padovani (2003), a 15-20% CKD to clinker ratio implies significant environmental problems. In the United States (US), two-thirds of the generated CKD is typically returned to the kiln, leaving one-third for landfill disposal (mainly) or sale. This reference indicates that a cement business needs more raw minerals to produce the required clinker. Selecting 20% to calculate for cement manufacturing in both countries, it means that one-third (6.67%) of clinker becomes waste.

i. Great Britain

In 2012, Great Britain produced 6.56 million tonne (Mt) clinker (MPA, 2015c).

Clinker 100 tonnes (t) change to be CKD 6.67 t. Thus, clinker 6.56 Mt change to be CKD

(6.56 Mt x 6.67 t)/ 100 t = **0.44 Mt**

Therefore, in Great Britain (2012), 0.44 Mt clinker changed to be CKD which required disposal in a landfill (mainly) or to be sold.

ii. Thailand

In 2012, Thailand produced 39.55 million tonne (Mt) clinker (Office of Industrial Economics, 2013).

Clinker 100 tonnes (t) change to be CKD 6.67 t. Thus, clinker 39.55 Mt change to be CKD

(39.55 Mt x 6.67 t)/ 100 t = **2.64 Mt**

Therefore, in Thailand (2012), 2.64 Mt clinker changed to be CKD which required disposal in a landfill (mainly) or to be sold.

CKD (Mt)	**=**	**[Clinker (Mt) × 6.67 (t)] ÷ 100 (t)**	**(1)**

(2) Raw Materials

Based on data of finished clinker from domestic production of both countries, the estimated volume of the main raw materials together with CKD is serially calculated according to the calcining reactions of clinker manufacturing processes shown as follows (based on Manning (1995)).

75% limestone or other minerals — 25% shale or other minerals

$CaCO_3$ — $MgCO_3$, SiO_2, Al_2O_3, CaO, Fe_2O_3, etc

Weight lost in firing (1,450$^{\circ c}$)

44% of CO_2 — 10% of CO_2 + H_2O

$CaCO_3 = CaO + CO_2$

100 56 44

Weight after firing

56% — 90%

100 (t) of clinker minerals are

75 t of limestone or other minerals — 25 t of shale or other minerals

So, their weights after firing are

75 x 0.56	25 x 0.9
42 t	22.5 t

Total clinker weight is

64.5 t

1t of clinker needs

75/64.5	limestone or other minerals	1.16 t
25/64.5	shale or other minerals	0.39 t

i. Great Britain

Limestone or other minerals	(6.56 Mt + 0.44 Mt) x 1.16 t = **8.12 Mt**
Shale or other minerals	(6.56 Mt + 0.44 Mt) x 0.39 t = **2.73 Mt**
Total main clinker minerals	10.85 Mt

ii. Thailand

Limestone or other minerals	(39.55 Mt + 2.64 Mt) x 1.16 t = **48.94 Mt**
Shale or other minerals	(39.55 Mt + 2.64 Mt)x 0.39 t = **16.45 Mt**
Total main clinker minerals	65.39 Mt

Limestone or other minerals (Mt)	**=**	**[(Clinker (Mt) + CKD (Mt)] × 1.16**	**(2)**
Shale or other minerals (Mt)	**=**	**[(Clinker (Mt) + CKD (Mt)] × 0.39**	**(3)**
Total main clinker minerals (Mt)	**=**	**[Limestone or other minerals (Mt) + Shale or other minerals (Mt)]**	**(4)**

(3) Clinker Fuels

Presently, all cement plants use only the dry process in Thailand (TFCM, 2015). Great Britain cement manufacturing still uses semi-dry and semi-wet processes for around 22% of total clinker capacity and the remaining 78% uses the dry process (BGS, 2014b). One-tonne clinker, depending on the conditions of clinker processes, requires heat quantity 3.2-5 megajoules per kilogram (MJ/kg) (Lemieux *et al.*, 2004). Comparing to the study of Ecofys *et al.* (2009), the dry process consumes specific energy per tonne clinker around 2.95 MJ/kg, while wet processing requires 6.7 MJ/kg. Therefore, this study selected 3.2 MJ/kg for calculating a dry process due to the efficiency of old cement processes in both countries that may require more energy and 5 MJ/kg for a semi-wet and semi-dry process, saving more heat than the wet process. Besides, a net calorific value of conventional fuel such as coal is around 28.30 MJ/kg and 18.20 MJ/kg for alternative fuels (Hiromi Ariyaratne *et al.*, 2013).

Moreover, MPA (2013c), reported that, in 2012, 40% of fuel is waste-derived for Great Britain cement manufacture. Similarly, Thai cement manufacturing uses wastes as an alternative fuel at 40% of (1) alternative waste heat value compared to the net calorific value or (2) alternative waste weight compared to the total fuel weight (Ministry of Natural Resources and Environment, 2006). Therefore, this study used 60% conventional fuels: 40% alternative fuels to calculate the quantity of clinker fuels using the below criteria:

i. Great Britain

22% semi-dry and semi-wet processes

- Specific heat consumption = 5 MJ/kg clinker
- 60% conventional fuels (coal): 40% alternative fuels
- Calorific value of conventional fuels (coal) = 28.30 MJ/kg
- Calorific value of alternative fuels = 18.20 MJ/kg

Therefore, 1 kg of the combined fuels provides the calorific value around

$$(28.30 \text{ MJ/kg} \times 0.6) + (18.20 \text{ MJ/kg} \times 0.4) = 24.26 \text{ MJ/kg}$$

The Specific Heat Consumption to produce 1 kg of clinker for semi-wet and semi-dry processes requires 5 MJ/kg. Thus, under this condition, 1 kg of clinker manufacturing requires the volume of combined fuels around

$$(5 \text{ MJ/kg} \times 1 \text{ kg clinker}) \div 24.26 \text{ MJ/kg} = 0.21 \text{ kg fuels}$$

Clinker from semi-wet and semi-dry processes (6.56 Mt + 0.44 Mt) x 0.22 = 1.54 Mt in 2012 required fuels

$$(1.54 \text{ Mt} \times 0.21 \text{ kg fuel}) \div 1 \text{ kg clinker} = 0.32 \text{ Mt}$$

Quantity of conventional fuels for semi-wet/ dry processes in Great Britain (2012) were

$$0.32 \text{ Mt} \times 0.6 = 0.19 \text{ Mt}$$

Quantity of alternative fuels for semi-wet/ dry processes in Great Britain (2012) were

$$0.32 \text{ Mt} \times 0.4 = 0.13 \text{ Mt}$$

78% dry processes

- Specific heat consumption = 3.2 MJ/kg clinker
- 60% conventional fuels (coal): 40% alternative fuels
- Calorific value of conventional fuels (coal) = 28.30 MJ/kg
- Calorific value of alternative fuels = 18.20 MJ/kg

Therefore, 1 kg of the combined fuels provides the calorific value around

$$(28.30 \text{ MJ/kg} \times 0.6) + (18.20 \text{ MJ/kg} \times 0.4) = 24.26 \text{ MJ/kg}$$

The Specific Heat Consumption to produce 1 kg of clinker for dry processes requires 3.2 MJ/kg. Thus, under this condition, 1 kg of clinker manufacturing requires the volume of combined fuels around

$$(3.2 \text{ MJ/kg} \times 1 \text{ kg clinker}) \div 24.26 \text{ MJ/kg} = 0.13 \text{ kg fuels}$$

Clinker from dry process (6.56 Mt + 0.44 Mt) x 0.78 = 5.46 Mt in 2012 required fuels

$$(5.46 \text{ Mt} \times 0.13 \text{ kg fuel}) \div 1 \text{ kg clinker} = 0.71 \text{ Mt}$$

Quantity of conventional fuels for dry process in Great Britain (2012) were

$$0.71 \text{ Mt} \times 0.6 = 0.43 \text{ Mt}$$

Quantity of alternative fuels for dry process in Great Britain (2012) were

$$0.71 \text{ Mt} \times 0.4 = 0.28 \text{ Mt}$$

Therefore, Great Britain used

0.19 Mt + 0.43 Mt = **0.62 Mt** conventional fuels

0.13 Mt + 0.28 Mt = **0.41 Mt** alternative fuels

ii. Thailand

100% dry processes

- Specific heat consumption = 3.2 MJ/kg clinker
- 60% conventional fuels (coal): 40% alternative fuels
- Calorific value of conventional fuels (coal) = 28.30 MJ/kg
- Calorific value of alternative fuels = 18.20 MJ/kg

Therefore, 1 kg of the combined fuels provides the calorific value around

(28.30 MJ/kg x 0.6) + (18.20 MJ/kg x 0.4) = 24.26 MJ/kg

The Specific Heat Consumption to produce 1 kg of clinker for dry processes requires 3.2 MJ/kg. Thus, under this condition, 1 kg of clinker manufacturing requires the volume of combined fuels around

(3.2 MJ/kg x 1 kg clinker) ÷ 24.26 MJ/kg = 0.13 kg fuels

Clinker from dry process (39.55 Mt + 2.64 Mt) = 42.19 Mt in 2012 required fuels

(42.19 Mt x 0.13 kg fuel) ÷ 1 kg clinker = 5.48 Mt

Quantity of conventional fuels for dry process in Thailand (2012) were

5.48 Mt x 0.6 = **3.29 Mt**

Quantity of alternative fuels for dry process in Thailand (2012) were

5.48 Mt x 0.4 = **2.19 Mt**

Total calorific value of all fuels (MJ/kg)	**=**	**[Calorific value of conventional fuels (MJ/kg) × 0.6] + [Calorific value of alternative fuels (MJ/kg) × 0.4]**	**(5)**

Quantity of all fuels (kg) for 1 kg of clinker	**=**	**[Specific Heat Consumption for clinker manufacturing (MJ/kg) × 1 kg of clinker] ÷ Total calorific value of all fuels (MJ/kg)**	**(6)**
Fuel requirement (Mt)	**=**	**[[Clinker (Mt) + CKD (Mt)] × Quantity of all fuels (kg) for 1 kg of clinker]÷ 1 kg of clinker**	**(7)**
Conventional fuels (Mt)	**=**	**Fuel requirement (Mt) × 0.6**	**(8)**
Alternative fuels (Mt)	**=**	**Fuel requirement (Mt) × 0.4**	**(9)**

(4) Fuel Ash

For its fuel ash calculation, 1 t of conventional and alternative fuels will change to be ash around 0.1 t (Hiromi Ariyaratne *et al.*, 2013).

i. Great Britain

1 t of conventional and alternative fuels changes to be ash around 0.1 t

1.03 Mt fuels in 2012 changed to be ash

$$(1.03 \text{ Mt x } 0.1 \text{ t}) \div 1 \text{ t} = 0.1 \text{ Mt}$$

Therefore, total clinker in Great Britain (2012, 6.56 Mt) included with fuel ash 0.1 Mt

ii. Thailand

1 t of conventional and alternative fuels changes to be ash around 0.1 t

5.48 Mt fuels in 2012 changed to be ash

$$(5.48 \text{ Mt x } 0.1 \text{ t}) \div 1 \text{ t} = 0.55 \text{ Mt}$$

Therefore, total clinker in Thailand (2012, 39.55 Mt) included with fuel ash 0.55 Mt

Fuel ash (Mt)	**=**	**[Fuel requirement (Mt) × 0.1 (t)] ÷ 1 (t)**	**(10)**

(5) CO_2 Emission

i. Great Britain

CO_2 emission from the calcination process and fuel combustion in 2012 was

[10.85 Mt – (6.56 Mt + 0.44 Mt)] + [0.62 Mt + 0.41 Mt] = 4.88 Mt

** 0.1 Mt of fuel ash were already counted in clinker volume in 2012*

ii. Thailand

CO_2 emission from the calcination process and fuel combustion in 2012 was

[65.39 Mt – (39.55 Mt + 2.64 Mt)] + [3.29 Mt + 2.19 Mt] = **28.68 Mt**

** 0.55 Mt of fuel ash were already counted in clinker volume in 2012*

CO_2 emission (Mt)	**=**	**[Total clinker minerals (Mt) – (Clinker* (Mt) + CKD (Mt))] + [Conventional fuels (Mt) + Alternative fuels (Mt)]**	**(11)**

** Fuel ash 0.1% of the quantity of fuel requirement (Mt) is already counted in clinker volume*

1.1.2 Forward Clinker Calculation

(1) Quantity of Domestic, Import and Export Clinker

i. Great Britain

A. Imported Clinker

In 2012, Great Britain imported clinker **0.21 Mt** (BGS, 2014a)

B. Exported Clinker

In 2012, Great Britain exported clinker **0.03 Mt** (BGS, 2014a)

C. Domestic Clinker

In 2012, Great Britain had domestic clinker

$$(6.56 \text{ Mt} + 0.21 \text{ Mt}) - 0.03 \text{ Mt} = \mathbf{6.74 \text{ Mt}}$$

ii. Thailand

A. Imported Clinker

In 2012, Thailand imported clinker **0.37 Mt** (Office of Industrial Economics, 2013).

B. Exported Clinker

In 2012, Thailand exported clinker 6.19 Mt and clinker for other uses 1.03 Mt (Office of Industrial Economics, 2013)

$$6.19 \text{ Mt} + 1.03 \text{ Mt} = \mathbf{7.22 \text{ Mt}}$$

C. Domestic Clinker

In 2012, Thailand had domestic clinker

$$(39.55 \text{ Mt} + 0.37 \text{ Mt}) - 7.22 \text{ Mt} = \mathbf{32.70 \text{ Mt}}$$

Domestic clinker (Mt)	**=**	**[clinker production (Mt) + import clinker (Mt)] – export clinker (Mt)**	**(12)**

1.2 Cement Calculations

This part uses quantity of domestic clinker from the previous calculation part to calculate cement production. Then, additives including gypsum were added to calculate the amount of Portland and other cement, combining with import/export cement data. Generally, cement production is separated into three main parts as cement for concrete (mainly), mortar and other uses. Using recorded ratios of Great Britain in the quantity of additives and cement for mortar, this study can reflect estimated figures for Thai cement industry.

1.2.1 Gypsum Quantity

Cement production requires 95% clinker and adds 5% gypsum (Worrell *et al.*, 2001) to produce Portland cement.

i. Great Britain

95 t of clinker use gypsum 5 t, 6.74 Mt of clinker, thus, the quantity of gypsum consumed in Great Britain (2012) was

(6.74 Mt x 5 t)/ 95 t = **0.35 Mt**

ii. Thailand

95 t of clinker use gypsum 5 t, 32.70 Mt of clinker, thus, the quantity of gypsum consumed in Thailand (2012) was

(32.70 Mt x 5 t)/ 95 t = **1.72 Mt**

$$\textbf{Gypsum quantity (Mt)} = [\textbf{Domestic clinker (Mt)} \times 5\ (t)] \div 95\ (t) \qquad (13)$$

1.2.2 Cement for Other Uses

The 5% remaining cement is for other benefits such as soil and pH stabilisation (WBCSD, 2009b). Great Britain has cement used for other reasons around 3% (MPA, 2015a). Therefore, this study follows the Great Britain ratio.

i. Great Britain

Volume of Portland cement 100 t uses for other benefits 3 t

Volume of Portland cement (6.74 Mt + 0.35 Mt) = 7.09 Mt in 2012 used for other benefits

(7.09 Mt x 3 t)/ 100 t = **0.21 Mt**

Therefore, remaining Portland cement was

7.09 Mt - 0.21 Mt = 6.88 Mt

ii. Thailand

Volume of Portland cement 100 t uses for other benefits 3 t

Volume of Portland cement (32.70 Mt + 1.72 Mt) = 34.42 Mt in 2012 used for other benefits

(34.42 Mt x 3t)/ 100 t = 1.03 Mt

Therefore, remaining Portland cement was

34.42 Mt - 1.03 Mt = 33.39 Mt

Portland cement	**=**	**Domestic clinker (Mt) + Gypsum quantity (Mt)**	**(14)**
Cement for other uses (Mt)	**=**	**[Portland cement (Mt) × 3 (t)] ÷ 100 (t)**	**(15)**
Remaining Portland cement (Mt)	**=**	**Portland cement (Mt) – Cement for other uses (Mt)**	**(16)**

1.2.3 Additives for the Cement Industry

i. Great Britain

In Great Britain, (MPA, 2015c) reported that **1.60 Mt** of additives were used for the cement industry.

Other additives for the cement industry (except gypsum)

(1.6 Mt - 0.35 Mt) = **1.25 Mt**

ii. Thailand

From the study of Great Britain, Portland cement 7.09 Mt used additives 1.60 Mt (MPA, 2015c).

For Thailand, Portland cement 33.39 Mt used additives

(33.39 Mt x 1.6 t)/ 7.09 t = 7.54 Mt

Other additives for the cement industry (except gypsum)

(7.54 Mt - 1.72 Mt) = **5.82 Mt**

Therefore, all cement in Thailand for 2012 were

33.39 Mt + 7.54 Mt = 40.93 Mt

Additives in Thailand (Mt)	**=**	**[Portland cement (Mt) in Thailand × Used additives (Mt) in Great Britain] ÷ Portland cement (Mt) in Great Britain**	**(17)**
Other addiitives (except gypsum) (Mt)	**=**	**Aditives (Mt) – Gypsump (Mt)**	**(18)**

1.2.4 Cement for Mortar

i. Great Britain

Using recorded data from related organisations to understand quantity of cement and fine aggregates for mortar in Great Britain (2012), there were 1) **2.20 Mt** of cement (MPA, 2014b) and 2) **5.47 Mt** of fine aggregates (BGS, 2014c).

ii. Thailand

Cement in Great Britain

(6.74 Mt + 0.35 Mt + 1.60 Mt + 1.46 Mt) - (0.31 Mt + 0.21 Mt) = 9.63 Mt

used for mortar 2.2 Mt (MPA, 2014b),

Cement in Thailand was

(32.70 Mt + 1.72 Mt + 7.54 Mt + 0.02 Mt) - (7.00 Mt + 1.03 Mt) = 33.95 Mt

used for mortar

(33.95 Mt x 2.2 Mt)/ 9.63 Mt = 7.76 Mt

Using these reasons:

1) Great Britain uses brick and block as a double masonry layer with an inside cavity (Mortar Industry Association, 2013),
2) Great Britain used brick 46% and concrete & mortar 41% by weight for residential building (Cuéllar-Franca and Azapagic, 2012),
3) main Thai construction materials are 79.4% concrete by weight followed by 13% brick and 5.6% steel respectively (Kofoworola and Gheewala, 2008),
4) Thai C&D waste is 74.9–79.4% concrete by weight (PCD *et al.*, 2007).

Thailand requires a half volume of Great Britain mortar ratio.

(7.76 Mt x 1)/ 2 = **3.88 Mt**

From Great Britain study, this country uses 2.20 Mt cement: 5.47 Mt primary fine aggregates (BGS, 2014c). Therefore, in 2012, Thailand used fine primary aggregate for mortar

(3.88 Mt x 5.47 Mt)/ 2.20 Mt = **9.65 Mt**

Cement for mortar (Mt) in Thailand	=	**[(Domestic cement (Mt) in Thailand × Cements for mortar (Mt) in Great Britain) ÷ Domestic cement (Mt) in Great Britain] ÷ 2*** * *Using half of Great Britain ratio because:* *(1) Cold weather condition, the majority buildings in Great Britain have masonry cavity wall as a double masonry layer with an inside cavity* *(2) Components of building materials (residential building):* - *Great Britain uses 41% concrete and mortar and 46% brick. Almost all bricks (96%) are made from clay requiring cement for binding.* - *Thailand uses concrete as the main construction material around 80% and produced concrete around 80% of total C&D waste*	**(19)**
Fine primary aggregates for mortar in Thailand (Mt)	=	**[Cement for mortar (Mt) in Thailand × Fine primary aggregates for mortar (Mt) in Great Britain] ÷ Cement for mortar (Mt) in Great Britain**	**(20)**

1.2.5 Quantity of Cement for Concrete including Import and Export Cement

i. Great Britain

A. Import Cement

In 2012, Great Britain imported cement **1.46 Mt** (BGS, 2014a).

B. Export Cement

In 2012, Great Britain exported cement **0.31 Mt** (BGS, 2014a).

C. Cement for Concrete

Quantity of domestic cement for concrete consumption in 2012 was

(6.74 Mt + 0.35 Mt + 1.60 Mt + 1.46 Mt) – (0.31 Mt + 0.21 Mt + 2.20 Mt) = **7.43 Mt**

ii. Thailand

A. Import Cement

In 2012, Thailand imported little volume of premium grade of cement about 16,000 t or **0.02 Mt** (Office of Industrial Economics, 2013)

B. Export Cement

In 2012, Thailand exported cement **7.00 Mt** (Office of Industrial Economics, 2013)

C. Cement for Concrete

Quantity of domestic cement for concrete consumption in 2012 was

(32.70 Mt + 1.72 Mt + 7.54 Mt + 0.02 Mt) - (7.00 Mt + 1.03 Mt + 3.88 Mt) = **30.07 Mt**

Cement for concrete (Mt)	**=**	**[Domestic clinker (Mt) + Gypsum quantity (Mt) + Additives for the cement industry (Mt) + Import cement (Mt)] – [Export cement (Mt) + Cement for other uses (Mt) + Cements for mortar (Mt)]**	**(21)**

2 Annual Concrete Stock Using Material Flow Analysis (MFA)

2.1 Aggregate Calculation

We model primary aggregates in Great Britain including recycled and secondary aggregates in both concrete and construction industries in 2012 using data from ONS (2014d) and MPA (2013c) and estimate the quantity of each type of construction, demolition and excavation (CD&E) waste in off-site operation especially concrete waste in case of recycled and secondary aggregates in 2012 based on CD&E waste arisings, use and disposal for England 2008 (WRAP, 2010). This classification follows the European Waste Catalogue (EWC) in each important route of waste management in Great Britain as waste treatment and transfer facilities, recycled aggregate sites and landfill.

2.1.1 Primary Aggregates

i. Great Britain

The amount of recorded primary aggregates used in each activity for the concrete and construction industries in Great Britain using 2012 data from ONS (2014d). The quantity of primary aggregates as fine aggregates (sand) and coarse aggregates (gravel and crushed rock) for concrete and construction in 2012 including 10,291,000 tonnes from marine-dredged material were used for making a Sankey diagram.

ii. Thailand

Using Great Britain data, concrete components are 7.43 Mt: 19.70 Mt: 28.34 Mt + 5 Mt (cement: fine primary aggregates: coarse primary aggregates + coarse recycled concrete aggregates) (MPA, 2013b; ONS, 2014d). This study use Great Britain ratio for Thailand.

Cement	30.07 Mt
Fine primary aggregates	(30.07 Mt x 19.7 Mt)/ 7.43 Mt = **79.73 Mt**
Fine primary aggregates (for mortar)	9.65 Mt
Coarse primary aggregates	[30.07 Mt x (28.34 Mt + 5 Mt)]/ 7.43 Mt = **134.93 Mt**

Fine primary aggregates for concrete in Thailand (Mt)	**=**	**[Cement for concrete (Mt) in Thailand × Fine primary aggregates (Mt) in Great Britain] ÷ Cement for concrete (Mt) in Great Britain**	**(22)**

Coarse primary aggregates for concrete in Thailand (Mt)	**=**	**[Cement for concrete (Mt) in Thailand × (Coarse primary aggregates (Mt) in Great Britain + Coarse recycled concrete aggregates (Mt) in Great Britain)] ÷ Cement for concrete (Mt) in Great Britain**	**(23)**

2.1.2 Recycled and Secondary Aggregates

i. Great Britain

To understand the pattern of recycled aggregates from the hard inert waste in only construction, demolition and excavation waste (CD&E waste) generated in Great Britain (2012), this study shows the quantity of recycled and secondary aggregates in 2012, based on the the European Waste Catalogue (EWC) classifications in waste management as waste treatment and transfer activities, recycled aggregate sites and landfill in Great Britain. Using the ratio of recycled and secondary aggregates in 2005 from DCLG (2007), it was 85% of recycled aggregates from C&D waste and 15% from other wastes named secondary aggregates.

To make a MFA diagram of CD&E waste management in Great Britain based on 2008 data, this study used references from (1) Volume of CD&E waste generation estimates in England (2008) (Defra, 2012a), (2) CD&E waste arisings use and disposal for England 2008 including volume of recycled aggregates in England 2008 (WRAP, 2010) and (3) Classification of CD&E waste from chapter 17 of the European Waste Catalogue (EWC; EPA (2002)).

Using the starting reference for calculation from MPA (2013c), it reported that recycled and secondary aggregates were 54 Mt in 2012, and 85% of recycled aggregates originate from C&D waste (DCLG, 2007). This assumed that the 2012 recovery rates of CD&E waste equal to 2008 ratios to emphasise on the volume of this waste from treatment and transfer facilities, recycle aggregate sites and landfill for Great Britain (2012). Then, the UK volume of CD&E waste (100 Mt) in 2012 (Defra, 2015b) is used to compare the results of the 2012 Great Britain diagram.

Therefore, 54 Mt of recycled and secondary aggregates in 2012 had recycled aggregates

$$(54 \text{ Mt x } 85 \text{ t})/\ 100 \text{ t} = 45.9 \text{ Mt}$$

Secondary aggregates from other waste sources were

$$54 \text{ Mt} - 45.9 \text{ Mt} = 8.1 \text{ Mt}$$

Recycled aggregates (Mt)	=	**[Recycled and secondary aggregates (Mt) × 85 (t) *] ÷ 100 (t)** ** 85% recycled aggregates came from C&D waste especially concrete waste*	**(24)**
Secondary aggregates (Mt)	=	**Recycled and secondary aggregates (Mt) – Recycled Aggregates (Mt)**	**(25)**

2.2 Concrete Calculations

In addition to cement and aggregates, an important component in concrete is additives that are around 4.5% in Great Britain (MPA, 2013a). Moreover, it was reported that the finishing concrete creates around 0.5% of waste during deliveries (WBCSD, 2009b), which used for calculating the concrete industry in both countries.

2.2.1 *Aggregates* for Concrete Components

i. Great Britain

In 2012, concrete used in Great Britain was

Cement	**7.43 Mt**
Fine aggregates	**19.70 Mt** (ONS, 2014d)
Coarse aggregates	**28.34 Mt** (ONS, 2014d)
Recycled and secondary aggregates	**5 Mt** (MPA, 2013b)

From MPA (2013b), the use of recycled and secondary aggregates as a proportion of total aggregates used in concrete production was 5.00 Mt.

7.43 Mt + 19.70 Mt + 28.34 Mt + 5.00 Mt = 60.47 Mt

Main concrete components (Mt) in Great Britain	=	**Cement for concrete (Mt) + Fine primary aggregates for concrete (Mt) + Coarse primary aggregates for concrete (Mt) + Recycled and secondary aggregates (Mt) for concrete**	**(26)**

ii. Thailand

Generally, Thailand uses only primary aggregates for the concrete industry. In 2012, Thailand had concrete quantity from principal components as cement and fine and coarse primary aggregates around

Cement	30.07 Mt
Fine aggregates	79.73 Mt
Coarse aggregates	134.93 Mt

30.07 Mt + 79.73 Mt + 134.93 Mt = 244.73 Mt

Main concrete components (Mt) in Thailand	**=**	**Cement for concrete (Mt) + Fine primary aggregates for concrete (Mt) + Coarse primary aggregates for concrete (Mt)**	**(27)**

2.2.2 Additives for Concrete

i. Great Britain

From the data without water use 6.8% of MPA (2013a), Great Britain used around 4.5% other additives.

Main concrete components 95.5 tonnes mix with additives 4.5 tonnes

In 2012, main concrete components 60.47 Mt mixed with additives

(60.47 Mt x 4.5 t)/ 95.5 t = **2.85 Mt**

ii. Thailand

Main concrete components 95.5 tonnes mix with additives 4.5 tonnes

In 2012, main concrete components 244.73 Mt mixed with additives

(244.73 Mt x 4.5 t)/ 95.5 t = **11.53 Mt**

Additives (Mt) for concrete	**=**	**[Main concrete components (Mt) × 4.5 (t)] ÷ 95.5 (t)**	**(28)**

2.2.3 Concrete Waste during Deliveries

Typically, the amount of concrete waste generated by ready-mix deliveries can be reduced as little as 0.4-0.5% of total production (WBCSD, 2009b). For precast concrete, WRAP (2008) reported that the production and use of precast concrete are resource efficient and limits the generation of waste on site due to unwanted packaging and easy handling design. Therefore, this study uses 0.5% waste during concrete deliveries in both case studies.

i. Great Britain

Concrete 100 t generate waste 0.5 t

In 2012, concrete 7.43 Mt + 19.70 Mt + 28.34 Mt +5.00 Mt +2.85 Mt = 63.32 Mt generated waste

(63.32 Mt x 0.5 t)/ 100 t = **0.32 Mt**

ii. Thailand

Concrete 100 t generate waste 0.5 t

In 2012, concrete 30.07 Mt + 79.73 Mt + 134.93 Mt + 11.53 Mt = 256.26 Mt generated waste

(256.26 Mt x 0.5 t)/ 100 t = **1.28 Mt**

Concrete waste (Mt) during deliveries	**=**	**[(Concrete (Mt) + Additives (Mt) for concrete) × 0.5 (t)] ÷ 100 (t)**	**(29)**

2.2.4 Lime for Mortar Ingredients

The other main component for making mortar is lime that helps the fresh mortar to retain water for combining with dry cement bricks/ blocks and to prevent cracking of the hardened mortar. The Cement & Concrete Institute (2009) introduces that there are 2 classes of mortar with lime ingredient as class I (1 lime: 5 cement ratio) and class II (1 lime: 2 cement ratio). This study used an average ratio to calculate lime quantity as 1 lime: 3.5 cement ratio.

i. Great Britain

To produce mortar, cement 3.5 t combines with 1 t lime

In 2012, Great Britain used 2.2 Mt of cement for mortar combined with

$$(2.2 \text{ Mt} \times 1 \text{ t lime})/3.5 \text{ t cement} = \mathbf{0.63\ Mt\ lime}$$

ii. Thailand

To produce mortar, cement 3.5 t combines with 1 t lime

In 2012, Thailand used 3.88 Mt of cement for mortar combined with

$$(3.88 \text{ Mt} \times 1 \text{ t lime})/3.5 \text{ t cement} = \mathbf{1.11\ Mt\ lime}$$

Lime for mortar (Mt)	**=**	**[Cement for mortar (Mt) × 1 (t) lime] ÷ 3.5 (t) cement**	**(30)**

2.3 Construction Calculations

To calculate the volume of concrete and mortar used in Great Britain (2012), this study used (1) four main building types: single residential building 25.17%, multi-residential building 11.84%, non-residential building 44.07% and Infrastructure 18.92% from launched value of new and repair/maintenance construction, and (2) the proportion of new residential completions (68% houses and 32% flats), to calculate concrete and mortar uses (ONS, 2013b; DCLG, 2014). For Thailand, the National Statistical Office (2013a), reported floor area in use of new and additional construction in 2012 as: single residential building 41.90%, multi-residential building 9.61%, non-residential building 32.19% and infrastructure 16.30%.

2.3.1 Concrete and Mortar Waste during Construction

There is a loss of around 5% concrete and mortar during construction (Building Research Establishment, 2002). However, a later study by Building Research Establishment (2008) showed that construction activities depending on each site operation had higher waste rates of concrete and mortar in all sampling sites than the previous research. This study assumed 5% concrete and mortar lost during construction as the minimum waste volume.

i. Great Britain

Concrete and mortar 100 t turn to be waste 5 t

In 2012, concrete and mortar (63.32 Mt - 0.32 Mt) + (2.20 Mt + 5.47 Mt + 0.63 Mt) = 71.3 Mt turned to be waste

(71.3 Mt x 5 t)/ 100 t = **3.57 Mt**

Total annual concrete and mortar used in 2012 was

71.3 Mt – 3.57 Mt = 67.73 Mt

ii. Thailand

Concrete and mortar 100 t turn to be waste 5 t

In 2012, concrete and mortar (256.26 Mt - 1.28 Mt) + (3.88 Mt + 9.65 Mt + 1.11 Mt) = 269.62 Mt turned to be waste

(269.62 Mt x 5 t)/ 100 t = **13.48 Mt**

Total annual concrete and mortar used in 2012 was

269.62 Mt – 13.48 Mt = 256.14 Mt

Concrete and mortar waste during construction (Mt)	**=**	**[concrete and mortar (Mt) × 5 (t)] ÷ 100 (t)**	**(31)**
Concrete and mortar for construction sectors (Mt)	**=**	**Concrete and mortar (Mt) - concrete and mortar waste during construction (Mt)**	**(32)**

2.3.2 Concrete and Mortar for Construction

i. Great Britain

ONS (2013b) gave values of launched construction, repair and maintenance by building types in 2012 as infrastructure, residential and non-residential building. Moreover, the proportion of new residential completions that were new houses (68%) and flats (32%) in 2012 (DCLG, 2014).

Buildings	Percent	Volume (Mt)
Residential building	**37.01**	**25.07**
Single-residential building (68%)	25.17	17.05
Multi-residential building (32%)	11.84	8.02
Non-residential building	**44.07**	**29.85**
Infrastructure	**18.92**	**12.81**
Total	**100.00**	**67.73**

ii. Thailand

National Statistical Office (2013a), announced floor area in use of Thai new and additional construction in 2012 as:

Buildings	Percent	Volume (Mt)
Residential building	**51.51**	**131.94**
Single-residential building	41.90	107.32
Multi-residential building	9.61	24.62
Non-residential building	**32.19**	**82.45**
Infrastructure	**16.30**	**41.75**
Total	**100.00**	**256.14**

Concrete and mortar for construction sectors (Mt)	=	**(Concrete and mortar (Mt) × % Single residential building*) + (Concrete and mortar (Mt)× % Multi-residential building*) + (Concrete and mortar (Mt)× % Non-residential building*) + (Concrete and mortar (Mt) × % Infrastructure*)** ** Great Britain used ratios of project value and ratios of single and multi-residential building* ** Thailand used ratios of floor area in use*	**(33)**