An Evaluation of Cement Manufacture Options for Sustainable Infrastructure

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ABSTRACT

Sustainable production and use of cement, including limiting additional environmental protection costs, efficiently producing cement and minimising natural resources used, are significant global industrial objectives. One of the major challenges facing the cement manufacturing industry is that ordinary Portland cement production emits approximately 5% of the world's carbon dioxide, and each kilogram of Portland cement produces 0.85 kg of carbon dioxide. High energy levels are also needed to produce cement, which requires heavy carbon dioxide emissions and accelerates the consumption of natural resources, which in turn affects climate change. One solution is to mix a certain amount of supplementary cementitious materials within ordinary Portland cement production. This outcome alleviates energy-intensive production, reduces carbon dioxide emissions and slows natural resource consumption as well as decreasing production facility investment. Geopolymer-based cement manufacturing is an alternative solution to improving this situation, as there is no carbonate content in the raw materials and less energy is required for production, which minimises carbon dioxide emission. Therefore, this is another method used to reduce the carbon footprint. In addition, fly ash is a by-product of coal-fired power stations and is now one of the major raw materials used to make fly ash based geopolymer cement, which slows abiotic depletion.

The goal of this research is to optimise the three areas of maximising profit in manufacturing cement, minimising natural resources depletion and reducing carbon dioxide emissions in the manufacturing process. Selecting the right tools to measure these factors was achieved by using the proposed advanced framework, which integrated tools such as linear programming with the simplex method, and used traditional mathematical and spreadsheet-based methods to seek optimal results.

Six scenario-based studies covered ordinary Portland cement; ordinary Portland cement with supplementary cementitious materials and fly ash based geopolymer cement in production under the same manufacturing conditions and the same boundaries in terms of the manufacturing process, seeking optimal solutions by using the linear programming equation method:

- Scenario 1 maximised the profit of mixed production ordinary Portland cement and ordinary Portland cement with supplementary cementitious materials.
- Scenario 2 maximised the profit of mixed-production geopolymer-based cement, including fly ash based and metakaolin-based geopolymer cement.
- Scenario 3 maximised the profit of fly ash based geopolymer and ordinary Portland

cement.

- Scenario 4 minimised carbon dioxide emissions from transport using the Carbon Dioxide Equivalent method.
- Scenario 5 minimised carbon dioxide emissions from transport using the Australian National Greenhouse Accounts Factors method (2014 to 2016).
- Scenario 6 made optimal use of raw materials for cement using abiotic depletion for ordinary Portland cement production.

Further, the linear programming equations consisted of ‘subject to function’ and ‘subject to constraints’, which played the vital roles in the scenario-based studies. The sources of developing the ‘subject to function’ equations are found in Chapter 3 - Methodology. For example, the Australian National Greenhouse Accounts Factors method (2014 to 2016) and the Carbon Dioxide Equivalent method acted as ‘subject to function’ to minimise carbon dioxide emissions from transport and to compare the benefits of the two methods. Optimal use of natural resources depletion was based on an abiotic depletion equation. The optimal mix production equation was derived from a typical cement plant operation, such as kiln, grinding, mix, machines hours, labour hours and so on. The ‘subject to constraint’ equations for scenario-based studies were derived from the primary and secondary data. The primary data were collected based on well-constructed interviews and questionnaire with assistance of a supplementary electronics survey if necessary. In addition, secondary data came from the literature, the annual financial reports of the target companies (2015), the Australian Bureau of Statistics (2014 to 2016), the Cement Industry Federation (2012 to 2013) and more.

To solve tailor-made, complex linear programming equation problems, traditional mathematical methods were used involving graphical and Gaussian-Jordan Elimination methods and spreadsheet-based methods with the assistance of the Solver®, which can produce answers, sensitivity analyses and limit reports to deliver optimal solutions. Here, one of the most important outcome of the research was a sensitivity analysis report, which reflected cement factory efficiency and profit performances.

By adding to the analysis, the additional constraint that the supply of fly ash was likely to be reduced because of scheduled power station closures in Australia by 2022, it was found that the cost of the raw materials for fly ash based geopolymer cement could then be 17% higher than for ordinary Portland cement. Metakaolin or ground-granulate blast slag-based geopolymer cement, both of which would positively affect carbon dioxide emissions in production, could pose potential solutions to this shortage.

To probe further domestic material consumption in Australia, the time-series for the regression model were developed using statistical methods, including ratio indices tools and XLminer Analysis ToolPak® to calculate raw materials consumption and forecast cement production. It also examined the status of further raw material reserves based on Chapter 3's assigned equation. However, this equation needed to carefully analyse curve characteristics based on the trend of domestic material consumption in Australia in the outcome of results. The solution in this study was the polynomial equation, including the linear equation, instead of the original exponential equation used in the French region. Here, one of the results was that the calcium carbonate and sand would be in short supply within five to 10 years based on 9.1 to 11.1 million tonnes cement production each year.

The whole-life-cycle method based on 20 years of producing fly ash based geopolymer cement, ordinary Portland cement and ordinary Portland cement with supplementary cementitious materials was also used to intensively examine each raw material's abiotic depletion and reserve status. These outcomes would send earlier messages to cement entrepreneurs organising cement manufacturing for sustainable infrastructure and provide them with optimal solutions as a result of expert, validated knowledge and opinion and optimisation of the proposed methodology.

CERTIFICATION OF THESIS

This thesis is entirely the work of Chi Shing **CHAN** except where otherwise acknowledged. The work is original and has not previously been submitted for another award, except where acknowledged.

Student and Supervisors Signatures of Endorsement are held at the USQ.

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TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES

LIST OF TABLES

LIST OF TABLES

LIST OF TABLES

NOMENCLATURE

ACC = Abatement cost curve
AD = Abiotic depletion
ADP = Abiotic depletion potential
A_i = The quantity of cement clinker produced (tonnes)
A_{ij} = The quantity of lime kiln lost in the production of lime (tonnes)
A_{ckd} = The quantity of cement kiln dust produced (tonnes)
Al_2O_3 = Clay
$Al_2O_3.2SiO_2$ = Metakaolin
$Al_2O_3.2SiO_2.2H_2O$ = Kaolin
AM = Alumina modulus
ASTM = American Society for Testing Materials
BEES = Building energy efficiency scheme
C = Coulombs
C_{sh} = Specific heat
CA = Cost analysis (A$)
$CaCO_3$ = Calcium carbonate
CapC = Capital cost (A$)
CaO = Lime
$2Ca.SiO_2$ = Dicalcium silicate (elite)
$3CaO.SiO_2$ = Tricalcium silicate
$3CaO_3.Al_2O_3$ = Tricalcium aluminate, C_3A- alkali solid solution
$4CaO.Al_2O_3.FeO_3$ = Tectra-calcium-alumina-ferrite
C_4AF = Calcium alumina-ferrite
$CaSO_4.2H_2O$ = Gypsum
CCA = China Cement Association
CEM = Cost estimation method
CIF = Cement Industry Federation
C_2S = Dicalcium silicate
C_3S = Tricalcium silicate
C_3A = Tricalcium silicate
C_4AF = Calcium alumina ferrite
CEO = Chief executive officer
C-S-A = Ternary C=CaO, S=SiO_2, A=Al_2O_3 phase diagram
CSI = Cement Sustainability Initiative
CO_2 = Carbon dioxide
CO_{e-m} = Carbon dioxide in terms of material
CO_{e-p} = Carbon dioxide in terms of process
CLC = Clay cost (kg/A$)
CO_2 = Carbon dioxide
CO_2C = Carbon dioxide cost ($CO_{2\text{-}e}$kg /kg/A$)
CO_{2-e} = Carbon Dioxide Emission Equivalent method
$C\bar{S}H_2$ = Gypsum
CSC = Conservative supply curve

NOMENCLATURE

CSIRO = Commonwealth Scientific and Industrial Research Organisation

d_{fa} = Distance of fly ash

d_g = Distance of gravel

d_{NaOH} = Distance of sodium hydroxide (NaOH)

d_m = Distance of components

d_{sifume} = Distance of silica fume

d_{slag} = Distance of slag

DMC = Domestic material consumption

DR = Extracted rate (kg/hr)

DR_1 = Extracted rate (kg/hr) from source 1

DR_2 = Extracted rate (kg/hr) from source 2

DRC = Extracted rate cost (kg/hr/A$)

$\dot{E}$ = Energy flow(J/hr)

EC = Energy cost (kw/hr/A$)

EC_i = The energy content factor of fuel types

E_{ij} = The emission CO_2 released from the production of cement clinker ($CO_{2\text{-}e}$ tonne)

EF_{ij} = The emission factor for cement clinker (tonnes of CO_2 emission per tonne of clinker produced)

EF_{tocj} = The emission factor for carbon-bearing non-fuel raw material (tonnes of CO_2 emission per tonnes of clinker produced

EF_{ijoxec} = The emission factor for each gas type (j)

ELCC = Extended life cycle cost

ERC = Extraction cost (kg/A$)

ExMA = Energy mass analysis

F = Ferrite compound

FA = Fly ash (kilogram)

F_{lkd} = The fraction of calculation achieved for lime kiln dust in the production lime (tonne)

FT = Fuel typed

g = Gram

GA = Geopolymer

GGBS = Ground granulate blast slag

GHG = Greenhouse gas

GHG_{total} = Total greenhouse gas

GJ = Gigajoule

GWP = Global warming potential

GYC = Gypsum cost (kg/A$)

hr = Hour

ΔH = Enthalpy change for reaction (kg/mol)

ΔH_f^0 = Enthalpy of formation (kg/mol)

h_{in} = Heat input (Joules/second)

h_{out} = Heat output (Joules/second)

NOMENCLATURE

I = Raw import material
IOC = Sand cost (A$)
ISO = International Standard Organisation
J = Joules
JSCE = Japan Society of Civil Engineers
KOH = Potassium hydroxide
LG_{MaintC} = Lifelong maintenance cost
LG_{ManufC} = Lifelong manufacturing cost
KJ = Kilojoule
Kw = Kilowatt
Kwh = Kilowatt hour
LC = Labour cost (A$/hr)
LCA = Life cycle assessment
LCCA = Life cycle cost assessment
LCI = Life cycle index
LSF = Lime saturation factor
LCI = Life cycle inventory
LP = Linear programming
LSC = Limestone cost (kg/A$)
m = Mass (kg)
$\dot{m}$ = Mass flow (kilogram/second)
m_{fa} = Mass of fly ash
m_g = Mass of gravel
m_{gg} = Mass of gibbsite
$m_{limestone}$ = Mass of limestone
m_m = Mass of metakaolin
m_{NaOH} = Mass of sodium hydroxide
m_{slag} = Mass of slag
m_{sifume} = Mass of silica fume
MaC = Manufacturing cost (A$)
MC = Machine cost (hr/A$)
Max = Maximising
Min = Minimising
Mol = Molecule
Mt = Million tonnes
NRD = Natural resource depletion
NRDC = Natural resources depletion cost (A$)
NSP = Pre-calciner
Q = An amount of energy is added into system at constant temperature (Joules)
$\dot{Q}$ = Rate of heat transfer (Joules/second)
Q_i = The quantity of fuel type
Q_e = The quantity of electricity purchased (kilowatt hours)
Qty = Quantity

NOMENCLATURE

OPC = Ordinary Portland cement
QAC = Sodium hydroxide (NaOH) cost
QFSC = Silica fume cost (kg per A$)
QFAC = Fly ash cost (kg/A$)
R = Resources (kg)
RC = Resources cost (kg/A$)
R_{1c} = Resources (kg) from source 1
R_{2c} = Resources (kg) from source 2
R_{1sb} = Resources from source 1 with respect to antimony
R_{2sb} = Resources from source 2 with respect to antimony
S = Silica
ΔS = Change of entropy (kg/mol)
S_b = Antinomy
SCM = Supplementary cementitious material (kg)
SCMC = Supplementary cementitious material cost (kg/A$)
SCM-OPC = Supplementary cementitious material with ordinary Portland cement (kg)
Sialate = Silicon-oxo-aluminate
NaOH = Sodium hydroxide
ºK = Kelvin temperature (ºK)
TaC = Tangible cost (A$)
TAM = Treasury total assets management
TMR = Total material requirement
V = Volt
Vol = Volume (m^3)
VMC = Variable material cost (A$)
W = Watt
WBDG = Whole Building Design Guide
WLC = Whole life cycle
WLCC = Whole life cycle cost
Wi = Unit mass (kg)
$\dot{w}$ = Rate of heat transfer (Joules/second)
WBCSD = World Business Council for Sustainable Development
Y = The scope 2 emission measured in CO_{2-e} tonnes/tonnes

CHAPTER 1

INTRODUCTION

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Every year, every kilogram of cement manufactured emits 0.66 to 0.85 kg carbon dioxide into the atmosphere (Turner and Collins, 2013; Huntzinger and Eatmon, 2009; Shen et al., 2015). UNSTATS (2010) have stated that cement production could represent nearly 10% of total anthropogenic carbon dioxide emissions. It is one of the main sources of accelerating global warming potential (GWP). Habert et al., (2011) have highlighted the difficulty of achieving the goal set by the Inter-Government Panel Group for Climate Change (IPCC) without any advanced cement manufacturing technologies or new material development (Chan et al., 2012). Davidovits (1991, 1993, 2001, 2005, 2009, 2012), Duxson et al., (2005, 2007, 2008), He and Zhang (2011) and Palomo et al., (1999) have developed fly ash based geopolymer, ground-granulate blast-furnace slag-based geopolymer (George and Mathrews, 2014) and metakaolin-based geopolymers (Latella et al., 2008) cement production formulations. They have even focused on mixed proportion design (Kim et al., 2013; Pazhani et al., 2010) or mixed proportions in supplementary cementitious materials (Lyon et al., 1997; Nasvi et al., 2014) with ordinary Portland cement to reduce carbon dioxide emissions (Mikulcic et al., 2014; Cao et al., 2016) and meet carbon dioxide reduction targets (Companies A and B) in Australia, these measures have actually been reducing emissions since 2014. Some researchers have also developed a carbon dioxide-captioned device to convert carbon dioxide gas into a useful carbonic acid solution by mixing it with pure water (Javed et al., 2010; Liang and Li, 2010). Although researchers have undertaken green development, including producing fly ash based geopolymer cement and supplementary cementitious material with ordinary Portland cement to reduce carbon dioxide emissions (Yang et al., 2014); shortcomings remain in cement production research in relation to maximising profit in three areas, minimising depletion of abiotic natural resources and reducing carbon dioxide emissions. This has provided an opportunity for this research to fill that gap.

1.2 OBJECTIVES

Cement is a commonly used civil and construction infrastructure material. It causes material resources depletion, uses considerable energy in cement production by emitting significant quantities of greenhouse gases, particularly carbon dioxide, which is one of the major sources of air pollution worldwide and is accelerating climate changes issues. Properly assessing the use of cement alternatives is thus necessary from a long-term sustainability viewpoint. To better understand these issues for determining cement for the environment, the objectives of this research are as follows:

(a) Identify carbon dioxide emissions in cement production, including calcium carbonate ($CaCO_3$) in the kiln process and energy consumption in milling, calcination, transport and more.

(b) Investigate the calculation methods of natural resources depletion and reserves in different regions, particularly in Australia, for cement production.

(c) Examine the life-cycle cost of the three areas based on the defined boundaries.

(d) Examine the optimal methods for the three areas with respect to carbon dioxide emissions, natural resources depletion and financial effects.

(e) Investigate and evaluate the various methods of calculating carbon dioxide.

(f) Develop a framework to effectively assess abiotic depletion, energy cost; fuel type used, raw material (including by-product such as fly ash, slag, etc.) consumption, life-cycle and cost assessments, including whole life cycle for the three areas.

This research has involved working collaboratively with cement manufacturers and construction industries in Australia for data collection.

1.3 AIM

The aim of this research is to adapt and extend the theoretical principles and methods in evaluating the carbon dioxide emissions, abiotic (e.g., mineral) depletion and cost analysis in optimal cement manufacturing, including feedstock, transport and production processes. It also examines the state-of-the-art cement production facilities and how they convert raw materials to ordinary Portland cement; ordinary Portland cement with supplementary cementitious materials and fly ash based geopolymer cement through a series of production processes using optimal sustainable manufacturing and infrastructure methods.

1.4 RESEARCH SIGNIFICANCE

This research is expected to develop an innovative framework based on sound theoretical principles to effectively evaluate the optimal ordinary Portland cement and fly ash based geopolymer cement manufacture from the extraction, production and distribution of raw materials and cement, and energy and carbon dioxide emissions under the same manufacturing conditions and the same boundaries in terms of the manufacturing process, seeking optimal solutions by using the linear programming equation method.

CHAPTER 1 INTRODUCTION

Cement is commonly used in buildings and roads and for highway infrastructure. The thesis makes the following contributions to the field:

(a) Investigating suitable methods of calculating carbon dioxide emissions, including the World Business Council for Sustainable Development, Australian National Greenhouse Accounts Factors (2014 to 2016) and Carbon Dioxide Emission Equivalent in cement production; this investigation outcome could provide a clue to developing a linear programming equation for a scenario-based assessment.

(b) Adapting and extending the suitable method of calculating natural resources depletion for Australian regions.

(c) Identifying potential cost drivers and sub-cost drivers for life-cycle cost or life-cycle cost assessment, including extended life-cycle cost methods suitable for the Australian business environment.

(d) Developing optimal solutions for minimising natural resources depletion and carbon dioxide emissions with respect to short-term and lifelong costs, and maximising three areas of profit based on scenario-based studies and validating the proposed framework performances.

1.5 RESEARCH CHAPTER OUTLINE

Chapter 1	This chapter illustrates the research background, objectives, aim and significance and gives the outline of each chapter.
Chapter 2	This chapter contains a literature review focusing on ordinary Portland cement and geopolymer-based cement with respect to carbon dioxide emissions from feedstock and sources; manufacturing and transport measurement methods; cost issues related to raw materials and operational expenses; and natural resources depletion assessment methods. The research questions were developed based on the outcomes of the literature review and evaluation of alternatives frameworks.
Chapter 3	Chapter 3 discusses the advanced proposed integrated framework, a three-level hierarchy chart that includes collection of both primary and secondary data, linear programming equations, sensitivity analysis and methods of calculating carbon dioxide emissions, natural resources depletion and financial effect, based on the Chapter 2 outcomes suitable for this research.
Chapter 4	This chapter includes data collection, traditional mathematical analysis and formulated linear programming equations for scenario-based further analysis. Primary and secondary data were collected from different sources. Primary data were from surveys and secondary data were from literature, the annual financial reports of the targeted companies, unions, cement associations, quarries, the Australian Statistics Bureau, etc. These data act as a bridge to developing six scenarios by using linear programming to seek optimal solutions, including minimising carbon dioxide emissions and natural resources depletion and maximising profits across three areas.
Chapter 5	This chapter examines the results and further validates the proposed methodology, evaluating three cement options in terms of sustainable manufacturing and infrastructure.
Chapter 6	This chapter discusses the overall research, including outcomes, objectives and research questions, limitation and future research in cement plants.

CHAPTER 2

LITERATURE REVIEW

CHAPTER 2 LITERATURE REVIEW

The scope of this chapter is to review what kind of cement production methods current researchers have been using, and the shortcomings of those methods. They include ordinary Portland cement, supplementary cementitious materials and fly ash based geopolymer cement production and their financial effect in terms of materials cost, distances of raw materials flowing from quarry sites to cement factories, mass flow in cement production, cement and fly ash based geopolymer cement composition, identified secondary cement production data, identified environmental assessment tools (particularly for carbon dioxide emissions measures), life-cycle cost assessment and life-cycle assessment, cost-analysis method, linear programming for optimal cement operation, identified natural resources depletion calculation methods for the three areas and the natural resources consumption trend in Australia. This provides the opportunity to evaluate cement manufacturing options for sustainable infrastructure. The research questions, alternative methods suitable for this research, proposed framework and primary cement production data collection methods were developed based on the literature findings.

2.1 GREEN DEVELOPMENT FOR THE CEMENT AND CONCRETE INDUSTRY

This section examines three types of cement (ordinary Portland cement, ordinary Portland cement with supplementary cementitious materials and geopolymer-based cement) with respect to composition and green development. Each type of cement has a specific role and enables the evaluation of three areas in green development or sustainable infrastructure that are suitable for this research. For example, adding supplementary cementitious materials into ordinary Portland cement production (Yang et al., 2014) reduces carbon dioxide emissions and uses less energy (Imbabi et al., 2012). For the same reasons, developing geopolymer-based cement, including fly ash based geopolymer cement and metakaolin-based geopolymer cement (Habert et al., 2010 and 2011), is driving down energy costs and eliminating carbon dioxide emissions in the production process, particularly by converting waste (e.g., fly ash and iron slag) into useful construction materials. This waste comes from coal-fired power stations and iron and steel refinery factories change them into viable products that reduce the rate of natural resources depletion. Different cements, including geopolymer-based cement, are hard to understand their applications in concrete and building industries and also manufacturing methods, Cavanagh and Guirguis (1992), Mindess (1983) and Gani (1997) have classified several types of Portland cement produced in Australia, as shown in Tables 2.2 to 2.3. Gani (1997) has reorganised the application of geopolymer-based cement in a defined molar ratio. This systematic approach enables the right cement and production purposes to be used. Concrete is a combination of mortar, ordinary Portland cement or geopolymer-based cement, with fine sand, aggregate and water for general civil and construction work. This kind of concrete is normally used to make ordinary-strength concrete. Concrete strength development over time depends on what types of Portland cement and geopolymer cement are used based on characteristics and application (Gani, 1997), as shown in Table 2.1. This research identifies ordinary Portland cement and fly ash based geopolymer cement commonly used in Australia, and the 'cradle-to-cradle' of the life-cycle assessment process (Weil et al., 2009) in cement production.

2.1.1 ORDINARY PORTLAND CEMENT AND CEMENT PRODUCTION

2.1.1.1 Ordinary Portland Cement

The use of cement, including lime-based cement and Roman cement, has a long history that goes back to Neolithic times. In 1818, Joseph Vicat (1821-1902) (Vicat, 2016), in France prepared artificial 'Roman cement' by calcining an artificial mixture of limestone and clay. This was the forerunner of Portland cement (Gani, 1997; Cohrs, 2012). Joseph Aspin, a builder from Leeds, England, developed Portland cement based on this technology, and patented it in 1824; it is still widely used (Gani, 1997; Peray, 1979; Cohrs, 2012). Here, the product was called Portland cement because the set product bore some resemblance to Portland stone. The first extensive use of Portland cement was in the construction of the London sewerage system from 1859 to 1867 (Gani, 2010). This led to increased popularity and, ultimately, its widespread use in the construction industry. Because of this demanding market and improvements in its reliability and strength, in 1844, Isaac Johnson modified ordinary Portland cement productivity (Cohrs, 2012) by heating its ingredients to a temperature at which they partially melted, shortening the calcining time and producing a fine, powdered cement through hard clinker that simplified the jaw crusher (Gani, 1997). This traditional production method has been widely used since 1844 (Gani, 1997). The first cement manufacturing in Australia took place in 1859, and the rotary kiln to produce cement clinker was introduced in the early 20th century the town of Waratah in Gippsland, Victoria (Cohrs, 2012).Wilkinson, Coignet and Hennebique (1880s) used iron bar to develop reinforced concrete in Europe in the 1880s (Cement Concrete and Aggregates Australian, 2014). Cement is commonly used in construction and building materials worldwide, and to maintain the cement quality, Australian Standards for cement were introduced in 1925 and adopted in 1926 (Gani, 1997 and Lea, 1980). Australia Cement Standards - AS 3972:2010 (general purposes and blended cements) or BD-010 and NZS 2350-Methods of Testing Portland, Blended and Masonry cement based on AS 3972:1997, Portland and Blended Cement to upgrade this version (Gani, 1997) are the guidelines to produce good quality cement for Australia and New Zealand markets. Further, the objective of this revision is to allow an increase in the proportion of mineral additions with the existing performance based specification. This change permits a reduction in the 'carbon footprint' of cement manufacture and helps meet the government's program to reduce greenhouse gas emission based on AS 3972:2010. In addition, this standard specifies the minimum requirements for hydraulic cement including general purpose and blended cements. It does not purport to provide for all the requirements that may be needed in specific application of AS 3972:2010.

Thus, the cement produced and sold to America must meet specifications established by the American Society for Testing and Materials (ASTM), the Standard specification for Portland cement is ASTM C150 / C150M - 17.

The general use of supplementary cementitious materials based on AS 3972:2010, including fly ash, ground-granulate iron blast-furnace slag and amorphous silica, significantly increases the durability of concrete and reduces the carbon footprint of both cement and concrete. AS 3972:2010 also the narrative documents referenced in another standard AS 2350 is for Methods of Testing Portland, Blend and Masonry Cement, AS 2350.2 is for Method 2: Chemical Composition and AS 3582 is for Supplementary Cementitious Materials for Use with Portland and Blended Cement (Gani, 1997). AS 3583 is for Methods of the Test for Supplementary Cementitious Materials for Use with Portland Cement (Potter, 1997). AS 3582.1 Part 1: Fly Ash, AS 3582.2, Part 2: Slag, Ground-Granulate Iron Blast-Furnace and so on (Fly Ash Australia, 2015). These kinds of standards provide a guideline for all cement factories to produce and sell in the Australian and New Zealand markets (Cement Industry Federation, 2012 and 2013; Visually, 2016; Woodward and Duffy, 2010; USGS, 2012).

Portland cement can be also defined as the product obtained by finely grinding clinker produced by calcining to incipient fusion (e.g., sintering) and an intimate and properly proportioned mixture of argil lance (e.g., clay and alumina-silicate) and calcareous material (Peray, 1979; Gani 1997).

Here, traditional ordinary Portland cement is made of limestone ($CaCO_3$) or lime (CaO), clay (Al_2O_3), sand (SiO_2), gypsum ($CaSO_4.2H_20$), iron (Fe_2O_3) or iron slag (Fe_2O_3) materials; the major ordinary Portland cement chemical composition (Pazhani et al., 2010; Peray, 1979; Valderram et al., 2012; Hunzinger and Eatmon, 2009) is made up of four compounds:

1) Tricalcium silicate ($3CaO.SiO_2$).
2) Dicalcium silicate ($2CaO.SiO_2$).
3) Tricalcium aluminate ($3CaO.Al_2O_3$).
4) Tectra-calcium aluminoferrite ($4CaO.Al_2O_3FeO_3$) and these compounds are designated as C_2S, C_3S, C_3A, and C_4AF.

where

C = calcium oxide (lime)
S = silica
A = alumina
F = iron oxide

This type of composition is based on ASTM types 1-V standard, further discussed in Section 2.1.1.1. The major cement types and their applications are shown in Table 2.1. The most commonly produced cement type is Portland cement, though other standard cement types are also produced on a limited basis (Peray, 1979).

Table 2.1 General Cement Types Including Ordinary Portland Cement, Characteristics and Application (Peray, 1979)

Focused in this type of cement

Current Name	Type	Characteristics	Uses
Normal (ordinary) Portland cement	I	Non-especially hydraulic cement	Most structures, pavements and reservoirs
High Portland cement	II	Generates less heat from its hydration and is more resilient to sulfate attack than type I	Structures with large cross-sections
High-early-strength Portland cement	III	Allows earlier removal of forms and shorter periods of curing	When high strengths are required within few days
Low heat Portland cement	IV	Generates less heat during hydration than type II; gains strength more slowly than type I	Mass concrete constructions
Sulfate - resisting Portland cement	V	High-sulfate resistance cement that gains strength more slowly than type I	Used when concrete is exposed to severe sulfate attack
Air - entraining Portland cement	1A, IIA, IIIA	Air-entraining agents, underground with the cement clinker, purposely causes air in minutes, closely spaced bubbles to occur in concrete	Entrained air makes the concrete more resistant to the effects of repeated freezing and thawing, used on pavements
Portland - blast furnace slag cement	1A, IS-A, MH, MS	Made by grinding granulated high-quality slag with Portland cement clinker; type IS cement gains strength more slowly in initial stages, but ultimately has about the same 28 days' strength as type 1 cement	Air entrainment type is IS-A, moderate heat-of-hydration type is MH and moderate sulfate resistance type is MS
White Portland cement	Not applicable	Desirable aesthetic qualities, high in alumina and contains less than 0.5% of iron	Architectural and ornamental work
Portland - Pozzolan cement	IP, IP-A	A blended cement made by intergrading Portland cement and pozzolanic materials	Used under certain conditions for concrete not exposed to the air

As shown in Table 2.1, there are five types of Portland cement, and each type has its owned characteristics and applications. By adjusting the relative amounts of the phases present in Portland cement, the cement properties can be altered to create different types of cement. In the cement production processes, significant quantities of carbon dioxide would be emitted in the kiln process, generating several types of Portland cement under different temperatures in the clinker. This research only focuses on ordinary Portland cement (circled red in Table 2.1).

2.1.1.2 Cement Production

The process flow of cement production is that raw materials are quarried or mined and transferred to the manufacturing facility to be crushed and milled into fine powder and delivered to the factory for drying, mixing and blending. They then enter a pre-heating and eventually a large rotary kiln at a temperature greater than 1400ºC to 1500°C (Hasanbeigi et al., 2010; Madlool et al., 2012; Atmaca and Yumrutas, 2014; Huntzinger and Eatmon, 2009; Turner and Collins 2013). The clinker or kiln product is cooled and excess heat is typically routed back to the pre-heater units. Prior to packing and transport, gypsum is added to the clinker to regulate the setting time, as shown in Figure 2.1; the setting time is used to examine the materials flows, energy used and carbon dioxide emission distribution. To measure carbon dioxide emissions, Turner and Collins (2013) have used the Carbon Dioxide Emission Equivalent (CO_2-e) method for determining carbon footprint in cement production. It produced each kilogram of cement production emitted 0.66 to 0.85kg carbon dioxide emissions for every kilogram of cement manufactured (Huntzinger and Eatmon 2009). The production contribution of ordinary Portland cement is approximately 5-7% of global anthropogenic carbon dioxide emissions (Turner and Collins, 2013; UNSTATS, 2010). One issue of Carbon Dioxide Emissions Equivalent method is there any methods to intensively and specifically measure each process of carbon dioxide emissions for cement manufacturing, such as measuring clinker carbon dioxide emissions, transport emissions and so on.

Because of improved clinker productivity as the result of less energy and carbon dioxide emissions in a kiln, different kiln technologies are used in cement production, such as new suspension pre-heater and pre-calciner kilns (NSP kilns), dry long rotary kilns with pre-heaters, dry rotary kilns with pre-heaters, dry long rotary kilns and shaft kilns (China Cement Association, 2016). The total clinker production in 2011 using 1,637 units of pre-calciner kiln technology in China produced 1,637 Mt (China Cement Association, 2016).

The most commonly used rotary dry processes (e.g. drying, pre-heater, pre-calciner, sintering, cooling, etc.) in cement kilns in Australia and China (Cement Industry Federation, 2013; China Cement Association, 2012) are shown in Figure 2.1.

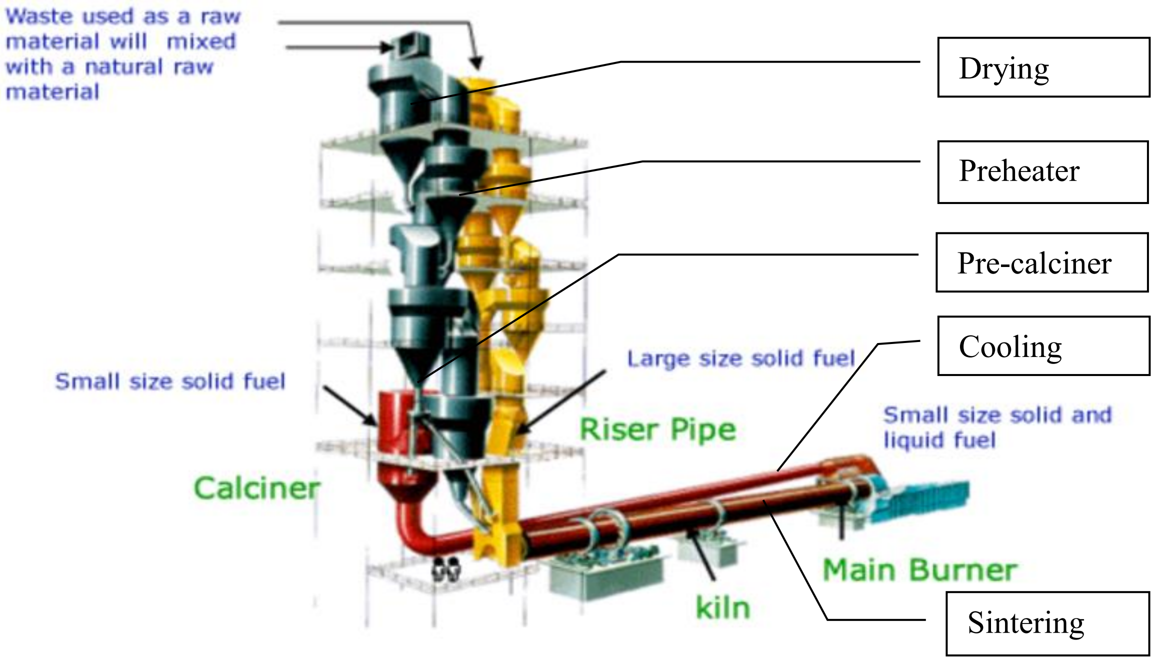


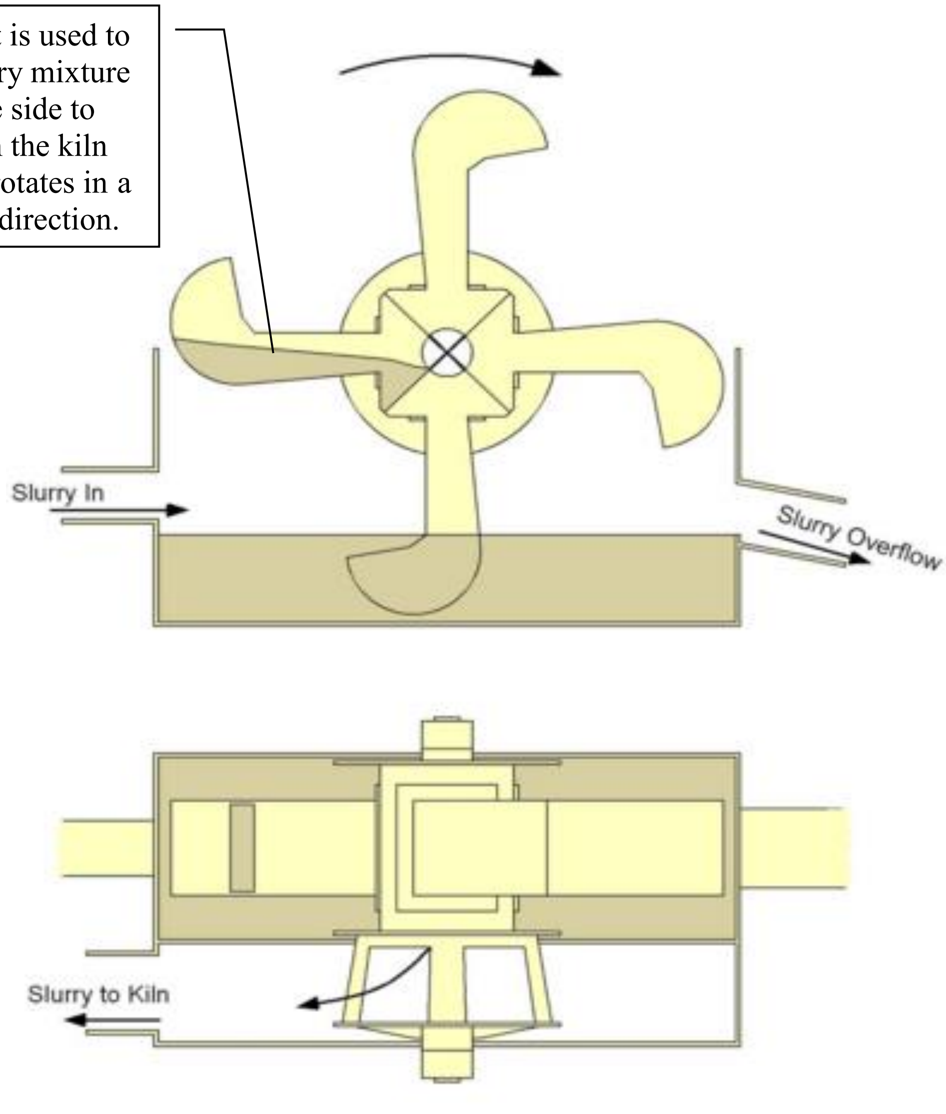
Figure 2.1Traditional Dry Kiln with Multi-stage Pre-heater/Recalciner Systems Diagram (Adapted and Extended and Image Courtesy of Cement Manufacturing and Process, 2016)

As shown in Figure 2.1, the limestone and other raw materials are ground wet and slurried at moisture contents of 30-40%. This slurry is fed into the upper end of the kiln and flows down the slope through the kiln to the hot discharge end. Dry mix is pneumatically pumped to the upper end of the dry kiln and flows through the sloped kiln (Gani, 1997). The differences between wet and dry kilns are as follows:

(a) The dry kiln process area has a diameter similar to the wet process kiln, but is shorter in length because it is not necessary to install an evaporation zone to remove extra moisture.

(b) Less heat is used in a dry kiln because it is not necessary to remove moisture from the clinker. Further, the kiln gas does not pass through a wet raw mix to be used for cogeneration of electrical power - rather, the hot exit gas is supplemental combustion air for the kiln fuel in case cogeneration equipment is absent.

Dry, wet and semi-wet process kilns (as shown in Figure 2.2) are still used in cement manufacturing because dust particles settle in the small water pool at the bottom of the kilns, and more energy is used to keep the semi-cement product dry. In these operations, the raw materials are the same, but the sequences and operations for raw material crushing, grinding and blending are different processes (Peray, 1979; Lea, 1980 and Gani, 1997).



This bucket is used to deliver slurry mixture from one side to another in the kiln process. It rotates in a clockwise direction.

Figure 2.2 The Wet and Semi-Wet Process Kiln Diagram (Image Courtesy of Cement Kiln, 2016)

Compared with wet and dry process kilns, wet process kilns include uniform feed blending, generally have lower kiln dust emissions and are compatible with moist climates, where complete drying of raw feed is difficult to achieve and uses more energy.

Dry process kilns have smaller diameters compared with wet process kilns, because there is no evaporation zone required (Peray, 1979) as a result of arid statues that save energy. Pre-heater kilns (suspension), as shown in Figures 2.1, 2.3 and 2.6, are one of the most energy-efficient types of kiln, because the raw material passes through each pre-heater for heat gain, becoming hotter before entering the rotary kiln for further processing (Gani, 1997; Cement Industry Federation, 2012 and 2013). This saves fuel and energy costs.

The cooler, as shown in Figures 2.1 and 2.6, is one area of energy loss of cement manufacturing because of the heat loss in clinker cooling. Atmaca and Kanoglu (2012) also stated that total energy consumption for cement production is about 100 kwh/tonnes of cement. About 65% of the total electricity energy used in cement plants is for grinding coal, raw materials and clinker (Schneider et al., 2011).

To reduce carbon dioxide emissions in cement production, Provis and Deventer (2009), Habert et al., (2010) and Zhang et al., (2014) have studied geopolymer-based cement as a replacement for ordinary Portland cement, as the result of fly ash based geopolymer cement production uses less energy (Davidovits, 1993, 2001, 2002, 2012) and fly ash is of the wastes from coal-fired power station and to convert them to construction material using fly ash and sodium hydroxide solution with a series of chemical reactions (Davidovits, 2009) to make fly ash based geopolymer cement. It is an environmentally friendly product (Duxson et al., 2007) and also slows down abiotic depletion. However, the cost of materials to produce fly ash based geopolymer cement is higher than for ordinary Portland cement (Chan et al., 2015).

One of the research gaps identified how to reduce carbon dioxide emissions and use less energy to produce cement without further investment in cement production. Most cement companies in Australia only produce ordinary Portland cement based on the recommendations of Cement Industry Federation (2015) report, but producing this cement is energy intensive and emits large quantities of carbon dioxide. To improve this situation, Yang et al., (2014) has indicated that one of the most economical ways is by adding supplementary cementitious materials into ordinary Portland cement in production to reduce carbon dioxide emissions throughout the cement production process that lead to less investment in facilities but only use more supplementary cementitious materials. However, Yang et al., (2014) did not quantitatively measure and to compare ordinary

Portland cement and ordinary Portland cement with supplementary cementitious materials by using life-cycle assessment method (Chan et al., 2015). This method has an inventory and stores majority of carbon dioxide emissions production data. However, this inventory does not include the carbon dioxide emissions data in production of ordinary Portland cement with supplementary cementitious materials and also cannot provide correct ratio between supplementary cementitious material and ordinary Portland cement to effectively reduce carbon dioxide emissions. To fill this gap, Figure 2.6 adapted and extended a traditional cement production (Cement Industry Federation, 2011) in Australia to defined cement production boundary, which included heat, gas emissions and particles emission and production facilities for carbon dioxide emissions assessment of each production process and further discussion of seasonal ratio in Chapter 4. Regarding the material flow and energy flow in kiln process as shown in Figure 2.1 and Figure 2.3, the essential production facilities for cement manufacturing are electrical motors, pumps, compressors, transformers, furnaces, fans, blowers, conveyors, chillers, cooling towers, kiln, transport and lighting systems (Madlool et al., 2012).

All this primary production equipment assists with producing cement, which is made from calcareous and argillaceous material and involves mining, crushing and grinding raw materials and calcining them in a rotary kiln as a result of producing clinker; mixing clinker with gypsum, fine grinding, storing it in a silo and packing the finished cement. The typical cement manufacturing process is shown in Figure 2.6. It is divided into three stages (Peray, 1979 and 2000; CCA, 2016 and Cement Industry Federation, 2014):

A. Stage 1: raw material preparation (Peray, 1979).
B. Stage 2: clinker production (China Cement Association, 2016).
C. Stage 3: cement grinding (Cement Industry Federation, 2014).

A. Stage 1: raw material preparation (Peray, 1979). This process includes crushing the quarried materials, drying the materials, coarse and fine-grinding raw materials and blending them. The mined material is like gravel is reduced to around 25 mm by being fed into primary and secondary crushers and further reduced to a suitable size until it becomes powder in the mill, which is a ball mill or vertical roller mill. The raw mix inside the mill must always be in dried condition, which is the best status for grinding, otherwise it may stick somewhere inside the mill; there is a crossover line with nonretuned, valve-supplied excess heat (hot air) from the kiln in the process line. After that, the fresh raw material particles are delivered from the mill and the coarse and fine particles are separated. The coarse particles are returned to the mill for further grinding until they reach the acceptable particles size via the separator. The fine particles are transported to the raw material silo for blending. A small amount of dust is generated by the precipitator during this process and conveyed to the semi-raw material silo; the remaining waste gas is released by fan. The flow of gravel, silica, slag, supplementary cementitious materials and so on also undergo the same operation until they reach the appropriate size and become powder; they are then stored in separated silos (Peray, 1979). The purposes of these separated silos also act as to avoid the natural chemical variations and unique clinker quality in the raw material by using variety keeping continuously blending silos, so raw material homogenisation is a fine-grinding process. Two widely used primary blending methods (Gao et al., 2009 and Peray, 1979) are:

(a) Mechanical agitation (Schneider et al., 2011 and Gao et al., 2009) is one of most significant factors governing the correct raw material ratio and composition in cement-making. It is often adapted by small cement factories (Gao et al., 2009) and laboratory scale (Han and Ferron, 2015). Commonly used methods are hand-mixing, mixing with a Habert planetary mixer and mixing with a Ross high shear mixer.

(b) Air mixing (Xu et al., 2015; Schneider et al., 2011; Shepherd, 2007; Gao et al., 2009) is generally used by large-scale cement companies. A blower distributes air into an inflatable box at the bottom of the silo and mixing chamber and the semi-raw material catcher, which is elevated to the upper end of the silos and contacts the swirling air moving in the opposite direction during landing, after which it is dropped into the mixing chamber. The blended semi-raw materials overflow from the chamber into the reservoir bottom catchers, and are then transported to the kiln. Part of the semi-raw material at the bottom of the silo is conveyed to the side silo catcher, and then elevated to the upper end of the silo by a life pump. This implies that the semi-raw material homogenisation process will take place again (Gao et al., 2009).

B. Stage 2: dry-type kiln and wet-type kiln, as shown in figures 2.1 and 2.6. Clinker production occurs from either kiln process; it is the upfront process of cement manufacturing. Coal is the traditional fuel used in the Chinese cement industry (Gao et al., 2009) and in Australia (Cement Industry Federation, 2014). It produces heat for the clinker production process as a result of converting limestone into lime and then reacting it with silica, aluminium oxide and ferric oxide (iron slag) to form clinker compounds: C_3S, C_2S, C_3A and C_4AF, as shown in figures 2.5 and Tables 2.2 and 2.3. To produce this type of ordinary Portland cement, a pre-calciner (NSP) with kiln (Gao et al., 2009 and Cement Manufacturing and Process, 2016) is one of the solutions, as it contains a pre-heater and pre-calciner system. The reheater includes four to six multi-stage cyclones (Figure 2.3, red box) and the pre-heater contains pre-calciner (Gani, 1997; Gao et al., 2009 and Peray, 1979). The operational process of the pre-calciner with kiln is that the hot exhaust gas stream, of up to 380°C, passes throughout the pre-heater and pre-calciner system and can provide better heat distribution to the raw materials before the kiln process, as shown by the red arrow in Figure 2.3. A semi-raw/raw material (e.g., as mark 1) is fed into the upper end of the pre-heater tower and passed through the end of the rotary kiln. Exhaust gas (e.g., as mark 2) from the rotary kiln passes concurrently through the downward-moving semi-raw material in the pre-heater cyclones (Gao et al., 2009), as shown in Figure 2.3.

A process such as this saves large quantities of energy (Cement Industry Federation, 2013), ensuring that the outcomes are C_3S, C_2S, C_3A and C_4AF materials. The best performances of the pre-calciner with the kiln is installed at a horizontal slope of 3 to 4° (Gani 1997; Peray, 1979) and rotated slowly to move the semi-raw material towards the direction of the flame (Appendices E.1 and F.1) at the lower end of the kiln, which is the hottest zone (Figure 2.3), meaning that chemical and physical changes taking place and clinker (as mark 4) is formed (China Cement Association, 2016). Although the pre-caliner kiln operation was explained in the previous paragraph, this research only focuses on heat and raw materials flow. Therefore, it provides information on energy quantity and types of fuel used in kiln processes in full-load condition for a tailored scenario study of optimal operation in terms of cement production cost (see Chapter 4).

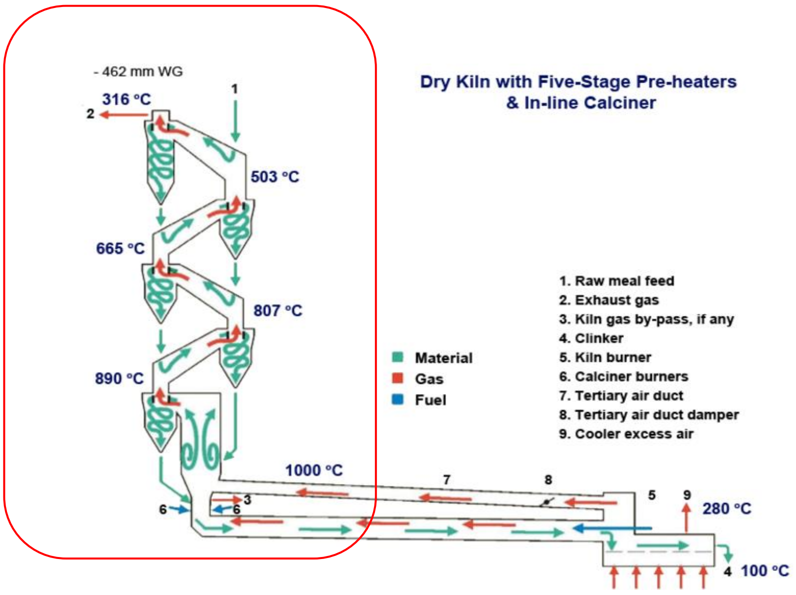


Figure 2.3 Material (Mass) and Energy Flow of the Kiln Process (Image Courtesy of Cement Manufacturing and Process, 2016)

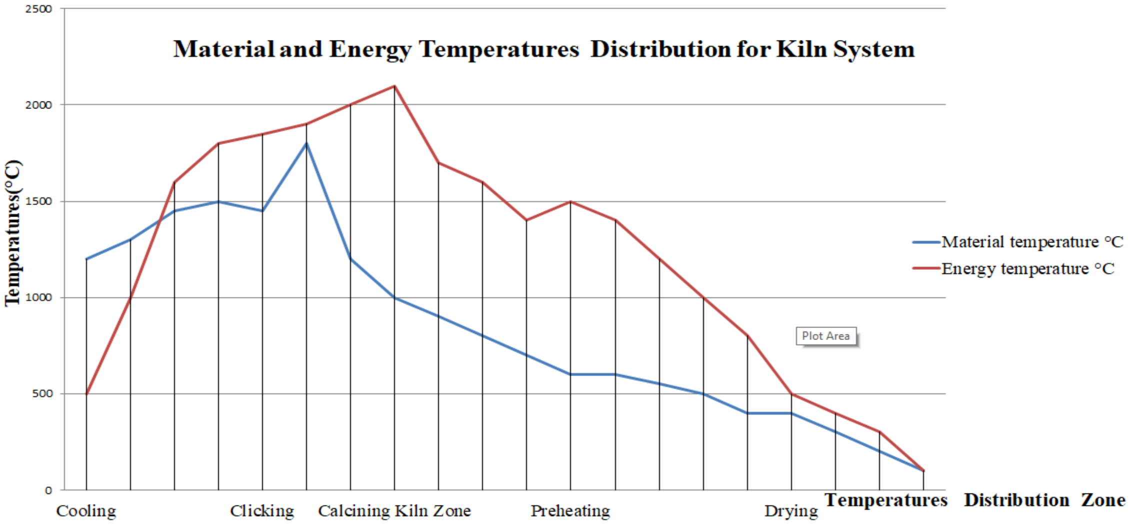


Figure 2.4 Raw Materials and Energy Temperatures Distribution for Kiln System Based on Figure 2.3 Outcomes

The energy and material temperature distributions are shown in Figure 2.4. The purposes of the two curves are outlined below:

(a) The red curve represents energy varieties in different processes, including cooling, clicking, pre-calcining kiln zone, pre-heating and drying processes in cement production.

(b) The blue curve represents material temperatures in various stages of processes, including cooling, clicking, pre-calcining kiln zone, pre-heating and drying in cement production.

The kiln elevates temperatures from 500°C to 1500°C using coal and chemical reactions, after which the kiln system gradually slows down to below 400°C in cement production (China Cement Association, 2016 and Yang et al., 2014). This process is significantly energy intensive. In cement production, the kiln plays the most important role, and four major phases in manufacturing Portland cement occur during clinkering, as shown in tables 2.4 and 2.5. The cement composition must lie in the triangle bounded by C_3S, C_2S and C_3A (Gani, 1997), as shown in Figure 2.5, which shows the relative amounts of raw materials (e.g., lime and kaolin) that should be formed as clinker with the desired composition-this provides a clue regarding what kind of material is being produced and how much energy is consumed in the kiln process in a robust environment.

Table 2.2 Types of Ordinary Portland Cement Produced in Australia (Cavanagh and Guirguis, 1992)

Hypothetical Phase Composition (Mass %) (Range)					
Type	C_3S	C_2S	C_3A	C_2AF	Common Designation
A	48-65	10-30	2-11	7-17	Ordinary
B	50-65	7-25	6-13	7-13	Rapid set
C	25-30	40-45	3-6	12-17	Low heat
D	50-60	15-25	2-5	10-15	Sulphate resist

where

C_3S = tricalcium silicate
C_2S = dicalcium silicate
C_2A = calcium ferrite
C_2AF = calcium alumina ferrite

Table 2.3 Types of Ordinary Portland Cement Produced in America (Mindess, 1983)

Hypothetical Phase Composition (mass %)							
Types	C_3S	C_2S	C_3A	C_3AF	$C\bar{S}H_2$	Heat evolved (7 days, KJ/kg)	Common designation
I	50	25	12	8	5	330	Ordinary
II	45	30	7	12	5	250	Ordinary
III	60	15	10	8	5	500	Rapid set
IV	25	50	5	12	4	210	Low heat
V	40	40	4	10	4	250	Sulfate resist

In addition, the Australian Standard AS 2350.2-1991 includes a disclaimer that the hypothetical compound composition percentage (by mass) calculated (as illustrated in Tables 2.2 and 2.3) from the chemical analysis does not imply that the oxides are entirely present as compounds, or that such compounds are present in the percentage calculation.

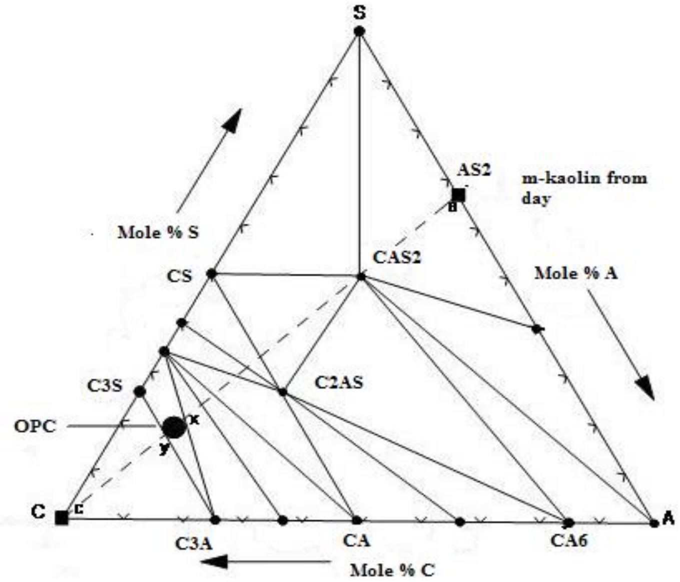


Figure 2.5 $CaO.SiO_2$. Al_2O_3 Phase Diagram (Image Courtesy of Bodil et al., 2015 and Gani, 1997; Pasquino et al., 2013)

Further, calcium oxide (CaO) is formed by the decomposition of limestone ($CaCO_3$) (Hokforts et al., 2015) and shown by point C inside the kiln under 1500°C (Messner et al., 1996; Milulcic et al., 2012; Milburn et al., 2006; Prouty, 2008; Carpenter, 2001; Roy, 1983; Pasquino et al., 2013) as shown in Figure 2.5. The compositions that can be made by mixing calcium oxide and metakaolin (m-kaolin) will lie somewhere along the AC horizontal line joining these two compositions (Carpenter, 2001). This is because the composition of the Portland cement clinker must lie within the triangle joining C_2S, C_3S and C_3A (Gani 1997; Peray, 1979). The maximum mole fraction of metakaolin to calcium oxide is given by the ratio of the lengths CX/AC (0.31) and the minimum fraction of metakaolin to calcium oxide in the ratio CY/AC (0.26) (Gani, 1997; Bodil et al., 2015; Chaunsali and Peerhamparan 2013). Additionally, the quality of the ordinary Portland cement composition in the kiln process is based on $CaO.SiO_2.Al_2O_3$ phase diagram combination.

The information shown in Tables 2.5 and 2.6 is particularly important. Because the relative amounts of the phases present are calculated using a Bogue's equation (Mindess, 1983; Taylor, 1989), which assumes that ordinary Portland cement in clinker formation and mechanism reactions proceeding to completion (Gani, 1997). However, the outcome amount based on Bogue's equation has a variation. Because a non-equilibrium condition occurs in the chemical reaction in the clinker process, solid solutions are formed by the phase with other ions such as magnesium, potassium, sodium, iron and so on. To solve this issue, a quantitative X-ray diffraction technique is one of the solutions used to measure the amount of the crystalline phase present in the cement clinker (Gani, 1997; Peray, 1979). Here, three traditional methods are used to calculate the composition contents of ordinary Portland cement in clinker, as outlined below:

(a) Silica modulus.
(b) Alumina modulus.
(c) Lime Saturation Factor method.

(a) Silica modulus is commonly used in cement manufacturing (Taylor, 1989; Roy, 1983) to calculate the composition of Portland cement clinker:

$$\text{Silica modulus (SM)} = \frac{S}{(A+F)}$$

The silica modulus is defined as the amount of liquid phase that is dependent on the value of this ratio. Typical values of the silica modulus are between 2.3 to 2.5. If the silica modulus is too high, then the amount of liquid phase produced 'I' low, which results in not all the materials being converted into clinker modules. The remaining, not-yet-melted dusty materials clog the kiln and are incompletely reaching (Gani, 1997) the formation of clinker materials and modulation.

(b) Alumina modulus is defined as the temperature at which melting commences. Typical values are about 2.

$$\text{Alumina modulus (AM)} = \frac{A}{F}$$

This equation shows that the lowest temperature at which liquid is formed occurs at AM = 1.6, which is optimum for the formation of clinker materials and modulation (Gani, 1997).

(c) The lime saturation factor method is also commonly used in cement manufacturing (Taylor, 1989; Roy, 1983) to calculate the composition of Portland cement clinker:

$$\text{Lime saturation factor (LSF) \% at } 100^{\circ}\text{C} \quad = \quad \frac{LSF}{(2.8S + 1.18A + 0.65F)}$$

where

S = CaO
A = SiO_2
F = Fe_2O_3

Here, applying the lime saturation factor equation is under completion reaction of the calcium oxide in the mix to form compounds can be expected 'I'. But if the lime saturation factor is less than (e.g., <) 100% or the value is more than (e.g., > 0 100%, there will always be some free lime left in the clinker. Typically, the lime saturation factor is 92-96% (Gani, 1997).

The outcome of the lime saturation factor is the result of affecting the composition quality of ordinary Portland cement and classifying the different types of ordinary Portland cement as A to D (Gani, 1997; Peray, 1979). The properties and uses of types A to D of ordinary Portland cement and their American-made equivalents (Bodil et al., 2015; Peray, 1979) are given below:

(a) Type A: ordinary Portland cement (ASTM type 1). This is the most common type of cement and is used for construction purposes. The cement has no exposure to sulfates in the soil or in ground water.
(b) Type B: rapid-set cement (ASTM type III). The rapid-set properties are mainly attributable to the greater fineness of the cement powder and, to lesser extent, to higher C_3S contents. The principal reason for its use is that the rapid setting properties mean that formwork can be removed early for reuse; it is also useful in cases where sufficient strength for further construction is required quickly. It is used for sea walls, piers, thin panels and so on. There is not much difference in the chemical composition of Australian and American-made ordinary Portland cement (Gani, 1997).
(c) Type C: low-heat cement. This is commonly used in massive dams and for large construction. The concrete must be placed in very hot weather because of the lower C_3S and C_3A content; it has slower strength development than ordinary cement, but its ultimate strength is the same (Bodil et al., 2015).
(d) Type D: sulfate-resist cement. Sulfate present in ground water can attack cement. In general, the reaction between the sulfate and the set cement forms products that causing the set cement to crack. The extended attack depends on the type of sulfate present in

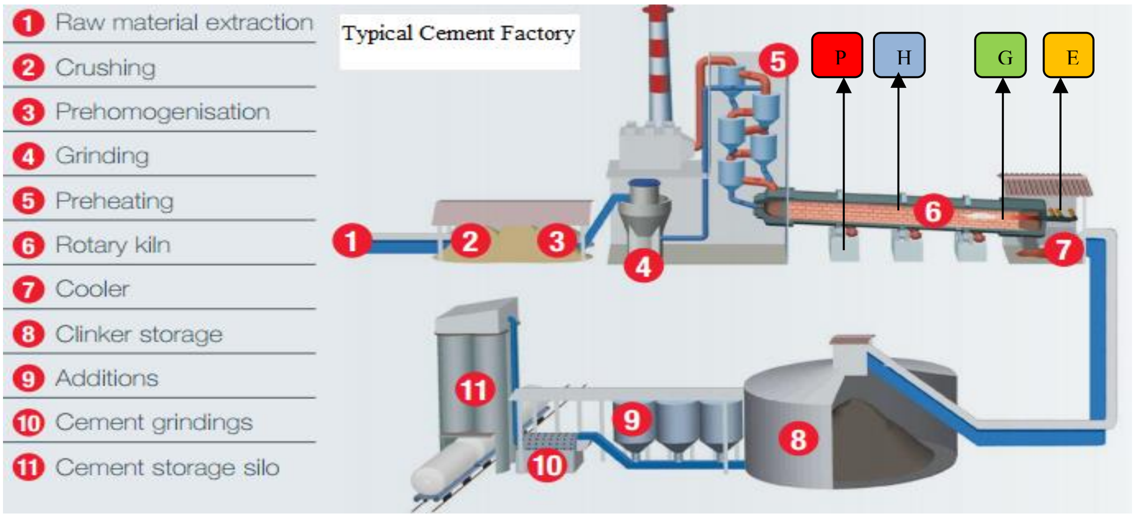
the water, such as calcium, sodium, magnesium and so on (Gani, 1997).

New Zealand cement manufacturers (NZIC, 2014) have also classified rapid-hardening cement, moderate-heat cement and special-purpose cement based on the NZS 2312 standard.

(i) Rapid hardening cement is used in precast concrete, pipes and tiles. It is finer ground so that it hydrates more quickly and has more gypsum than other cements.
(ii) Moderate heat cement is used for the construction of hydro-electric dams, as the heat produced by ordinary Portland cement creates uneven expansion and thus cracking when such a large volume of concrete is used.
(iii) Special cement is only export, including sulfate-resisting, fly ash blend, blast-furnace cement and so on.

In Australia, the majority of the time (300 days per year) (Company A, 2015 and Cement Industry Federation, 2012), cement factories produce ordinary Portland cement and ordinary Portland cement with supplementary cementitious materials based on the AS 3972-2010 (Cement Industry Federation, 2014 to 2016) (this is one of the main reasons large quantities of carbon dioxide are created in cement production). The rest of the time, other types of cement would be produced, (Cement Industry Federation, 2014) and repair and maintenance tasks undertaken for production facilities (Company B, 2015) to maintain good conditions.

C. Stage 3: cement grinding (Figure 2.6, item 10). This is the downstream process just after clinker in cement production. The fine milling (internal structure image in Appendix D.1) grinds gypsum with clinker to produce grey powder. All cement types contain approximately 4-5% gypsum (Gani, 1997; Gao et al., 2009). The fine particles are conveyed to the cement silo and ready to pack. Here, ordinary Portland cement, including supplementary cementitious materials cement, is the final product, which is identified as cradle-to-cradle. The cradle-to-function, production and boundary are also identified in Figure 2.6 and Table 2.4 via the life-cycle assessment method (Guinée et al., 2002; Huntzinger and Eatmon, 2009).



Legend

🟥 P Particles emission 🟦 H Heat 🟩 G Gaseous emission 🟨 E Energy

Figure 2.6 A Typical Dry-Type Clinker for Process Flow of Ordinary Portland Cement Production Including Emission and Energy (Adapted and Extended Huntzinger and Eatmon, 2009; Image Courtesy of Cement Federation Industry Report, 2013)

Figure 2.6 is identified as cradle-to-function, cradle-to-cradle and boundary by using the life-cycle assessment method. Table 2.4 is based on Figure 2.6 to develop and illustrate each production event with respect to cradle-to-function in detail within the defined boundary.

Table 2.4 Boundary, Cradle-to-Function and Cradle-to-Cradle of Cement Production

Cradle-to-Function	**Cradle-to-Cradle**
Transport	
Mixer including sand, clay etc.	
Coarse grinding	
Kiln	
Mixer/Additions including gypsum and/or supplementary cementitious materials	Ordinary Portland cement and/or ordinary Portland cement with supplementary cementitious materials
Fine grinding	
Pack and silo	

Boundary of cement and /or with supplementary cementitious materials production

Table 2.4 adapts and extends the cement production processes shown in Figure 2.6 by using the life-cycle assessment method to classify each cement production method into cradle-to-function, cradle-to-cradle or defined boundary to provide the same conditions of cement production for evaluation in Chapter 4.

2.1.2 SUPPLEMENTARTY CEMENTITIOUS MATERIALS WITH ORDINARY PORTLAND CEMENT

The combination of fly ash, slag and silica fume is known as supplementary cementitious material (Potter and Guirguis, 1991; Hanna and Marcous, 2014; Lothenbach et al., 2010; Zhang et al., 2014). Fly ash is the by-product of coal-fired power stations; silica fume is a fine pozzolanic material (Lothenbach et al., 2010; Davidovits, 2012 and 2001; Allahverdr et al., 2011; Duxson et al., 2007; Duxson and Provis, 2008; Deevasan and Ranganath, 2011) produced by electric arc furnace. The slag (e.g., ground-granulated iron blast-furnace slag) is the by-product of making iron (Habert et al., 2011 and Potter and Guirguis, 1991; Duxson and Provis, 2008). Supplementary cementitious cement has been used in concrete in Australia since 1949, at the leading edge of this technology's development (Potter and Guirguis, 1991). It is widely used in concretes, either in blended cement or added separately in the concrete mixer (Lothenbach et al., 2010). The use of supplementary cementitious materials such as blast-furnace slag, a by-product of pig-iron production, or fly ash from coal combustion, represents a viable solution to partially substituting ordinary Portland cement (Turner and Collins, 2013). This kind of material is effective for reducing carbon dioxide emissions in cement production (George and Mathrews, 2014; Gabel and Tillman, 2005); without an additional clinking process (Yang et al., 2014), a significant reduction is achieved (McLellan et al., 2011; Potter and Guirguis, 1991).

However, if too many supplementary cementitious materials are added to ordinary Portland cement in the production process, this leads to the pre-stress concrete becoming hard to aggregate (Duxson and Provis, 2008; Duxson et al., 2007; Zhang et al., 2014). Therefore, the combination of a certain amount of supplementary cementitious materials with the right fraction of ordinary Portland cement (Yang et al., 2014) is one economical way to reduce carbon dioxide emissions and use less energy (Juenger et al., 2011; Potter and Guirguis, 1991; Zhang et al., 2014, Hasanbeigi et al., 2010, Duxson et al., 2005; Duxson et al., 2007 and Shi et al., 2011).

The issue remains of how supplementary cementitious materials should be added to ordinary Portland cement manufacturing to sufficiently reduce carbon dioxide emissions and save energy without affecting the performance of ordinary Portland cement concrete pre-stress statues (Lothenbach et al., 2010; Hanna and Marcous, 2014; Hardjito et al., 2005). The trend of supplementary cementitious material consumption using seasonality indices for time-series analysis is one solution (Cement Industry Federation, 2013; Carpenter et al., 2000). To achieve this gap, Chapter 4, Data Collection and Analysis, explains how to solve this issue.

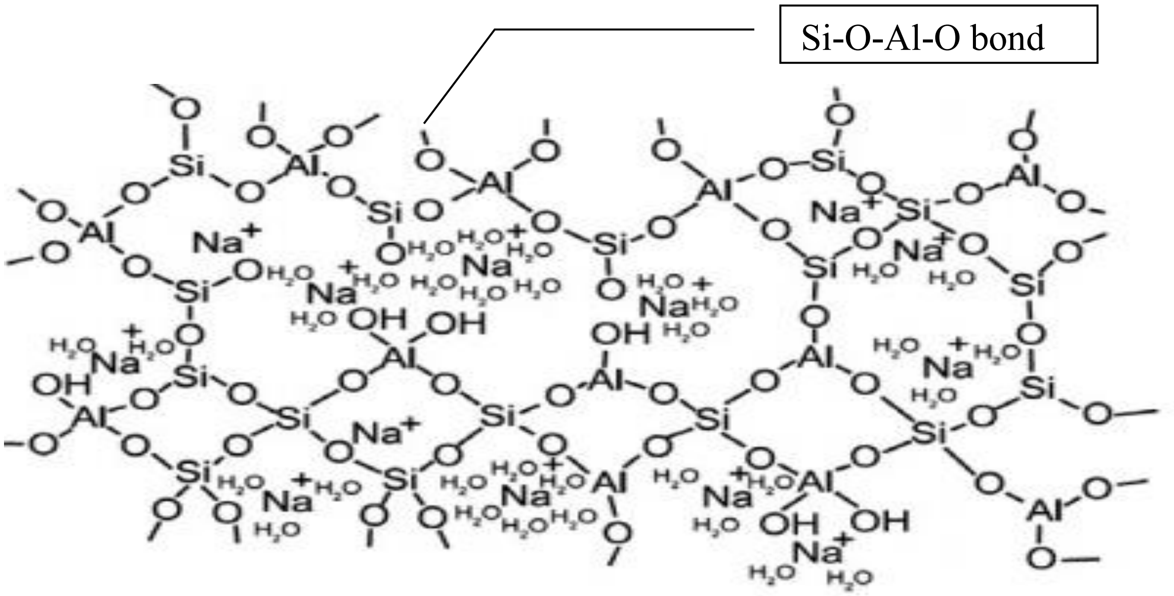
McLellan et al., (2011) have examined the environmental and financial benefits of supplementary cementitious material with ordinary Portland cement, but failed to quantitatively measure how many supplementary cementitious materials, in terms of cost, should be added to the ordinary Portland cement production process, and how much carbon dioxide would be reduced in manufacturing. Thus, Company A (2015) based on McLellan et al's., (2011) theoretical method uses supplementary cementitious materials with ordinary Portland cement in cement production to minimise greenhouse gas emissions. In 2012, company A's carbon dioxide emissions reduced 770,000 tonnes (Company A, 2015) as a result of one of the effective methods to reduce carbon dioxide emissions in cement production and maximise use of production facilities (Lothenbach et al., 2010). However, Company A (2015) also met same problem of McLellan et al., (2011) theoretical method that is correct ratio between supplementary cementitious material and ordinary Portland cement. Time-series model (Lafare et al., 2016) is a solution to seek ratio indices to solve this problem as discussed in Chapter 4.

Yang et al., (2014) and He and Zhang (2011) have also examined supplementary cementitious materials in terms of their generic relationship between composition, particle size and exposure conditions (temperature or relative humidity) and the effect of supplementary cementitious materials on alkali-silica reaction and mechanical performances to improve carbon dioxide emissions in concrete production. However, their results only apply to laboratory-scale experiments and thus do not apply to mass production of ordinary Portland cement with supplementary cementitious material, the total materials cost of this, the correct ratio of supplementary cementitious materials with ordinary Portland cement (Cement Industry Federation, 2013) and the feedstock of raw materials. In addition, supplementary cementitious materials are by-products (including fly ash) from coal-fired power stations; silica fume and slag are also by-products from iron ore refinery factories. The locations of these factories rely on quarry on distance travelled and types of fuel used that affecting carbon dioxide emission from transport. To bridge this gap, two tailored scenarios address the optimal transport solution by using linear programming equations: the ‘subject to function’ equation from the Australian National Greenhouse Accounts Factors (2014 to 2016) in Scenario 4, and the Carbon Dioxide Emission Equivalent method in Scenario 5, both in Chapter 4. The sources of ‘subject to constraints’ are from literature, annual financial reports from companies A to C and the surveys. Chapter 4 also uses time-series with regression model-seeking indices (Grcar, 2011 and 2012) to discover the correct ratio of supplementary cementitious materials with ordinary Portland cement. If too many supplementary cementitious materials are mixed with ordinary Portland cement, the aggregation time can affect the quality (Yang et al., 2014) and a cost for the extra raw materials involved (Yang et al., 2013) in the cement production.

2.1.3 FLY ASH BASED GEOPOLYMER CEMENT

Fly ash based geopolymer was introduced by Davidovits in 1991 and its structure (Skvara et al., 2009; Hardjito et al., 2005) as shown in Figure 2.7. Geopolymer is a solid aluminosilicate material usually formed by alkali hydroxide or alkali silicate activation of a solid precursor, such as coal fly ash, clay and/or metallurgical slag (Sarker, 2008; Habert et al., 2010). Fly ash based geopolymer is made from fly ash, slag, silica fume, sodium silicate, sodium hydroxide and/or potassium hydroxide or alkali-solution sodium silicate solution via a series of chemical reactions.

The basic principle of producing geopolymer (Davidovits, 1991) is to use the reaction of solid aluminosilicate with highly contracted aqueous alkali hydroxide or silica solution to produce a synthetic alkali aluminosilicate material generally called a ‘geopolymer’ (Duxson et al., 2005; Lyon et al., 1997; Davidovits, 2012); this is further described in Davidovit’s patent procedures (see Appendix J). This method is only used for small-scale or laboratory-sized manufacturing. This invention changed the ordinary Portland cement production method and converted one of its coal-fired power plant by-products into a useful construction material. In addition, the geopolymer polymerisation process involves a very fast chemical reaction under alkaline conditions of the Si-O-Al-O mineral as a result of a three-dimensional polymeric chain and ring structure (Duxson et al., 2007).



Si-O-Al-O bond

Figure 2.7 Geopolymer Structure Model (Image Courtesy: Skvara et al., 2009)

The chemical composition of geopolymer material is like that of a natural zeolite structure, the -Al-O-Si- bond, which is any of a large group of minerals consisting of hydrated aluminosilicate of sodium, potassium, calcium and barium material. The major difference is in the microstructure: geopolymer is amorphous instead of crystalline (Palomo et al., 1999). The fundamental chemical and structural characteristics of geopolymers are derived from metakaolin; fly ash and slag are explored in terms of the effects of raw material selection on the properties of geopolymer composites (Duxson et al., 2005 and 2007).

Many researchers and cement manufacturers have identified the main advantage of producing fly ash based geopolymer cement as having less carbon dioxide emissions in the production process, a smaller environmental effect (Davidovits, 2001, 1991, 1993, 2002 and 2012; Duxson et al., 2008; Habert et al., 2011; Hardjito et al., 2005; Heah et al., 2013; Hicks, 2011, Van Deventer et al., 2012; Turner and Collins, 2013 and Lyon et al., 1997) and reduced energy use (McLellan et al., 2011; Milulcic et al., 2013). It is classified as one type of green cement (Davidovits, 2009).

Several types of geopolymers are on the market. Gani (1997) has used the molar ratio of the Si and Al ratio method to determine three common ways of applying geopolymer, as shown in Table 2.4. This research is based on Table 2.4 (Gani, 1997), and adapted and extended the mix ratio of Si/Al; so it was larger than 1 but fewer than 2 within this range.

One of the prerequisites of this study was to evaluate three areas within the defined boundary. Chan et al., (2015) used ISO14040 application theory and conducted a study of carbon footprint for cement production that included all manufacturing processes, including raw materials, production and distribution in the same defined boundary: Australia.

In addition, Milburn et al., (2006) and Chan et al., (2015) have pointed out that it is easy to tackle the cement or geopolymer-based production methods that provide the same production conditions in cement manufacturing options in evaluating this research study.

Table 2.5 Application of Geopolymer-Defined Molar Ratio (Gani, 1997)

	Application
1	Brick, ceramics, fire protection
2	Low CO_2 cement, concrete, radioactive and toxic waste
3	Heat-resistant composites, foundry equipment, fibre-glass composites
>3	Sealant for industry
20<Si/Al<35	Fire-resistant and heat-resistant fibre composites

Habert et al., (2010) have also examined three sources of ash types to prepare geopolymer-based cement and concrete:

(a) Fly ash based geopolymer: the fly ash comes from coal-fired power stations.
(b) Ground-granular blast slag based geopolymer: the ash or dust is gathered from the crushing process.
(c) Metakaolin-based geopolymer: the ash is collected from a large inclinator or volcano ash, which is full of metakaolin.

Previous research by Gani (1997) in Table 2.5 used molar ratio to determine geopolymer application and Habert et al., (2010) also identified three sources to produce geoploymer-based cement for the pre-stress and carbon dioxide emissions in the production process. In fact, both of them seldom developed linear programming equations to seek the optimal solution. Six scenarios in Chapter 4 were developed to fill these gaps.

Because fly ash material is very expensive compared with raw materials for ordinary Portland cement production (Chan et al., 2015) and this research using linear programming equation seeks to minimise this cost. Coal-fired power stations are one of major sources of power supply in Australia (Australian Statistics Bureau, 2015) and produce 1.2 million tonnes of fly ash (Cement Industry Federation, 2014) every year. Therefore, coal-fired power stations are a reliable means of producing fly ash, which is also one of the major sources of making geopolymer cement. Its value lies in that fact that it generates less carbon dioxide, slows natural resources depletion and converts by-products from coal-fired power stations into construction materials. Fly ash or pulverised fuel ash is one of the solid wastes produced by coal-fired thermal power stations and is a fine grey powder, mostly consistently of spherical glassy particles with pozzalonic properties; these can react with lime to become cementitious compounds. The size of fly ash is appropriately 100 μm (Chandra, 1997), and it is carried along the flue gases stream and captured by electrical and mechanical precipitators (dry process), as shown in Figure 2.8. This fly ash is delivered to a day tank for further treatment using compressed air jets through a seamless pipeline. Use of fly ash for cement and concrete is classified as ASTM C618 in America and AS 3582.1 Part 1: Fly Ash in Australia.

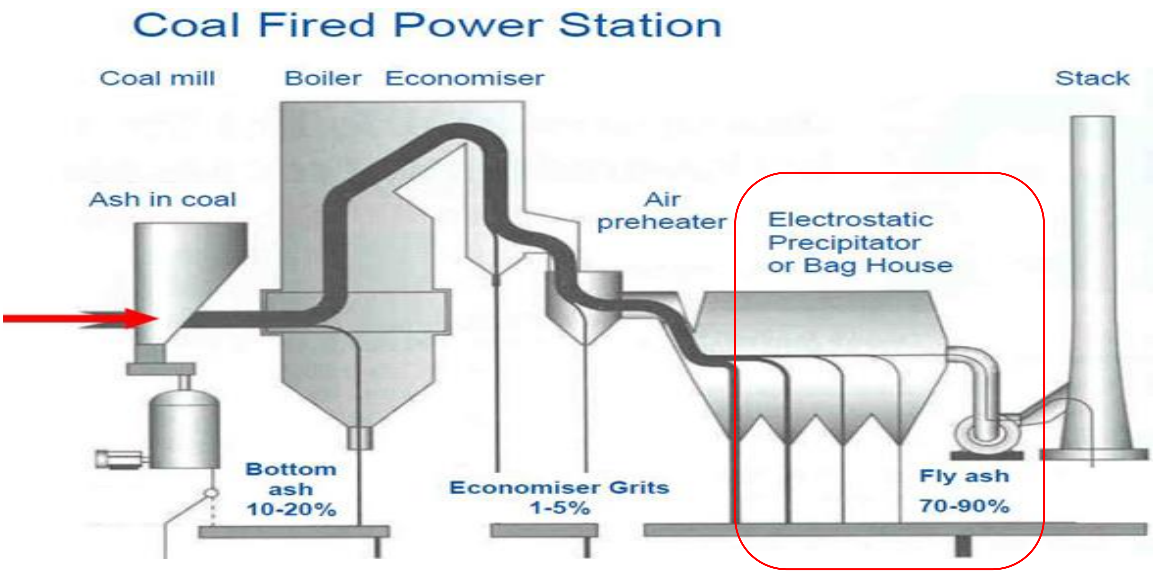


Figure 2.8 Collecting Fly Ash in Coal-Fired Power Station (Image Courtesy of Fly Ash Australia, 2015)

Most geopolymers requires heat curing, hardens rapidly at room temperature and provides compressive strengths in the range of 20 MPa after only four hours at 20ºC; the final 28-day compression strength is in 70-100MPa (Davidovits, 2009;

Habert et al., 2011); geopolymer cement behaviour is like that of zeolites (Davidovits, 1993), which are members of aluminosilicate family of micro-porous solids, consisting of Si, Al and others (Yang et al., 2014). Fly ash based geopolymer's outstanding properties compared with those of ordinary Portland cement are also well known: it has high compressive strength, low shrink, acid resistance, fire resistance, no toxic fumes emission, low thermal conductivity, excellent heavy metal immobilisation, low temperature stability and low manufacturing energy consumption for construction purposes and engineering application (Abdel-Gawward and Abo-EI-Enein, 2014).

Although Abdel-Gawward and Abo-EI-Enein (2014) have mentioned the many advantages of geopolymer-based cement, particularly in production, they have not addressed the financial effects of manufacturing this type of fly ash based geopolymer cement compared with that of manufacturing ordinary Portland cement and supplementary cementitious materials in terms of energy consumption. Ahmaruzzaman (2010), Sarker (2008) and Hardjito et al., (2005) have also studied the use of energy and heat in the fly ash based geopolymer cement production process, as shown in Figure 2.3, but their studies have not discussed the whole life-cycle production cost of fly ash based geopolymer cement and ordinary Portland cement - only Chan et al., (2015) has explored the extended life-cycle cost. Here, Chapter 5 examines this cost issue by using the whole life-cycle method (Sandin et al., 2013; Shapiro, 2001; Chan et al., 2015).

Further, in relation to issues of climate change and lower carbon dioxide emissions, Davidovits (2005) has developed green chemistry for sustainable construction products using geopolymer-based materials to make tiles instead of using traditional ceramic tiles. This method saves energy and has less environmental effect, although the material cost is higher than that of ordinary Portland cement, and Davidovits' results only apply to laboratory-scale manufacturing. To reduce carbon dioxide emissions, Duxson and Van Deventer (2010), Duxson and Provis (2008) and Claudio et al., (2013) have also developed a mix design and novel hybrid organic–inorganic material methods, an innovative synthetic approach based on co-reticulation in mild conditions of epoxy-based organic resins and metakaolin-based geopolymer inorganic matrix (Tailby and MacKenzie, 2010; Swanepoel and Strydom, 2002; Rovnanik, 2010), enabling good homogeneous dispersion (without the formation of agglomerates) of the organic particles, which is easily obtained by hand-mixing and this process creates enhanced compressive strengths. The geopolymer's toughness allows for wider use of these materials for structural application, and lowers carbon dioxide emissions and production costs (Turner and Collins, 2013; McLellan et al., 2011); it also uses less energy, because the fly ash based geopolymer mixture requires elevated temperatures at 60ºC to 80ºC for 24 hours. This method, as illustrated by Turner and Collins (2013), McLellan et al., (2011), only applies to small-scale production and does not offer insight into large-scale cement manufacturing and some procedures that are seldom used in production of ordinary Portland cement and fly ash based geopolymer-based cement (Zhang et al., 2014; Davidovits, 2002 and 2009). By contrast, Figure 2.9 shows the process flow of a typical geopolymer-based cement factory in North Queensland. The fly ash and sodium hydroxide (NaOH) are supplied by a local coal-fired power plant and chemical plant. The sodium hydroxide (NaOH) storage tank is placed on the top of the tower and provides enough chemical liquids to react with the fly ash at 80°C and with other materials, such as sand and slag; it is mixed completely and then finely ground. Finally, it becomes fly ash based geopolymer cement and then cools down in an ambient temperature. All fly ash based geopolymer cement is stored in a silo, ready for delivery to clients. The main advantage of producing fly ash based geopolymer cement is that it is less energy intensive. However, this study identifies the material location in North Queensland based on Figure 4.6, Map of Cement Production and Import Centre (DITR, 2006). Further discussion is in Chapter 4, Figure 4.7 (Map of Domestic Feedstock Sources, McLellan et al., 2011) and also known gypsum sites in Australia (see Chapter 4, Figure 4.8), far away from geopolymer-based cement factories. Because large trucks would deliver the raw material and by-product from coal-fired power stations to cement factories via large trucks, significant quantities of carbon dioxide would be emitted.

One finding is that diesel fuel is dominant in transport particular in heavy trucks and cement production, as shown in Figure 4.4, and typical fuel quantities for cement production is based on Figure 4.5 data. This presents the opportunity to probe how much carbon dioxide is emitted when manufacturing cement. Therefore, one of the objectives of this research is to identify methods of calculating carbon dioxide, based on the literature review, and examining the theoretical emission outcomes of cement production processes to develop scenario-based studies (Chapter 4) with the assistance of Appendix C.3 and Appendix G Simulation results. This study also presents data to develop a whole life-cycle carbon dioxide emissions investigation (Chapter 5, Table 5.4).

1	Raw material
2	Silo
3	Mill
4	Silo
5	Sodium hydroxide solution
6	Filter bag
7	Mixer
8	Material handling
9	Cure
10	Fly ash based geopolymer cement silo

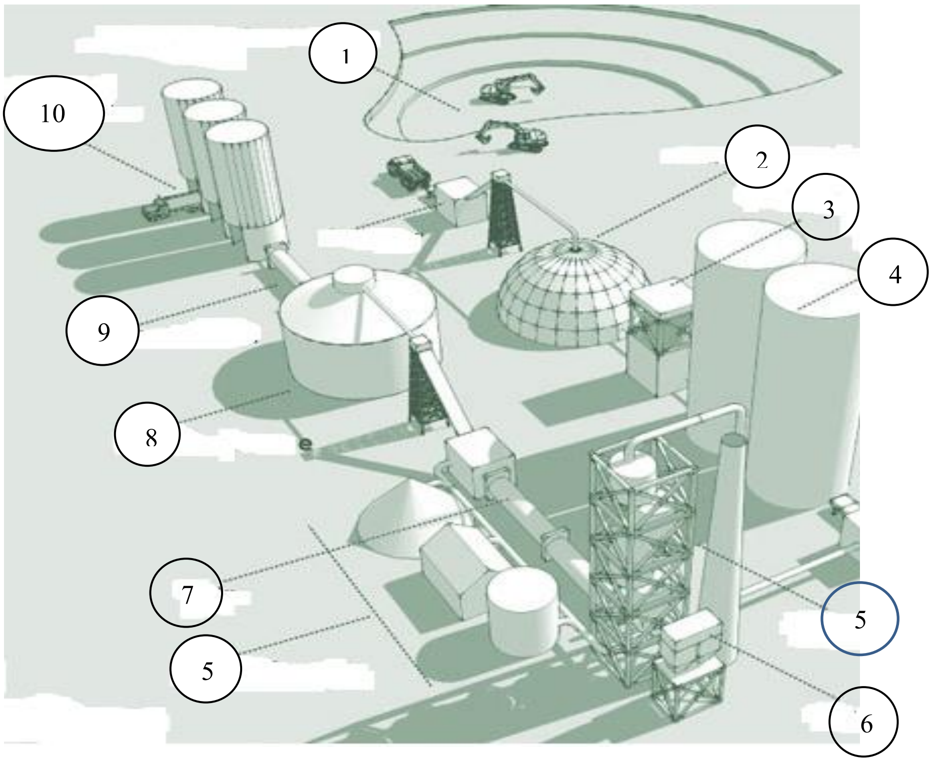


Figure 2.9 Typical Geopolymer-Based Cement Manufacture (Adapted, Extended and Image Courtesy of CMI, 2015)

Figure 2.9 shows typical small-scale geopolymer-based cement production. To provide the same production conditions, Table 2.6, based on Figure 2.9, developed cradle-to-function, cradle-to-cradle and boundary by using the life-cycle assessment method for evaluation in Chapter 4 for the scenario studies.

The typical process flow of fly ash based geopolymer cement production and the identified boundary for LCA ISO 14040 are shown in Figure 2.9 and Table 2.6. The cradle-to-cradle is fly ash based geopolymer cement that provides the same conditions for the cement manufacturing options evaluation in Chapter 4. In addition, this cement factory consists of raw material stores, vertical mill, sodium hydroxide chemical tanks, mixer, silos and a material handing system. The plant is capable of producing 0.1 million tonnes of fly ash based geopolymer-based cement each year, with 24-hours-a-day, seven-days-a-week operation. One of the raw materials in a liquid state, sodium hydroxide, is outsourced from the nearest factory and is not a factory-owned product. This study identified significant transport-related carbon dioxide emissions because the raw materials were located across Australia, as were clients.

Table 2.6 Cradle-to-Function, Cradle-to-Cradle and Boundary for Fly Ash Based Geopolymer Cement Production

Cradle-to-Function	Cradle-to-Cradle
Transport	
Grinding	
Mixer	
Pack and Silo	Fly Ash based Geopolymer Cement

Boundary of Geopolymer-based Cement Production, Including Fly Ash based Geopolymer cement, Metakaolin-based Geopolymer Cement, etc.

Table 2.6 was developed based on Figure 2.9 by using the life-cycle assessment method, which provided the same production conditions for evaluating geopolymer-based cement, including fly ash based geopolymer cement and metakaolin-based geopolymer cement production for the scenario studies in Chapter 4.

2.2 SUSTAINABLE ASSESSMENT METHODS

2.2.1 LIFE-CYCLE ASSESSMENT, LIFE-CYCLE COST ASSESSMENT AND WHOLE LIFE-CYCLE ASSESSMENT ON ENVIRONMENT

Habert et al., (2010) have defined the term ‘sustainability’ as providing the typical person in future societies with a standard of living, including both material and environmental welfare, at least as high as that of a typical person alive today. However, sustainability is a concept and does not quantitatively measure environmental cost. Thus, most environmental current researchers use the life-cycle assessment and life-cycle cost assessment methods, which are the most popular environmental assessment tools and calculate the environmental and economic costs caused by a product or a service during its entire life-cycle, from the purchase of raw material and components to cost of production and investments to usage, maintenance and waste management (Lin et al., 2009; Shinichiro and Yasushi, 2006; Ortiz et al., 2009; Neale and Wagstaff, 2007; Reenaas and Helge, 2012; Sandin et al., 2013; Weil et al., 2010, Feiz et al., 2011 and Palle, 2014). Each method consists of four stages to evaluate the whole life cycle and cost of sustainability: the goal, boundary and scope stage, the inventory stage, the life impact assessment stage and the interpretation stage (Habert et al., 2011; Chan et al., 2015).

Numerous researchers, including Turner and Collins (2013), Sandin et al., (2013), Huntzinger and Eatmon (2009), Zhang et al., (2014) and Yellishetty et al., (2011), have also used life-cycle assessment to study ordinary Portland cement based concrete production. The results show greater environmental effects, particularly in terms of carbon dioxide emissions. Shapiro (2001) has used life-cycle assessment to identify the environmental effects resulting from a product, process or activity, but this assessment did not directly relate to the cement and construction industries and only applies the life-cycle assessment method to an environmental impact assessment.

Li et al., (2009) have combined life-cycle cost and life-cycle assessment, which serves two purposes: to assess environmental and financial costs in one quantitative assessment. Ammenberg et al., (2014) has also used a similar integration of the two methods. The work of both Li et al., (2009) and Ammenberg et al., (2014) does not relate to the cement and construction industries and also relies on expensive, well-known environmental software to carry out calculations. Thus, this successful integration of assessment methods only indicates carbon dioxide emission reduction improvements are needed to make better environmental effects in a cement manufacturing process without any extra costs and also enrich the database system at an inventory stage, and defines strategic management decisions for new production development. In this research, the spreadsheet-based method, derived from fundamental environmental theory, was used to complete the calculations; this is illustrated in Chapter 5.

In addition, to life-cycle cost assessment in transport asset, the New South Wales Transport Asset Standards Authority has also used the International Infrastructure Management Manual (2006), the AS/NZS 4536:1999 and the TAM04-10, which were developed by the New South Wales Treasury Total Asset Management (TAM) - Life-Cycle Costing; the TS 10504:2013, which was developed by the Australian Engineering Office Guide to Engineering Management; and ISO 15686-10 (Building and Constructed Assets) - Service Life Planning, the methods of which provide the guidelines for transport-related sustainability considerations in Australia generally. All of the guidelines mentioned in the previous paragraph, its method provides a comprehensive list for assessments, including cost of drivers, cost elements, dependability date and lifespan and demolition costs. All costs and savings can then be being directly compared and fully informed decisions made.

The New South Wales Transport Asset Standards Authority's life-cycle cost formula adds up capital cost, lifetime operating costs, lifetime maintenance costs, disposal costs and residue value. However, this method is only used for transport and is only part of assessing civil infrastructure sustainability and cement production. Meanwhile, the Australian National Audit Office (2015) has also developed a life-cycle cost for measuring the performance of the Department of Defence in accordance with the authority contained in the Auditor-General Act 1997. The purpose of this document in terms of life-cycle cost is to present a technique for estimating the total cost of ownership of an asset over its lifetime and to assist decision-makers (e.g., government officials) with reaching more informed decisions concerning asset management. The life-cycle cost analysis method is used in the areas of major capital equipment for facilities and minor capital and administrative acquisition within the Department of Defence. This life-cycle cost method covers three major areas and consists of seven stages:

(a) Capability proposal stage: in the Department of Defence, this is carried out by preparing capability proposals seeking to acquire major defence equipment. Indeed, defence policy calls for the use of life-cycle cost at all major decision points throughout the material cycle, including the capability proposal stage.
(b) Acquisition stage: this consists of initial planning leading to preparation of a request for a tender or similar document, followed by tender selection and contract negotiation. At the acquisition stage, a reasonable estimate of the total cost of ownership of a capability is possible.
(c) In-service stage: during the in-service stage, life-cycle cost can be used to optimise arrangements for logistic support and to identify systems or components that become expensive to support and should therefore be modified or replaced.
(d) Facilities stage: the department has sometimes used life-cycle cost to assist in making decisions on the acquisition of land, buildings and other facilities.
(e) Administrative acquisition: the department has also applied the principles of life-cycle costing to acquiring administrative equipment, such as photocopiers.
(f) Data and model stage: the two major requirements for applying life-cycle cost are readily accessible data in an easy-to-use format, and suitable models, techniques and methodologies to analyse the data.
(g) Budgeting stage: the department has processes that allow operating cost variations to be incorporated in the future budget (Australian National Audit Office, 2015).

The, Australian National Audit Office (2015) also redeveloped the life-cycle cost method to assist managers responsible for decisions regarding acquisition, owning, operating and using major assets or products, such as buildings, vehicles and major plants. This life-cycle cost standard defines it as the process of assessing the cost of a product over its life-cycle or portion thereof. Considering the costs of the whole life of an asset provides a sound basis for decision-making. With this information, it is possible to do the following:

(i) Assess future resources requirements (budgeting).
(ii) Assess comparative costs of potential acquisitions (investment appraisal).
(iii) Decide between sources of supply (source selection).
(iv) Account for resources used now or in the past (reporting and auditing).
(v) Improve system design.
(vi) Optimise operational support.
(vii) Assess when assets each reach the end of their economic life and replacement is required (disposal).

These two life cycle cost and life cycle assessment methods are used in different ways: at the Department of Defence, the process is to conduct the just life-cycle cost assessment before submitting tenders to suppliers. However, the objective of the Australian National Audit Office (2015) considers the domestic cost of a product’s lifelong operation, regardless of suppliers and tenders. Another difference of the life-cycle cost method for the Department of Defence is the seven stages, which ensure that tenders provide environmentally friendly products environmentally friendly products with targeted cost. Australia and New Zealand have also developed an AS/NZ 4536:1999 or ISO 14045:2010 for life-cycle cost assessment. These two methods can be used for both private and public sectors. The core principle of these two methods is to estimate the total cost of asset ownership over a lifetime and provide sufficient financial information regarding the facilities cost to decision-makers, allowing them to reach more informed decisions regarding the acquisition and management of assets. In this literature review, both life-cycle assessment and life-cycle cost assessment can be shared environmental effects in production and cost data (Horath, 2004; Ibbotsun and Karra, 2006, Li et al., 2014; Le et al., 2009; Marceau et al., 2004; Nakamura, 2007; Nisbel et al., 2002) by using the common life cycle database at the inventory stage (McLellan et al., 2011; Li et al., 2009). Although two well-known life-cycle cost methods were launched in the Australian market in early year of 2,000, the New South Wales Transport Asset Standards

Authority has also developed another life-cycle cost method for transportation facilities asset management. The elements of this method are capital cost, maintenance cost, operational cost, disposal cost and residual cost. The life-cycle cost is obtained as follows:

Life Cycle Cost (LCC) = I + Repl – Res + E + W +OM&R + O

where

LCC = Total LCC in present value (PV) dollars of a given alternative
I = PV investment costs (need not be discounted if incurred at base date)
Repl = PV capital replacement costs
Res = PV resident value (resale value, salvage value less disposal costs)
E = PV of energy costs
W = PV of water costs
OM&R = PV of non-fuel operating, maintenance and repair costs
O = PV of other costs (e.g. contract costs)

Madlool et al., (2012) have also used Total Material Requirement (TMR) with Energy - Mass Analysis (ExMA) methods to collect carbon dioxide emissions data in electricity power production. This provides a best pre-requisite situation for building the inventory and making the life-cycle assessment and life-cycle cost in a fruitful, as in beneficial situation. Meanwhile, Chan et al., (2015) have used the AS/NZS 4536:1999 and ISO 14040 methods to develop extended life-cycle cost (ELCC) to compare ordinary Portland cement and fly ash based geopolymer production. This method adds lifelong manufacturing cost and lifelong material cost to eliminate facility items, and assumes no deprecation rate and that all production facilities are in good conditions through the production cycle. This is a pioneer method by using extended life-cycle cost to measure the whole-life-cycle cost of cement production and this method outcome result is promising due to same result of well-known environmental tool calculation (Chan et al., 2015). But this method needs to collect a big data to support the calculation. Additionally, It also offers a clue about building the function of the equation in the linear programming equation, seeking optimisation of three areas. This is discussed in Chapter 4.

The Whole Building Design Guide (WBDG, 2016) is one of the alternatives of the life-cycle cost analysis and is a web-based guide of design objectives for the sustainable built environment. It is a method for assessing the total cost of facility ownership, and also provides the lowest overall cost of ownership consistent with its quality and design function of buildings and building systems; it quantifies these effects and expresses them in dollar amounts. This method also only works early in the design process, as the result estimates of costs and savings are available based on sensitivity analysis and break-even analysis outcome results. However, this method does not consider raw material costs, such as for cement, sand and limestone and life-cycle cost in building design. Le et al., (2009), Marcus et al., (2005) and Lin et al., (2009) have also used life-cycle assessment and life-cycle costing to assess to conduct the environmental effects and costs assessment with the assistance of Gabi software. The main advantages of this combination could be assessing the environmental effects and life-cycle costs in one single assessment, and also enriching database system in Gabi software and data sharing with another environmental assessment tool. Identifying each cost driver related to the activities within the defined boundaries and function units was the major challenge of this integration because of the time scale in the inventory phase. Yang et al., (2014) have used current life-cycle assessment method with the Korean life-cycle index to resolve this issue by using a reliable data sources from Japanese Civil Engineers life-cycle database system to assess the carbon dioxide emission in cement production.McLellan et al., (2011) also transferred Australian cement carbon footprint production data such as context, carbon dioxide emission in cement production, energy used, raw materials cost per unit in the specific region, quantities used and so on to an Eco-invent life-cycle database. The purpose of this data immigration is to quantify the range of potential costs and effects in Australia’s cement and concretes industries. Further, this database system is able to link with the World Sustainable Business for Development Council inventory system, providing an idea of the overseas carbon dioxide emissions standard (Yang et al., 2014). Further, the whole-life-cycle cost for the Commonwealth Property Management Guide offers advice about the use of whole-life-cycle cost-estimating process for capital works projects and cost-benefits analysis (Milburn et al., 2006). This process life consists of two steps:

(a) Step 1: define the cost elements.
(b) Step 2: estimate the cost, including capital and acquisition costs, initial estimate (first stage) and detailed estimate (second stage) costs.

This method is similar to that of AS/NZS 4535:1999. However, whole-life-cycle cost uses sensitivity analysis to the estimate lifelong cost. The life-cycle cost commonly used in the Australian stainless steel industry (Le et al., 2009; Li et al., 2014; Marcus, 2005;

Nakamura, 2007; May and Brennan, 2003; Lin et al., 2009) has the ability to provide positive long-term performances with a minimum downtimes and maintenance costs (Australian Stainless Steel Development, 2016). Further, the whole-life-cycle cost is an alternative tool for conducting the life-cycle cost assessment. The procedure is the same as for life-cycle assessment, including goal and boundary, inventory, interpretation (e.g. methodology) and recommendation (Milburn et al., 2006). Chapter 5 discusses this further.

2.2.2 CARBON DIOXIDE EMISSION CALCULATION METHODS

The production of ordinary Portland cement involves serious collateral environmental effects, such as environmental pollution caused by dust and enormous energy consumption (Yang et al., 2014), and releases significant amounts of carbon dioxide into the atmosphere. It is one of the world's largest industrial sources of carbon dioxide emission, accounting for 1.6Gt / year in 2005 (Barker et al., 2009; Habert et al., 2011). It is an interesting question how to measure carbon dioxide emission throughout the manufacturing processes of the cement industry. By conducting a review of the literature, this study has identified several key methods of calculating carbon dioxide emissions, which are discussed in the next section.

2.2.2.1 Carbon Dioxide Emission Equivalent Method

The Carbon Dioxide Emission Equivalent (CO_2-e) method is the standard unit of measurement, which is adjusted to include the effects of other greenhouse gas emissions from the same fuel or process that contribute to global warming effects. Calculation of CO_2-e is based on the collective contributions of carbon dioxide, methane, nitrous oxide and synthetic gases emitted during each activity, taking into account the energy content of the fuel, the global warming gas types produced, and the respective gas global warming potential. When the fuel is fully combusted, the carbon dioxide emission equivalent is equal to the quantity of fuel combusted to undertake a particular activity (kg) multiplied by the emission factor and global warming potential (Turner and Collins, 2013). Huntzinger and Eatmon (2009) used the Carbon Dioxide Emission Equivalent and life-cycle assessment methods with the assistance of well-known environmental software to study the carbon dioxide emission of cement production. This research used different approaches by using fundamental environmental theory including life-cycle cost and life-cycle assessment, along with data collected in Australia to conduct carbon dioxide emission assessment in cement production.

2.2.2.2 Australian National Greenhouse Accounts Factors Method (2014 to 2016)

The Australian Government has also developed the Australian National Greenhouse Factors Accounts (2014 to 2016), an environmental assessment tool to measure how much carbon dioxide is emitted by the whole industry in Australia. Some useful features of the Australian National Greenhouse Accounts Factors (2014 to 2016) method are the measurement of carbon dioxide emission in cement production including lime from limestone, purchased electricity and transport, etc. The detailed calculations of the Australian National Greenhouse Accounts Factors (2014 to 2016) method will be discussed in Chapter 3 - Methodology. Chapter 4 is based on selected equations from Chapter 3 from the Australian National Greenhouse Accounts Factors (2014 to 2016) method to develop the 'subject to function' equation, which is the first part in a linear programming equation for scenario studies for carbon dioxide emission in transport. The Carbon Dioxide Emission Equivalent method is an alternative source to develop the 'subject to function' for another scenario study. The others, 'subject to constraints' are the same equations under the same cement production environment. Both scenario outcome results would be expected to provide information about which method is more flexible and efficient to evaluate carbon dioxide emission under the same cement production environment

To construct the linear programming equations based on the Australian National Greenhouse Accounts Factors (2014 to 2016) method, a preliminary factor is that an equation involves measuring the carbon dioxide emissions of cement production in more detail than the Carbon Dioxides Emission Equivalent method. This is because this method is also very clear on how to calculate carbon dioxide emission with respect to transport, limestone production and the purchase of electricity, and requires more data support calculation including dust quantities and kiln size.

To meet this requirement, primary and secondary data will be collected from related sources such as literature, the Australian Bureau of Statistics (2014 to 2016), Companies A to C (2014 to 2016), surveys and so on. Further discussion is in Chapter 4. Carbon Dioxide Emission Equivalent and Australian National Greenhouse Accounts Factors (2014 to 2016) were discussed in this section. The World Business Council for Sustainable Development Method will be discussed in the next section.

2.2.2.3 World Business Council for Sustainable Development Method

The World Business Council for Sustainable Development (WBCSD) and World Resources Institute have developed the Greenhouse House Gas (GHG) Protocol for corporate standards, which is the most widely used international accounting tool for governments and business leaders to understand and quantify carbon dioxide, and manage greenhouse gas emissions (Theodosious, 2010). The WBCSD method can also be combined with other methods, including the Carbon Dioxide Emission Equivalent (Turner and Collins, 2013; Theodosious, 2010) method, Australian National Greenhouse Factors Accounts method (2014 to 2016), and so on. Therefore, the Carbon Dioxide Emission Equivalent method and the Australian National Greenhouse Accounts Factors (2014 to 2016) are the main methods of carbon footprint calculation in this research.

This research has identified several carbon dioxide emission measuring tools for different regions, and a considered evaluation will be given at the end of this chapter. The expected outcomes will be used for Chapters 3 and 4.

2.2.3 NATURAL RESOURCES DEPLETION

2.2.3.1 Natural Resources for Ordinary Portland Cement and Geopolymer-Based Cement

Cement production, which is highly dependent on the availability of natural resources, will face severe resources constraints in the future (Gao et al., 2009) in China. The need for a sustainable trade-off between cement production and natural resources consumption is an increasingly important global issue (Habert et al., 2013). In 2011, world cement production was approximately 3.3 to 3.8 billion metric tonnes (USGS, 2012) in clinker and correspondingly more than 3.00 billion metric tonnes of limestone was consumed in cement production (Schneider et al., 2011) and 5.4 billion metric tonnes of raw materials were consumed globally for cement production. The production of one tonne of Portland cement requires 1.5 tonnes of raw material including clay, sand, slag and lime (Gani, 1997). China produced 1.06 billion metric tonnes of the cement in 2011 and 75% were ordinary Portland cement (USGS, 2012). The major constituent of ordinary Portland cement is limestone, and its deposits will be depleted in 59 years (USGS, 2012). In 2014, the cement industry in Australia produced around 9.1 million metric tonnes (Cement Industry Federation, 2013), meaning that it consumed 13.65 million metric tonnes of raw materials. Therefore the aim of this study is to review the distribution of raw materials for ordinary Portland cement and the geopolymer-based cement industry, investigating the sustainability of this industry and of exporting these materials to other countries to earn currency. Feedstock, sources and locations for ordinary Portland cement, ordinary Portland cement with supplementary cementitious materials and fly ash geopolymer-based cement manufacturers are shown in Figure 4.7. The majority of fly ash sources are from coal-fired power stations in Queensland, because of the presence of many coal-fired power stations were along the coast and rivers. Therefore, it is necessary to deliver fly ash by ship or heavy vessel to the cement factories as shown in Figures 4.6 and 4.7. However, slag is located in the southern part of Australia because most iron refinery companies are located close to the feedstock in order to reduce transport operation costs and the carbon dioxide emissions of vessels. Sand and gravel are distributed throughout Australia. From Figure 4.7, it can be seen that the three major cement factories are in the southern part of Australia, and no major factory operates in the Northern Territory. This is because cement factories are normally located as close as possible to raw materials suppliers such as limestone quarries, to reduce transportation fees and carbon dioxide emissions. Natural resources depletion in Australia is considered state-by-state. To avoid paying extra carbon tax or slow down the speed of depletion and buy cheaper raw materials from the international market, some raw materials are imported. The total cement and clinker produced in Australia were 9 million tonnes and 6 million tonnes respectively in 2013 to 2014, representing a turnover of A$2.3 billion (Australian Cement Industry Statistics, 2014). It was a significant source of air pollution and associated climate change issues.

The demand for natural resources for the cement industry has increased so much that it has been widely considered a serious threat to our economic and social equilibrium (Barbier, 2012) for several decades. It is also associated with environmental problems such as climate change, biodiversity loss, and ecosystem degradation (IPCC, 2007). Depletion is an accounting method that companies use to allocate the cost of extracting natural resources, unlike depreciation and amortisation, which mainly describe the deduction of expenses due to the ageing of equipment and depletion as a cost recovery system for accounting and tax reporting.

There are two types of depletion; cost depletion and percentage depletion (Habert et al., 2010). Cost depletion is a way of accounting a calculation of cost incurred by the extraction of natural resources, including abiotic and biotic materials. The percentage of depletion is uses either one or two accounting methods to calculate the gross income derived from extracting fossil fuels and minerals, etc. (Diaz and Harchaoui, 1997). Guinée (2002) used abiotic depletion indicators, energy and mineral assessment for evaluating minerals including sand, gravel or lime and energy resources. Turner and Collins (2013) also studied the value of natural resources, in an approach designed to take more account of a rational decision of ecosystem conservation versus development, involving different stakeholders, than a purely economic cost-benefit analysis. Bartlett (2006) also used integrated natural resources into national accounts and used a microeconomic model to gain insights into how to evaluate depletion in practice. Habert et al., (2010) used a midpoint method, CML2001 (Guinée, 2002), to evaluate French resources and compared them with American mineral stock based on indicators methods. However, different countries have their own mineral reserves and one cannot make assumptions about one country on the basis of another. These indicators only provide series referral information regarding a shortfall in certain minerals for the cement industry in the coming year, and these may be either imported from other countries or sought in new domestic sites to meet the demands of the market.

Domestic material consumption (DMC) is derived from the total amount of materials directly used in the economy (e.g., domestic extraction plus imports), minus the materials that are exported (Lothenbach et al., 2010). Schandl and West (2010) have pointed out that the domestic material consumption in the Asia-Pacific region from 1975 has been increasing since 1975. Schandl and West (2010) in their report further analysed which countries were the fastest growing in the consumption of domestic materials per capita for the Asia-Pacific region and its constituent sub-regions for 1975, 1990 and 2005, calculated in tonnes per capita as shown in Figure 3.1 and Table 4.9. In addition, in the past three decades, China’s economy has experienced huge growth (Zhang et al., 2014). Australia and New Zealand took advantage of this opportunity, generating significant income, but consequently causing a natural resources depletion issue. Although Figure 3.1 does not show very recent statistical information, it covers 30 years of domestic materials consumption data in the Asia-Pacific region and is still useful to develop a scientific model for the prediction of a domestic materials consumption model for the coming years (Marcos et al., 2013, Grcar, 2011 and 2012; Harnett and Horrell, 2013; Ragsdale, 2007) by using traditional mathematical methods, including time-series for regression model and the seasonality ratio method (Copeland, 2013; Lafare et al., 2016). Further details of the calculation methods will be discussed in Chapter 3. The expected outcome of this ratio result (Ragsdale, 2007; Harnett and Horrell, 2013; Lafare et al., 2016) was to develop a forecast model for domestic material consumption and reserves (Habert et al., 2010). Chapters 4 and 5 will discuss this further.

Natural resources can be divided into biotic and abiotic categories. Raw materials for cement are classified as abiotic materials, and the abiotic depletion indicator is expressed in kilograms with respect to the reference of Antimony (SB) molecular weight (Guinée et al., 2002), which is a chemical element with the symbol SB and atomic number 51. The operation of this formulas is based on the multiplication of the abiotic depletion potential (ADP_i) of resources I with m_i, the mass of resources i used, ADP_i is calculated with extraction rate and (ADP_i) with m_i, the mass of resources i used, ADP_i is calculated with extraction rate and ultimate resource i. This study is concerned with collecting the extraction rates in data from only three of the major quarries and cement companies around Queensland.

Harris and Fraser (2002) also developed an economic production mathematical model, which considered only capital, production cost and natural resources, including renewable and non-renewable natural resources costs, generating an optimal control of economic growth and neutral resources depletion (NRD) in the defined region. But this economic production model does not consider labour costs or inflation rate variation from country to country, and considers the whole-life-cycle as remaining constant. This research has extended the investigation to the whole-life-cycle to assist the evaluation of natural resources depletion.

2.2.4 COST ANALYSIS

Cost is the spending a business incurs for items closely associated with production (Lasher, 2013). Harris and Fraser (2002) used natural resources accounting to identify cost but they used microeconomics approaches, which is used by the Bureau of Economic Analysis, calculating the current per unit rent of resources times the number of units of depletion. Humphrey et al., (2012), Fatemi and Fooladai (2013) also studied sustainable finance, cost and transaction costs in environmental policy, in which all social, environmental costs and benefits are explicitly accounted for. But they did not focus on natural resources for cement and concrete cost analysis. Porwal and Kreuzer (2010) have studied the relationships between economic growth, natural mineral resources, social, political and an environmental cost effect. However, results were very difficult to interpret because of the need to balance each aspect to calculate sustainable costs such as the extraction costs for natural resources for the cement and concrete industries. Serafy (1999), Smith (1974) and Collins (2013) also studied green accounting approaches to estimate and analyse the natural resources depreciation of Australia's non-renewable resources. However, raw materials for cement production are abiotic, and some of them are by-products, including slag and fly ash etc., so this method does not directly relate to this research. The AS/NZS 4536:1999 or ISO 14040 developed a life-cycle cost assessment (LCCA) method including defined acquisition cost, base date, cost driver, cost element and dependability for scientifically evaluating a product or service based on the life-cycle assessment method, which was discussed in Section 2.2.1. Numerous researchers have used different methods to perform cost analysis but none of them is specifically related to the cement industry while identifying cost drivers to conduct a life-cycle cost or whole-life-cycle cost assessment for cost analysis and estimation. This is because there are so many uncertain costs, including sunk cost, inflation rates, environmental costs and policies, raw materials costs and tax, etc. in the lifelong period. These kinds of factors would affect the whole-life-cycle cost outcomes results.

To solve this issue, Horngren et al., (2005) provided several possible cost analysis and estimation methods including an industrial engineering method, conference method, account analysis method and quantitative analysis method, examining the events for different situations, industries and countries. The method is outlined below.

(a) The *industrial engineering method,* also called the work measurement method, estimates cost functions by analysing the relationship between inputs and outputs in physical terms.

(b) The *conference method* estimates cost functions based on analysis and opinions about costs and their cost drivers gathered from various departments of a company.

(c) The *account analysis method* estimates cost functions by classifying various cost accounts as variable, fixed or mixed with respect to the identified level of activity. The account analysis approach is widely used because it is reasonably accurate, cost effective and easy to use.

(d) The *Quantitative analysis method* uses a formal statistical mathematical method to fit cost function to pass data observation. It uses three types of data: primary data, secondary data from literature, and annual financial reports and Australian Bureau of Statistics etc. to develop time-series for regression models etc. Based on the outcome of a plot graph, this type of study can examine the inter-relationship between cost resources and carbon dioxide. This research also adapted and extended the method used by Horngren et al., (2005), which was illustrated in Chapter 4, Section 4. 4.

(e) The *regressive analysis method of quantitative analysis* uses all available data to estimate the cost function. Regressive analysis is a statistical method that measures the average amount in the dependent variable associated with a unit change in one or more independent variable. There are two types of regressive analysis: simple regressive and multiple regressive analyses.

  (i) Simple regressive analysis estimates the relationship between the dependent variable and one independent variable.

  (ii) Multiple regressive analysis estimates the relationship between the dependent variable (such as ordinary Portland cement or fly ash based geopolymer cement) and two or more independent variables. The time-series for the regressive model will be discussed in Chapter 4.

The type (e) method above is one of the solutions from Horngren et al., (2005) to solve the issues discussed previously. This is because a lot of data would need quantitative analysis and cost estimation in this research. For example, raw materials may be considered independent variables, including limestone, clay, sand, gypsum, slag, sodium hydroxide (NaOH), potassium hydroxide (KOH), fly ash, etc., which are the major raw materials to make cement, may be treated as dependent variables. One of the solutions to discover the relationship is by using a spreadsheet-based statistical method, which will be discussed in Chapter 4. Another purpose of this method of providing information to develop linear programming equation (Lai and Chen, 1996) is by probing further cement production performances by using Solver®. One of the reports available from Solver® is a sensitivity analysis report (Sarkar et al., 2012; Ali and Sik, 2012; Boyer and Ponssard, 2010), which evaluates three areas: maximising mix production, minimising natural resources depletion and carbon dioxide emission in manufacturing cement performances. A time-series for regression model and seasonality indices to forecast future natural depletion and the correct ratio of supplementary cementitious material to ordinary Portland cement and what kind of fuel in cement production to reduce carbon dioxide emission was also based on this method. Regarding the study of costs relating to energy, Hasanbeigi et al., (2010) developed the conservation supply curve (CSC) and the carbon dioxide abatement cost curve (ACC) to evaluate cost effectiveness for the cement industry. This method uses the energy-related CO_2 tax based on the outcomes of the CSC and ACC, but the method was developed to suit cities in Thailand, and different countries have different energy supply policies. Schneider et al., (2011) and Utlu et al., (2006) also identified that cement grinding, raw material grinding and clinker processes intensively use energies; this is one of the major costs of cement production and emits considerable carbon dioxide, causing material depletion issues. O'Brien et al., (2009) and McLellan et al., (2011) quantified greenhouse gas emissions and costs with water embodied in concrete as a function of fly ash content to determine the critical fly ash transportation distance, beyond which the use of fly ash in concrete increases embodied greenhouse gas emissions. Alroomi et al., (2012) and Horngren et al., (2005) have used cost estimation methods and cost analysis for construction projects. This method is used in America and may not suitable for Australian business environment. Additionally, cost estimation is only suitable for short-term cost assessment of construction infrastructure and is different from life-cycle cost (Li et al., 2014); life-cycle costs are important because some effects such as carbon dioxide, energy and environment and so on would have considerable lifelong effect costs.

2.2.5 LINEAR PROGRAMMING EQUATION

Linear programming equation is one of the available tools to provide the optimal solution (Lawrence and Pasternack, 2014; Rehman and Asad, 2008; Lai and Chen, 1996) to users. Li et al., (2014), Loijos et al., (2010), Marcus (2005) and Sherris (2009) have successfully applied this tool for the optimisation of different industries. However, few current researchers have used this tool for cement and concrete manufacturing management for cement options. . Linear programming equations consist of subject to function and subject constraints, which involve a large amount of data and equations (Messner et al., 1996; Marcus et al., 2003) and a higher level of mathematical skill including statistics, linear algebra and matrices knowledge (Grcar, 2011 and 2012; Gass, 2002). By using the Gauss-Jordan elimination (Grcar 2011 to 2011) method with the assistance of a spreadsheet (Excel® with Solver® and XLMiner Analysis ToolPak®)

problems can be solved in an efficient manner. This study has adapted and extended the theories above and used them in the research process with the aim of discovering how to maximise profit, and minimise natural resources depletion and carbon dioxide emission.

2.3 COMPARISION AND SELECTED ALTERNATIVES

Many methods were identified in the literature review. The aim of the section was to select the best alternatives.

2.3.1 COMPARISION ALTERNATIVES

This study illustrates numerous examples of research in three areas: carbon dioxide emission, natural resources depletion and financial effect, as shown in Tables 2.5 to 2.8. The 'spade' symbol presents their contribution in three areas. The role of each table is as below:

(a) Table 2.5 lists factory operational methods, including cement facilities and cement structure in both American and Chinese factories.
(b) Table 2.6 lists the CO_2 calculation and methods of driving down CO_2.
(c) Table 2.7 lists natural resources depletion and CO_2 calculation methods.
(d) Table 2.8 lists the natural resources depletion calculation and financial effect measure.

Different nations have used various cement facilities and methods to produce ordinary Portland cement and fly ash based geopolymer cement as shown in Table 2.6, which provides an opportunity for a comparison, adaptation and extension of their methods for this research.

In short, most of them were focused on financial effect, including the costs and profits of cement production. It was seldom a priority to discuss natural resources depletion, optimisation, sensitivity analysis and carbon dioxide emission in the cement production processes. There is therefore an opportunity to fill this gap by adapting and extending those researchers' methods to evaluate cement production in Australian cement factories.

Australia and New Zealand have their own cement production styles, facilities, characteristics, natural resources distribution and regulations including Cement Standards such as AS 3972:2010 - NZS 3122:2009 (Australian Bureau of Statistics, 2015). In the literature review, Figures 2.6 to 2.9 and Table 2.4 are identified the typical cement manufacturing boundaries because of the self sufficiency of cement production in Australia such as facilities, raw materials and so on. The next section discusses what the current research achieves in three areas and selects the right alternatives that are:

Table 2.7 Cement Production Methods from Literature

Sources	**Methods**	**Three Areas**		
		CO_2 Emission	NRD	Financial Effect
Gani (1997)	Studied cement production in England			♠
Peray (1979)	Studied cement production in America			♠
Valderrama et al., (2012)	Used life-cycle assessment method for carbon caption in cement production in America	♠		
Cement Industry Federation, Australia (2014)	Reviewed cement production and operation in Australia	♠		
Weil et al., (2009)	Used life-cycle assessment method to study geopolymer structure and production method in America	♠		
Copeland A. (2013)	Used seasonality method to develop price with assistance of well-known software			♠
Xu et al., (2015)	Used statistical method to study the cement production in China.	♠		♠

Legend

🟩 Concerned only financial effect

🟧 Concerned carbon dioxide emission in cement production

🟥 Concerned carbon dioxide emission and financial effect in cement production

🟥 Concerned natural resources depletion

🟨 Concerned natural resources depletion and financial effect in cement production

Numerous researchers have used the Carbon Dioxide Equivalent method, as shown in Table 2.5. This table uses a 'spade' symbol within red, purple and pink boxes to measure the quantities of carbon dioxide emission in their field studies of cement production in a number of nations. The Australian National Greenhouse Accounts Factor and World Business Council for Sustainable Development methods are seldom used to conduct carbon dioxide emission evaluation. In addition, some researchers have used well-known environmental and expensive software to assist them to conduct their research building the life-cycle inventory for life-cycle assessment, but different countries have their own environmental and accounting standards. Their life-cycle inventory data results are for referral data. Further, the majority of articles related to carbon dioxide emissions discuss only the concrete industry. So, there is an opportunity for this study to use fundamental theory or equations with the assistance of cheaper and reliable software, like spreadsheet version 2013 with Solver®, to conduct calculations, seeking sensitivity analysis in cement production.

Table 2.8 Calculation CO_2 Emission Methods from Literature and Australian National Greenhouse Accounts Factors (2014 to 2016)

Sources	**Methods**	**Three Areas**		
		CO_2 Emission	NRD	Financial Effect
Davidovits (1993)	Invented fly ash based geopolymer to reduce CO_2 emission.	♠		
Duxson and Provis (2008)	Announced MK-based geopolymer emitted less CO_2 compared with other types of cement production.	♠		
Nogoeirra et al., 2010	Used CO_{2-e} method to quantitatively measure CO_2 emission in cement industry.	♠		
Huntzinger and Eatmon (2009)	Used CO_{2-e} method to quantitatively measure CO_2 emission in cement industry.	♠		
Habert et al., (2010)	Used life-cycle assessment methods.	♠		
Zhang et al., (2014)	Used CO_{2-e} method to quantitatively measure CO_2 emission in cement industry.	♠		

Table 2.9 Calculation CO_2 Emission Methods from Literature and Australian National Greenhouse Accounts Factors (2014 to 2016) (Continuous)

Sources	**Methods**	**Three Areas**		
		CO_2 Emission	NRD	Financial Effect
Turner and Collins (2013)	Used CO_{2-e} method to quantitatively measure CO_2 emission in cement industry.	♠		
Yang et al., (2014)	Use CO_{2-e} method to measure CO_2 emission.	♠		
Australian National Greenhouse Accounts Factors (2014) Method	Based on Australia cement environment to redeveloped Australian Greenhouse National Account Factors to estimate CO_2 emission.	♠		
Huntzinger and Eatmon (2009)	Used LCA methods to study cement manufacture.	♠		
Ishak and Hashim (2015)	Used low carbon method to measure cement plant.	♠		
ISO 14040 (2014)	Used LCA.	♠		
World Business Council for Sustainable Development (2014)	Greenhouse Protocol including life-cycle assessment method and also able to link with another environmental tools database systems to quick assess CO_2 emission in cement production.	♠		

Table 2.10 Calculation CO_2 Emission Methods from Literature and Australian National Greenhouse Accounts Factors (2014 to 2016) (Continuous)

Sources	**Methods**	**Three Areas**		
		CO_2 Emission	NRD	Financial Effect
Chan et al., (2015)	Developed and used extended life cycle costing based on life cycle assessment method	♠		
Zhang et al., (2014)	Used life-cycle carbon footprint measurement OPC and concrete.	♠		
Lafare et al., (2016)	Used seasonal trend based on life-cycle method	♠		
Marcos et al., (2013)	Developed prediction recession with linear dynamic harmonic regression	♠		
Tunstall (1992)	Developed environmental indicators	♠		
Khanrel and Cao (2015)	Developed Gaussian-Jordan Elimination (Grcar, 2101 and 2012) method to solve algebra equations	♠		

Table 2.7 illustrates with the ‘spade’ symbol that numerous researchers from different nations have used different methods to conduct natural resources depletion studies. Researchers such as Habert et al., (2010) and Guinée (2002) have used abiotic depletion potential and advanced software to conduct natural resources depletion assessment in France. This study will adapt and extend Habert et al., (2010), based on the fundamental theory with the assistance of life assessment to conduct the research because their methods related to cement and construction industries.

Table 2.11 Calculated NRD Method from Literature

Sources	**Methods**	**Three Areas**		
		CO_2 Emission	NRD	Financial Effect
Guinée (2002)	Used abiotic depletion to measure natural resources.	♠		
Burghes et al., (2006)	Developed a mathematical model to measure the natural resources depletion and economics.	♠		
Schandl and West (2010)	Used statistical methods measure resources.	♠		
Boesch and Hellwegh (2010)	Used social equilibrium methods to measure NRD.	♠		

Table 2.12 Calculated NRD Method from Literature (Continuous)

Sources	Methods	Three Areas		
		CO_2 Emission	NRD	Financial Effect
Barbier (2012)	Used economical methods to measure the natural resources depletion with respect to currency.		♠	
Habert et al., (2013)	Based on LCAI to develop abiotic depletion, resources exhaustible and abiotic depletion potential methods to measure natural resources depletion and compared with France and America cement industries.		♠	
Van Oers et al., (2002)	Used LCA methods and abiotic resources depletion methods to study Dutch industry.		♠	
Yellishetty et al., (2011)	Used LCA and abiotic resources assessed the steel industry.		♠	
Grcar (2011 and 2012)	Solving linear programming problems using Gaussian-Jordan Elimination method.		♠	

Table 2.8 group natural resources depletion and financial effect measure methods. These studies identified life-cycle assessment and life-cycle cost, and linear programming methods were used in their research. This provides an opportunity to adapt and extend their analysis with respect to cement events to develop a linear programming method with sensitivity analysis skills and using life-cycle costing concepts to conduct the evaluation.

Table 2.13 Calculation NRD Methods Including Financial Effect Measure

Sources	**Methods**	**Three Areas**		
		CO_2 Emission	NRD	Financial Effect
Smith (1974)	Developed a method to measure the relationship between natural resources and environmental effect		♠	♠
Lai and Chen (1996)	Used linear programming to seek optimal cost			♠
Messner et al., (1996)	Used linear programming to seek optimal with respect to cost			♠
Shih (1999)	Used linear programming to seek an optimal solution			♠
Serafy (1999)	Used green accounting method to measure resources depletion cost			♠
Harris and Fraser (2002)	Used microeconomics methods			♠

Table 2.14 Calculation NRD Methods Including Financial Effect Measure (continuous)

Sources	**Methods**	**Three Areas**		
		CO_2 Emission	NRD	Financial Effect
AS/NZS 4536:1999 or ISO 14040	A standard to measure the life-cycle cost			♠
Horngren et al., (2005)	Used cost estimation methods to measure the cost			♠
Brunnschweiler (2008)	Measure relationship of economics and NRD		♠	♠
Sarker et al., (2011 and 2008)	Used sensitivity analysis methods to provide optimal solutions			♠
Loijos et al., (20102)	Used Sensitivity analysis methods to provide optimal solutions			♠
Ali and Sik (2012)	Used Sensitivity analysis methods to provide optimal solutions			♠

2.3.2 SELECTED ALTERNATIVES

Identifying the best alternative for this research was complicated, because numerous researchers in different nations have used different methods to measure carbon dioxide emission, natural resources depletion and financial effect, as shown in Tables 2.7 to 2.10. For example, much of the literature has used the Carbon Dioxide Emission Equivalent method to measure carbon dioxide in cement production, but Australian National Greenhouse Accounts Factors (2014) has also developed another method, including kiln, transport, limestone, electricity (energy) consumption, and so on, to measure carbon dioxide emission within the defined boundary of the manufacture of cement. World Trade Sustainability and Development also developed a set of methods to measure carbon dioxide emission based on the life-cycle assessment and life-cycle cost methods, which could link with various database such as the American Eco-coin (McLellan et al., 2011) and a database from Japanese Civil Engineers Association, a life-cycle inventory from life-cycle assessment to provide carbon dioxide emission data. But these data sources are from different industries, different regions and using different calculation methods, including environmental calculation software, etc., and do not unique in the database system in inventory stage for life-cycle assessment. To close this gap, one of the solutions is to base research on these methods, but to adapt and extend them to use in this research within defined boundary. In Chapter 4 this will be discussed in detail.

Linear programming and sensitivity analysis are the best methods to evaluate the three areas under the same conditions. This is because the linear programming method can provide flexible equations and data to provide an optimal solution by using function and subject to constraints equation methods to quantitatively measure each scenario-based event for three areas of production. Formulating this research strategy, an integration of potential methods in a proposal framework is one solution to examine three areas of performance in the cement industry of the Australia and New Zealand region.

Regarding natural resources depletion assessment, several researchers have used different approaches to probe natural resources depletion with respect to cost, environmental issues, rate of depletion and economic growth, etc. However, only Habert et al., (2013) directly focused on the cement and concrete industries by using the abiotic depletion potential method, and they only studied a French region. This provides an opportunity to extend their methods for use in Australia.

There are also several methods to calculate carbon dioxide emission, discussed in the previous section. Different calculation methods would affect data collection strategies to satisfy equation parameters. The aim of Chapter 3 was to develop the Methodology based on the findings of Chapter 2. This Methodology includes linear programming equations seeking optimal solutions for the financial effects of cement production, calculation of carbon dioxide emissions, calculation of natural resources depletion and reserves, and examining the trend of data series, seasonality and forecasting, etc.

2.4 SUMMARY

This chapter has provided a literature review in the areas of cement production, supplementary cementitious material with ordinary Portland cement and fly ash based geopolymer cement. It identified numerous methods of calculating carbon dioxide emission throughout the production processes, methods of calculation of natural resources depletion, methods of solving linear programming equations seeking optimal solutions, including maximising mix production and profits, minimising carbon dioxide emission and consuming less abiotic material, etc., and also life-cycle and life-cycle cost assessments with whole-life-cycle cost. The proposed advanced integrated framework was developed based on this literature to gain better insight into the environment for society and also into the flow of natural resources for the cement industry. Several methods were identified in the literature review, and selection of alternatives was also discussed at the end of this chapter. Only the methods best suited to the research have become part of the advanced proposed framework. Further discussion of the proposed advanced framework, including detailed calculation methods, will be discussed in Chapter 3. This research has also identified several carbon dioxide pollution sources in cement production, as outlined below:

(a) The material itself contains carbon dioxide. Preparing calcium oxide (lime) as heated calcium carbonate ($CaCO_3$), which decomposes into carbon dioxide and lime once heated to 1400°C to 1500°C.

(b) Temperatures are elevated with the kiln system, including pre-heater, pre-calciner, rotary kiln and kiln cooler (Huntzinger and Eatmon, 2009) processes. The heat requirement is 1.76kJ/mole (Milulcic et al., 2013) and reaches temperatures of up to 1450°C.

(c) Milling is one of the processes of geopolymer cement production, but it is energy intensive and consequently emits considerable carbon dioxide (Atamaca and Kanoglu, 2012 and Madlool et al., 2012).

(d) In preparing sodium hydroxide (NaOH) from brine, which uses an electrolysis method, one of the by-products is sodium hydroxide (NaOH), but this production process is also energy intensive, emits a lot of carbon dioxide and is very costly (Chan et al., 2015). On average, energy costs in the form of fuel and electricity represent 40% of the total production costs for one tonne of cement (Oggioni et al., 2011). It is also raw material intensive and one of the reasons for causing natural resources depletion. Imbabi et al., (2012) studied trends and developments in green cements and concrete technology in term of the economics of the production of cement but did not study the inter-relationship between natural resources and raw materials for the cement industry.

(e) This research has also identified that the production of ordinary Portland cement uses a lot of raw materials such as limestone, gypsum, sand, clay and others. This could rapidly cause abiotic depletion (Diaz and Harchaoui, 1997 and Australian Resources, 2017). Habert et al., (2010) used abiotic depletion potential and reserve methods to evaluate natural resources depletion and reserve status with the assistance of software to probe further non-renewable depletion in France and the United Stated of America using case studies. However, regarding the main aim, to find reserve data for domestic material consumption of every single country each year, was hard to realise, as it was difficult to collect reliable data, and accuracy might be affected by hidden or unknown natural resources stock. So, Habert et al., (2010) solved this problem by using the well-known software CML which successfully identified the domestic consumption in France as an exponential equation. The data from this approach is limited to regional natural resources. This research was adapted and extended into the ‘reserve equation’ mentioned by Habert et al., (2010) and used in the Australian cement production environment. However, one of the items in the ‘Reserve’ (Habert et al., 2010) equation is only used in the context of a format to express ‘Domestic material consumption’ and this causes unclear and increasingly difficult implementation in the Australia region. In order to solve this issue, this research will use the first principle of statistical methods (Grcar 2011 and 2012), with the assistance of the add-on function XLMiner Analysis ToolPak® in Excel® (2016 version) to plot a time-series curve for a regression model based on previous years’ domestic material consumption data in Australia, determining curve characteristics and equations including polynomial, exponential and power curves. The expected outcome of the 'domestic material consumption' equation is:

(i) Exponential equation which is a variable, occurs in the exponent. For example: $\log_b(m^r) = r\log_b(n)$

(ii) Polynomial equation including linear and quadratic equation, which is expressed in variable and coefficients. It only involves addition, minus, subtraction and multiplication. For example: $ax^2 + bx + c$. Where a, b and c are constants, x is variable.

(iii) Power equation, which is expressed as x^a, where 'x' and 'a' are variables.

These three types of curves act as time-series models or equations, the results of which were informed by the trend of seasonality in forecasting (Copeland, 2013) domestic material consumption. Burghes et al., (2006) also developed a mathematical model to evaluate sustainable development of raw materials for cement and construction industries in English regions but have not yet studied the indices for the forecast.

2.5 RESEARCH QUESTIONS

In the literature review, this study identified numerous researchers using different methods in ordinary Portland cement cement and geopolymer-based including fly ash and metakaolin production methods for optimisation. Those researchers have calculated raw materials or by-products use, carbon dioxide emission in production and financial effect. But the methods or equations have some limitations. For example, Habert et al., (2010) used abiotic depletion potential with assistance software to calculate natural resources consumption, but this method was only applicable to France. Further, researchers have seldom compared ordinary Portland cement and geopolymer-based cement in abiotic depletion potential, financial effect and carbon dioxide emission in every scenario based on favourable conditions. Therefore, the research questions for this study are as listed below.

A. Boundary for Environmental Effect Measure

(a) How do life-cycle assessment and life-cycle cost based on ISO 14040 series provide a clear guideline for cement production?

B. Calculation Carbon Dioxide Emission Method

(a) Why does the Australian National Greenhouse Accounts Factors (2014), more accurately, flexibly and intensively study carbon dioxide emission in cement production, but not Carbon Dioxide Emission Equivalent and World Business Trade Council for Sustainable Development methods?

(b) Which carbon dioxide emission method is superior to others and what are their limitations?

C. Abiotic Depletion Potential (ADP)

(a) How and why does ADP provide vital information for natural resources depletion?

(b) Does it provide information to quarry companies, mining, cement, civil and construction infrastructure sectors, and Australian Government envisaging optimal use of natural resources in Australia, in order to formulate a new strategy to examine livestock status?

D. Financial Effect Measure

(a) How does this study to identify the cost drivers and sub-cost drivers formulate quantitative measures of cement production optimisation?

(b) How do the production facilities and raw material costs affect production performance and capability planning in an optimal manner?

E. Optimisation

(a) Why should we consider linear programming equations to effectively measure three areas based on scenario-based methods to study cement-based including supplementary cementitious materials and geopolymer-based cement production?

(b) Where are the sources of equations for construct functions of equations and objectives of equations?

(c) What kind of method will use to solve problems if more than three-unknown in linear programming equations? What is the limitation of graphical method?

(d) Do linear programming equations provide sensitivity analysis results?

(e) How do linear programming equations examine less carbon dioxide emission and raw materials use and maximisation of profit in cement production?

(f) Does linear programming provide sufficient information to evaluate three areas in cement manufacturing options?

CHAPTER 3

METHODOLOGY

CHAPTER 3 METHODOLOGY

3.1 INTRODUCTION

The aim of this chapter is to develop the proposed advanced integrated framework which can effectively quantitatively measure abiotic depletion potential, natural resources consumption, reserve, raw material and by-product, carbon dioxide emission in the production processes, and sensitivity analysis of three areas. It provides a platform to bridge the research gap in calculating minimising carbon dioxide emission, using fewer natural resources for cement production and improving profit by using linear programming equations skills, providing better environmental options and identifying national resources reserves as well as the cost effectiveness of three areas for the cement industry.

3.2 PROPOSED ADVANCED FRAMEWORK

The proposed methodology is a three-level hierarchy chart as shown in Figure 3.1. Each level has its purpose and function as listed as below:

A. Level1: literature review, case studies (survey) and spreadsheet-based models with the assistance of traditional mathematical methods.

(a) Literature review. This consists of secondary data collection from current researchers and an outline of their shortcomings, and seeks an opportunity to adapt and extend existing methods of developing equations, including carbon dioxide emission, natural resources and energy calculation methods to suit the aims and objectives of this research. This was achieved in Chapter 2.

(b) Case studies (survey). This consists of primary data collection through surveys from three well-known cement factories in Australia. All survey questions are provided in Chapter 4 and Appendix B. Secondary data are also collected, from literature, annual financial reports from the targeted companies, cement associations of Australia, the Australian Bureau of Statistics, the Mineral Council of Australia, the Australian Government’s Department of Environment and Energy, Commonwealth Scientific and Research Organisation (CSIRO), the Australian Bureau of Meteorology, and Australian Standards, etc.

(c) Spreadsheet-based models and traditional mathematical methods. These are used to analyse each scenario performance based on linear programming equations with Solver®. Sensitivity analysis is one of its outcomes. In addition, traditional mathematical methods including statistics, linear algebra, matrices and Gaussian-Jordan Elimination methods (Grcar, 2011 and 2012), are included in the calculating processes.

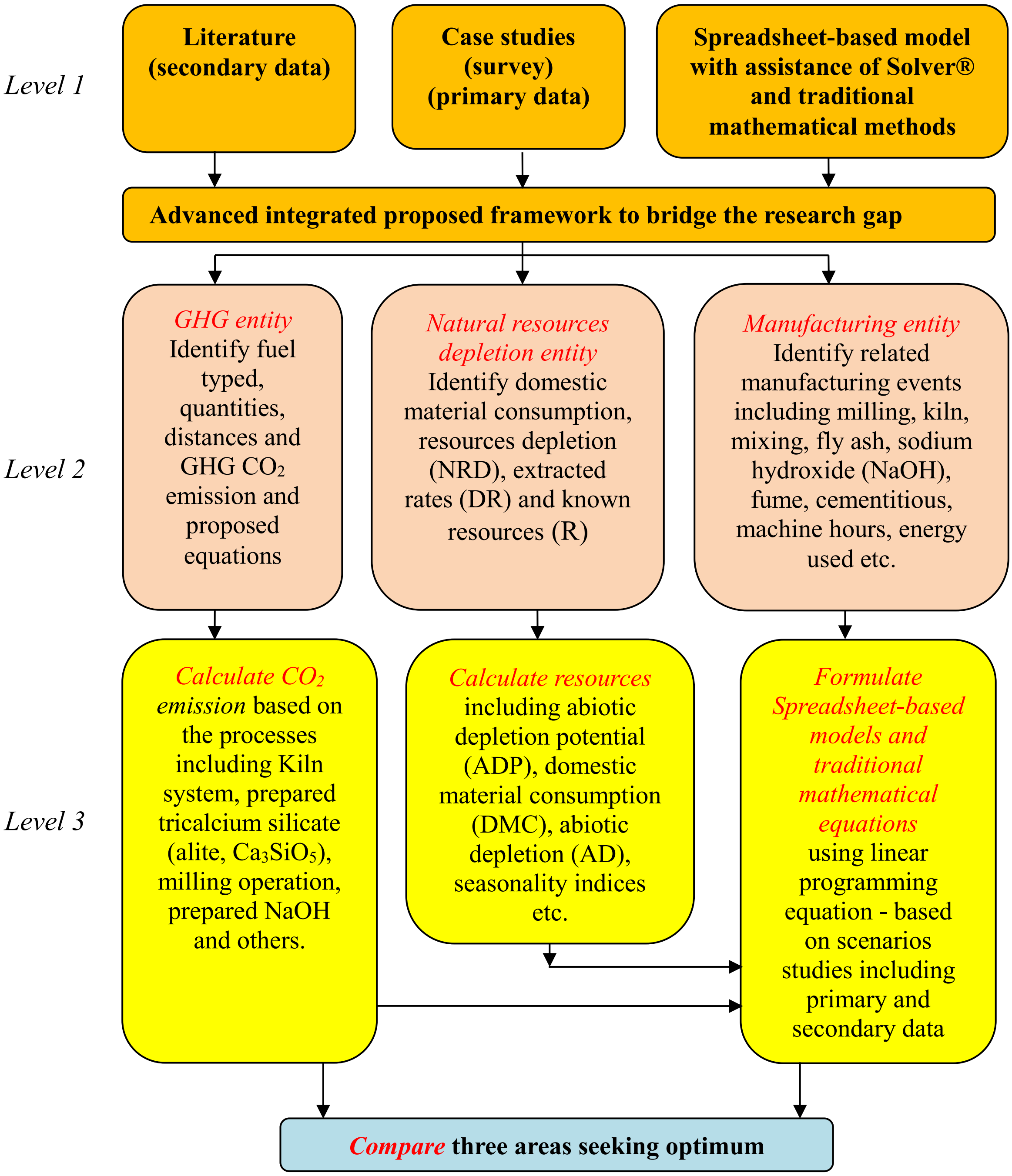


Figure 3.1 The Proposed Advanced Integrated Framework

B. Level 2. This level follows on from the outcome of level 1, and is divided into three entities for further processes, which are:

(a) *Greenhouse gas entity*. The purpose of this entity is the assessment of the status of carbon dioxide emission throughout the production processes of the three categories. The operation is to identity types of fuel used, quantities used, greenhouse gas data and the calculating methods used in cement production. After that, all data passes downward to environmental and carbon cost sub-entities for further calculation.

(b) *Natural resource entity*. The purpose of this is to identify daily and yearly extraction rates of resources. All data are passed to sub-entities in level 3 for abiotic depletion potential calculation.

(c) *Manufacturing entity*. The purpose of this is to identify raw materials, manufacturing processes and timing to finish the whole of a production batch (Chan and Yung, 2008). This production process includes mixing, coarse grinding, kiln, fine-grinding and packing etc., as well as the consumption of fly ash, sodium hydroxide (NaOH), potassium hydroxide (KOH), silica fume, sodium silica, supplementary cementitious material, sand, clay, slag, gypsum, limestone, lime, machine utilisation rates, energy used, etc. All data passes throughout corresponding sub-entities for calculation and analysis purposes.

C. Level 3. This level is the calculating level and includes three sub-entities. The first entity is for calculating carbon dioxide emissions, based on the equations in Chapter 2. The second entity is used to calculate the status of natural resources. The third entity provides the pre-requisite conditions to develop linear programming equations. All data are from level 2. The detailed functions of level 3 sub-entities are listed below.

(a) *Calculation of carbon dioxide emission of sub-entity*. The purpose of this entity is to compute carbon dioxide emission throughout the production processes within the defined boundaries.

(b) *Calculation of natural resources depletion sub-entities*. The purpose of this entity is to calculate the abiotic depletion potential, reserve consumption throughout the overall production processes, including prepared alite (e.g. Ca_3SiO_5 or $3CaO.SiO_2$), kiln system, milling and prepared sodium hydroxide (NaOH) sub-entities. The operation is that level 1 will pass daily extraction rate, daily natural resources, yearly extraction rate and yearly natural resources into this entity for assessment. The outcome is abiotic depletion potential, which gives guidelines to natural resources depletion status. If the abiotic depletion potential is lower than setting values, a new quarry site will be considered, preventing feedstock and source resources from becoming exhausted.

(c) *Formulation spreadsheet-based model and traditional mathematical methods.* The linear programming equations were developed based on primary and secondary data and equations from the literature. These equations and their functions were discussed in Chapter 2. Primary and secondary data serve as 'subject to constraints' of equations' for each scenario. Linear equations will be solved using spreadsheet-based models with the assistance of Solver® and traditional mathematical methods, including graphical methods, upon many unknowns in each set of equations, to seek optimisation. Detailed calculation methods will be discussed in Chapter 4.

(d) *Comparison entity.* This is the last level of the hierarchy chart. The purposes of this level are to merge upstream results and compare three areas of performance with respect to minimising carbon dioxide emission, using fewer raw materials to prevent earlier natural resources depletion, and maximising profits.

The purposes of levels 1 and 3 were discussed in the previous section. The detailed calculation of carbon dioxide emission in cement production, natural resources depletion including abiotic depletion potential and reserve, will be discussed in the coming sections, which outline how the level 2 calculation works.

3.2.1 CARBON DIXOIDE EMISSION CALCULATION METHODS

3.2.1.1 Carbon Dioxide Emission Equivalent Method

A. The Carbon Dioxide Emission Equivalent method is one of the most commonly used methods to calculate carbon dioxide emission of different industries for different nations (Huntzinger and Eatmon 2013; Yang et al., 2014). In the literature review findings, the following equation was obtained:

$$CO_{2-e} = GWP * Q * EC \qquad \text{……………..} \quad (3.1)$$

Table 3.1 Emission Factors Used to Estimated CO_2 Liberated for Different Fuel Types

Energy source	**Emission factor EC*GWP**	**Unit**
Diesel	2.68	kg CO_2-e/L
Electricity	1.35	kg CO_2-e/KWh
Liquid Petroleum Gas (LPG)	1.54	kg CO_2-e/L
Explosives	0.44	Kg CO_2-e/kg product

where denotes

$CO_{2\text{-e}}$,$CO_{2\text{-m}}$ and $CO_{2\text{-p}}$ = Carbon Dioxide Emission Equivalent method in material and production process (e.g. milling)

i = Represents a raw material constitute of cement

n = Total number of constituents added into cement

W_i and $CO_{2\text{-i-LCI}}$ = The unit mass (kg) and CO_2 emission inventory (CO_2-kg/kg)

FT = Fuel type

Q = The quantity of fuel combusted to undertake a particular activity (kg)

EC = Energy content of the specific fuel type(s) used to undertake the activity (J/kg)

GWP = Global warning potential

B. Yang et al., (2014) based their work on the Japanese Society of Civil Engineering (JSCE) life-cycle inventory (LCI) database to develop a method of calculating carbon dioxide emission in cement and concrete production as follows:

The total CO_2 footprint (C_e) for 1 kilogram of ordinary Portland cement as obtained:

$$C_e = CO_{2-m} + CO_{2-p} \qquad \text{.................} \quad (3.2)$$

Calculation of carbon dioxides emission for supplementary cementitious materials including ground-granulate blast slag and fly ash as obtained:

$$CO_{2-m} = \sum_{i=1}^{n} W_i * CO_{2-i-LCI} \qquad \text{.................} \quad (3.3)$$

Table 3.2 CO_2 Emission of Producing Ordinary Portland Cement, Ground-Granulate Blast Slag and Fly Ash (Yang et al., 2014)

Substance	CO_2 Emission	Unit
Ordinary Portland cement (OPC)	$\boxed{0.9310}$	CO_2-kg/kg
Ground-granulate blast slag (GGBS)	0.0265	CO_2-kg/kg
Fly ash (FA)	0.0198	CO_2-kg/kg

A comparison of the results from Yang et al., (2014) and Habert et al., (2010) shows that the figures from Yang et al., (2014) (Table 3.2, red box) were higher than those from Habert et al., (2010) because of the different sources of data (Habert et al., 2011), cement production technology and different equations used. One of the main reasons for data variation is that Yang et al., (2014) used the Japanese Society of Civil Engineering (JSCE) life-cycle inventory database method which is part of the processes of life-cycle assessment for the evaluation of the environmental effect of cement production. These sets of data were affected by the cement production technology. For example, if a cement company used a wet type of kiln instead of a dry-type of kiln, the carbon dioxide emission would be higher, as shown in Table 3.2 (red box).

Australian National Greenhouse Accounts Factors (2014 to 2016) also has its own standard to measure carbon dioxide emission. The advantages of this method were that it individually and intensively measured the carbon dioxide emission status of each cement production process. However, the Carbon Dioxide Emission Equivalent method is a rapid calculation of carbon dioxide emission quantities (Chan et al., 2015) and collects less data compared with Australian National Greenhouse Accounts Factors (2014 to 2016). But the CML method (Habert et al., 2010) and life-cycle assessment method ISO 14044 (2014) work well with well-known software. This means the sources of data in the inventory would be affected by the outcomes results just the same as in the cases of Habert et al., (2011) and Yang et al., (2014) (discussed in the previous section). Therefore, the World Trade Council for Sustainable Development method is one of the solutions to share other carbon dioxide tools.

3.2.1.2 World Business Council for Sustainable Development and Australian National Greenhouse Accounts Factors (2014 to 2016) Methods

3.2.1.2.1 World Business Council for Sustainable Development

The World Business Council for Sustainable Development is a well-known global organisation related to worldwide sustainable business and development. It is linked with 70 nations and chief executive officer-led organisations, and covers 200 businesses. The Cement Sustainability Initiative (World Business Council for Sustainable Development, 2016) and Cement Sector Scope 3 GHG (Accounting and Reporting Guidance from World Business Council for Sustainable Development) provide comprehensive information in boundary, purchased goods, services and calculation methodologies. for cement production. This method provides six categories but only four out of six are related to this research. These are:

- Category 1: kiln in capital goods, fuel and energy-related activities.
- Category 3: upstream transportation and distribution.
- Category 4: business travel.
- Category 6: downstream transportation and distribution.

In addition, this method can work in conjunction with other methods, enabling the sharing of data. The defined boundary and inventory from the ISO 14000 series method and calculation of carbon dioxide emission by using the Carbon Dioxide Emission Equivalent method are the same approaches. It is therefore a useful and flexible tool.

3.2.1.2.2 Australian National Greenhouse Accounts Factors (2014 to 2016) Method

The Australian National Greenhouse Accounts Factors method (2014 to 2016) also developed a series of carbon dioxide emission methods. This research only used part of the calculation methods from this method, including clinker production, limestone production, transport and electricity purchasing, etc. This is because this research only focused in cement industry. First, kiln stage is examined to determine how much carbon dioxide is emitted in cement clinker production (Australian National Greenhouse Accounts Factors, 2014) as obtained:

$$E_{ij} = (EF_{ij} + EF_{toc,j}) * (A_i + A_{ckd} * F_{ckd}) \qquad \ldots\ldots\ldots\ldots\ldots \qquad (3.4)$$

where denotes

E_{ij} = the emission CO_2 released from the production of cement clinker (CO_2-e tonne)
EF_{ij} = the emission factor for cement clinker (tonnes of CO_2 emission per tonne of clinker produced)
A_i = the quantity of cement clinker produced (tonnes)
A_{ckd} = the quantity of cement kiln dust produced (tonnes)
$EF_{toc,j}$ = tonnes of CO_2 emission per tonnes of clinker produced see Table 3.3
F_{ckd} = the degree of calcinations of cement kiln dust

Table 3.3 Clinker Production Emission Factors (Australian National Greenhouse Accounts Factors, 2014 to 2016)

Source	**Emission factor (tonnes CO_2-e per tonne) for CO_2**
EF_{ij}	0.534
$EF_{toc,j}$	0.01

Carbon dioxide emission in lime production (Australian National Greenhouse Accounts Factors, 2014) as obtained:

$$E_{ij} = (A_i - A_{lkd} * F_{lkd}) * EF_{ij} \qquad \ldots\ldots\ldots\ldots\ldots \qquad (3.5)$$

where denotes

E_{ij} = is the emission of CO_2 from production of lime (CO_2-e tonnes)
A_i = is the amount of lime produced (tonnes)
A_{ij} = is the quantity of lime kiln dust lost in the production of lime (tonnes)

Flkd is:

(a) The fraction of calculation achieved for lime kiln dust in the production of lime during the year; or

(b) If the data are not available - the value 1.

$EF_{ij} =$ is the CO_2 emission factor (tonnes of CO_2) / tonnes lime produced as shown in Table 3.4.

Table 3.4 Lime Production Emission Factors (Australian National Greenhouse Accounts Factors, 2014)

Source	**Emission factor (EF_{ij}) (tonne CO_2-e per tonne) for CO_2**
Commercial lime production	0.675
In-house lime production	0.73

The difference between 'in-house lime production' and 'commercial lime production' carbon dioxide emission is 0.73 - 0.675 = 0.055 tonne CO_2-e per tonne, because of manufacturing facilities and difference in manufacturing methods as shown in Table 3.4.

Carbon dioxide emission as a percentage of total emissions is calculated by adding together the emissions of each fuel type and each greenhouse gas (Australian National Greenhouse Accounts Factors, 2015). This study identified that fossil fuels, including coal, diesel oil and gasoline gas, are the major energy suppliers in the production process. There is 'no' heavy vehicle from 'Euro iii' or higher use in transport. Fuel combustion emissions equations are further classified into solid fuels (e.g. coal), gaseous fuels (e.g., Town gas) and liquid fuels (e.g. diesel) as obtained:

$$E_{ij} = \frac{Q_i * EC_i * EF_{ijoxec}}{1000} \qquad \ldots\ldots\ldots\ldots\ldots \quad (3.6)$$

where denotes

E_{ij} = the emission of gas types (j) like carbon dioxide (CO_2-e tonnes)
Q_i = the quantity of fuel type
EC_i = the energy content factor of fuel type
If Q_i = measured in gigajoules, and then EC_i is 1
EF_{ijoxec} = the emission factor for each gas type (j) (which includes the effect of an oxidation factor) for fuel type (i) (kilogram CO_2-e per gigajoule) of the type (j) according to Table 3.5

The major difference when using this equation (3.6) is the fuel-typed selection related to fuel combustion emission factors in the cement production and illustrated in Tables (3.5) to (3.7).

Table 3.5 Emission Factors for the Consumption of Natural Gas (Australian National Greenhouse Accounts Factors, 2014)

Fuel combusted	**Energy contented Factor (GJ/t, unless otherwise indicated)**	**Emission factors Kg$CO_{2\text{-}e}$/GJ (relevant oxidation factors incorporated)**		
		CO_2	CH_4	N_2O
Town gas	$39.0*10^3$	59.9	0.03	0.03
Liquefied natural gas	25.7	60.2	0.2	0.2

Table 3.6 Emission Factors for the Consumption of Liquid Fuels (Australian National Greenhouse Accounts Factors, 2014 to 2015)

Fuel combusted	**Energy Contented Factor GJ/t (unless otherwise indicated)**	**Emission factors Kg$CO_{2\text{-}e}$/GJ (relevant oxidation factors incorporated)**		
		CO_2	CH_4	N_2O
Diesel oil	38.6	69.9	0.1	0.2
Biodiesel	34.6	0.0	0.07	0.2
Fuel oil	39.7	73.6	0.04	0.2

Table 3.7 Emission Factors for the Consumption of Coal-based Products (Australian National Greenhouse Accounts Factors, 2014)

Fuel combusted	**Energy contented Factor (GJ/t, unless otherwise indicated)**	**Emission factors Kg$CO_{2\text{-}e}$/GJ (relevant oxidation factors incorporated)**		
		CO_2	CH_4	N_2O
Coal coke	27.0	107	0.04	0.2
Brown coal	10.2	93.5	0.02	0.4
Charcoal	31.1	0	4.8	1.1

Indirect emission from consumption of purchased electricity (Australian National Greenhouse Accounts, 2014) as obtained:

$$Y = \frac{Q * EF}{1000} \qquad \ldots\ldots\ldots\ldots\ldots \qquad (3.7)$$

where denotes

Y = the scope 2 emission measured in CO_2-e tonnes
Q = the quantity of electricity purchased (kilowatt hours)
EF = the scope emission factors, for the State. Here, this study chose three cement companies are in Queensland. So, the Emission factor is 0.79 - referred to Table 3.8 highlighted in yellow colour

Table 3.8 Indirect (Scope 2) Emission Factors for Consumption of Purchased Electricity from the Grid (Australian National Greenhouse Accounts Factors, 2015 to 2016)

STATE, Territory or Grid	**Emission Factor kg CO_2-e KWh**
New South Wales and Australian Capital Territory	0.86
Victoria	1.18
Queensland	0.79
South Australia	0.61
South West Interconnected System in Western Australia	0.76
Tasmania	0.2
Northern Territory	0.68

The emission factor in Victoria, highlighted in cyan, is the highest in Australia, as shown in Table 3.8. Tasmania has the lowest emission factor, marked in purple, and Queensland is marked in yellow. The emission factor multiplied by the quantity of electricity purchase values and divided by one thousand is equal to the quantities of carbon dioxide emission incurred through the use of electricity. This equation is part of the Australian National Greenhouse Factors Accounts (2014 to 2015) method and does not use the Carbon Dioxide Emission Equivalent method. It is therefore a more accurate estimation of carbon dioxide emission in this respect.

3.2.2 ABIOTIC DEPLETION POTENTIAL AND RESOURCE DEPLETION

Natural resources can be divided into ‘abiotic’ and ‘biotic’ resources. The term ‘abiotic resource’ means metal, coal, iron ore, lime and other mineral-based natural resources. A biotic material is wood, fish, animals and other life-based resources. Every year, Australia exports large quantities of abiotic and biotic resources worldwide. This brings in income but causes natural resources depletion and environmental issues.

In addition, cement manufacture is one of the industries that intensively uses abiotic natural resources and energy, causing environmental issues such as extra carbon dioxide emission. A resource depletion index can serve as a quantitative tool to evaluate the level of depletion for natural resources (Lee, 1998) for a sustainable natural resources development paradigm. To achieve this goal, one of the solutions is to analyse previous domestic material consumption and cement output each year in Australia using a time-series regression model-seeking seasonality indices (Copeland, 2013), which is discussed in Chapter 4. The term ‘resources depletion’ is defined by Lee (1998) as resources (either stock or flow resources) which have been consumed and discarded and can no longer be used by human beings. Recently, the threat of increased scarcity of abiotic resources has been challenging human societies around the globe, particularly the research community (Yellishetty et al., 2011). The aim of an abiotic depletion potential study is to provide useful insights in assessing the potential future threat of a shortage of mineral resources for the production of cement in Australia. To help avoid shortages, seasonality indices (Copeland, 2013) can be one solution.

Researchers have used several different approaches to study this issue. A GIS-based overlay analysis method was used in one study to quantify the geologic and geographic factors and compare their overall effect on new cement plant production and expansion of existing operations (Iahak and Hashim, 2015). This method only studied one of the major raw materials, limestone, for cement manufacture and did not concern itself with the rest of the raw materials. Carneghem et al., (2010) based their work on five methods, based on mass and energy (i.e., consumed mass and energy). The CML, environmental assessment software, were developed by Guinée (2002) and Habert et al., (2010) used CML to assess French concrete industry and nothing related abiotic depletion. Therefore, Nixon et al., (2003) have used the eco-indicators 99-method with the assistance of CML to evaluate the abiotic depletion of resources consumption. However, the data sources to develop database for CML are only suitable France and not for Australia. Thus, all these methods depend on where and how the data were collected, and each has advantages and disadvantages. There is further discussion of this in Section 3.2.2.1, which determines the methods that are most suitable and to this research for the evaluation of the three areas in the Australian cement industry.

3.2.2.1 Abiotic Resources Depletion Potential

Definitions of natural resources depletion, both biotic and abiotic are numerous. Habert et al., (2010) and Guinée (2002) used an abiotic depletion potential method as an indicator to measure the rate of natural resources, particularly in cement and concrete manufacture. Smith (1974) defined indicators as environmental attributes that measure or reflect environmental status or conditions of 'change'. Following Tunstall (1992, 1994), Gallopin (1997) identified major functions of indicators as:

- To assess conditions and changes.
- To compare across different places and situations.
- To assess conditions and trends in relation to goals and targets.
- To provide early warning information.
- To anticipate future conditions and trends.

This study adapted these fundamental theories, extending and applying them in an Australian natural resources environment. The equations (3.8) and (3.10) will play an active role in this study. These equations were previously used in France (Habert et al., 2010); this means that the data and equations for domestic material consumption will have a certain degree of variation from this in the Australia and New Zealand region (Australia Bureau of Statistics, 2015). This study needs to use statistics to track the trend of previous years' consumption and develop an equation of domestic material consumption, ensuring that Habert et al's., (2010) exponential equation as a domestic material consumption status is suitable for use in an Australian case. The collection of primary data and analysis is discussed in Chapter 4 - Data Collection and Analysis. Substituting back all related data into the equations (3.8) to (3.10), the expected outcome is reserve and abiotic depletion potential, which acts as yardstick to measure the rate of depletion and resources in Australia.

Abiotic depletion is due to the consumption of resources, and can be expressed as the sum of the products of the resources' masses consumed with respective characterisation factors for abiotic depletion (Yellishhetty et al., 2011). Although Burghes et al., (2006) and Smith (1974) have used different equations-based approaches to study natural resources depletion for the mineral industry, Habert et al., (2010) and Yellishetty et al., (2012) used abiotic depletion potential. They did not apply this theory to the cement and concrete industries. Habert et al., (2010) and Yellishetty et al., (2012) only used it in France and America, providing abiotic depletion potential indicators to quantitatively measure the rate of depletion of natural resources as obtained:

$$\text{Abiotic depletion} \quad \sum_i CF_i * m_i \qquad \text{……………..} \quad (3.8)$$

where denotes

CF_i = characteristics factors for abiotic depletion of resource I, where CF_i =1
m_i = mass of resources i consumed in the process

This study based on equation (3.8) adapted and extended the theory to develop the function of equations with respect to linear programming equations for scenario-based study.

(a) The abiotic depletion potential equation (Habert et al., 2010; Yellishetty et al., 2011) is to determine the natural resources depletion in term of year-based abiotic depletion potential for the cement industry. This research is based on Habert et al., (2010) but adapted and extended as an abiotic depletion potential indicator for Australia and a characteristics factor based on global reserves and extraction rates.

(b) One factors of calculating abiotic depletion potential is to collect extraction rates from quarry industry for cement and examined natural resource stock is expressed as:

$$ADP_i = \frac{DR_i}{(R_i)^2} * \frac{(R_{Sb})^2}{DR_{Sb}} \qquad \text{……………..} \quad (3.9)$$

Where

ADP = abiotic depletion potential
DR_i = extraction rate (kg year^{-1}) for resources i
DR_{sb} = extracted rate (kg per year) for resources i and antimony.
It is equal to $6.06 * 10^7$ kg year^{-1}and R_{Sb} is equal to $4.63 * 10^{15}$kg

This research only considers extraction rates related to the cement industry, including sand, clay, stone, and gravel brine (because its by-product is sodium hydroxide) (NaOH), coal (because fly ash is its by-product), steel or iron ore (because slag is its by-product), etc. Different quarrying companies have different capabilities, different reserves of the site and different quarrying conditions for preparing raw materials (Australian Quarrying Institution, 2014) as the result of there being no standard extraction rates, DR_i throughout the nation. Therefore, the outcomes of the abiotic depletion potential results are treated as referral data and vary from state to state in Australia. Chapter 5 provides further discussion.

3.2.2.2 Resources Calculation

Global and domestic trading of natural resources are a major economic growth area of the past decades in Australia, which is one of the leading resource based economies in the world. It is, however, exhibiting diseconomies of scale; the costs associated with current resources use are rising faster than the increase in output or economic growth (Barbier, 2012). The material flow of resources from one country to other countries depends on supply and demand principles and is consequently causing natural resources depletion (Schneder and Berger, 2011).

Cement manufacture and civil and construction infrastructure are good examples of sectors that use a lot of raw materials, including limestone, gypsum, fly ash, sand, gravel, brine for producing sodium hydroxide (NaOH) and by-products like slag and fly ash. Quarrying companies based their growth on demand and extracted these raw materials to satisfy the market. This has caused global environmental problems and natural resources depletion issues. Australia is rich in minerals, and is classified as a resource-based country, having quarried a great deal for the mineral trading industry in the past two decades. However, the resources will eventually be exhausted. Habert et al., (2010) developed a method of calculating potential resources for evaluating potential feedstock and sources as obtained:

$$R = \int_{total}^{exhaust} [DMC(t) * (1 - \frac{I}{DMC}(t)]dt \qquad \ldots\ldots\ldots\ldots\ldots \quad (3.10)$$

where

DMC = domestic material consumption
I = imported or current stock material
R = reserved stock

Domestic material consumption in France is calculated by exponential equation (Habert et al., 2010) and it is necessary to solve curve characteristics using a data time-series for a regression model to analyse the trend of previous domestic material and cement output each year in Australia, reflecting resource depletion, determining what kind of curve is suitable for a domestic material consumption equation. Chapter 4 will also develop a 'ratio' method including $\frac{I_i}{DMC}$ and $\frac{ADP_i}{ADP_0}$ with seasonality indices $\frac{DMC_i}{DMC_0}$, (Lafare et al., 2016) to forecast domestic material consumption (DMC) status. Three types of curves (Ragsdale, 2007) are:

(a) Exponential curve.
(b) Power curve.
(c) Polynomial curve, including linear, etc.

The results will be the domestic material consumption equation to calculate 'Reserve' in the Australian cement production environment. Further discussion can be found in Chapters 4 and 5. Additionally, there are two parameters calculated where I refer to the import values, such as metakaolin and sodium hydroxide (NaOH), etc. Domestic material consumption refers to the domestic material consumption of the studied area. In this study, domestic material consumption and data were sourced from the Australian Bureau of Statistics (2013 to 2014), Australian National Greenhouse Accounts Factors (2014); Australian Government: National Income, Expenditure and Product information (2014); USGS (2012 to 2015) information, and then using the curve fit method to find out which types of curve are suitable for domestic material consumption. Further discussion can be found in Chapter 5. In addition, I and domestic material consumption are either constant or increase over time in the current economic environment. An increasing $\frac{I}{DMC}$ ratio means that I is increasing faster than domestic material consumption, which can be expressed as the fact that to support consumption, local stock is not sufficient. In Australia this is not because the cement sectors are unwilling to pay carbon tax, as it was abolished on 17 September 2014. In a decreasing scenario where I and domestic material consumption are either constant or decreasing scenario in $\frac{I}{DMC}$ ratio means that I is decreasing slower than domestic material consumption, which can also be expressed as the fact that even if consumption is decreasing (Habert et al., 2011), local stock will face shortages soon. Therefore, a new source is necessary to ensure continuous production.

Reserve could be calculated with the following procedures:

(a) Step 1: calculation of the amount of time until the actual start of exhaustion of the material, I_{total} and $I_{exhaust}$.

(b) Step 2: calculation of the potential reserve (R) using integration or regression method.

3.2.3 LINEAR PROGRAMMING, SENSITIVITY ANALYSIS, LIFE-CYCLE COST AND COST ESTIMATION METHODS

This research has identified linear programming with sensitivity analysis with the assistance of life-cycle cost and cost estimation methods as the best way to develop six scenarios to measure the optimisation of the three areas of maximising profits but emitting less carbon dioxide and minimising natural resources depletion.

3.2.3.1 Linear Programming and Sensitivity Analysis

In the literature review, linear programming and simplex methods are identified for sensitivity analysis (Lai et al., 1996; Sarker et al., 2012; Loijos et al., 2010; Boyer and Ponssard, 2012; Lai and Chen, 1996; Messner et al., 1996 and Shik, 1999); because of their flexible parameters for linear programming (LP) (Shih, 1999; Messner et al., 1996), as the results provide an optimal solution for cement manufacture with respect to cost and minimising of carbon dioxide emission and natural resources depletion.

This research uses linear programming and sensitivity analysis methods to seek optimisation of three areas of manufacture with respect to minimising natural resources depletion and carbon dioxide emission and maximising profit, in production of ordinary Portland cement, ordinary Portland cement with cementitious materials and fly ash based geopolymer cement production. To achieve this goal, this research has identified that linear programming is one the best tools to evaluate optimal production, based on a scenario study. To construct a linear programming model for each scenario, the objective function and subject to constraints are the core of the linear programming equation, which have decision variables, chosen based on what the model needs. Optimisation problems have an objective function whose value is to be optimised (either maximised or minimised) based on constraints. Regarding building the scenario, there are two steps (Horngren et al., 2005) associated with development of linear programming equations problems for each single scenario:

A. Step 1: Scenario development including company background, data collection, subject to function and subject to constraint of linear programming equations development for Chapter 4.

B. Step 2: Optimisation.

A. Step 1: Scenario development.

(a) Where does the decision variable come from?

The decision variables are minimising carbon dioxide emission and abiotic depletion and minimising profit. The set of data are from literature reviews and research questions via interview and questionnaire (e.g., Appendices A and B).

(b) What is the purpose of objective function and constraints in linear programming equations?

The linear programming equation consists of objective function and subject to constraints. This means what this research is intended to achieve via a linear programming equation. The assigned equation is the major source to develop the subject of function and subject to constraint parameters come from the literature review, Cement Industry Federation (2014 to 2016), Australian Bureau of Statistics (2014 to 2016), etc.. This data are treated as secondary data and companies A to C survey is primary data. Further sources of developing objective functions derived from the assigned equations are:

(i) Carbon dioxide emission in transport, using electricity and fossil fuel for delivering raw material to the cement factory, using the Carbon Dioxide Emission Equivalent method from equations (3.2) to (3.4) and Australian National Greenhouse Accounts Factors (2014 to 2016) from equations (3.9), (3.10) and (3.11) including lime production, transport and purchased electricity.

(ii) Abiotic natural resources depletion from equations (3.12) to (3.13). However, there was a problematic issue in this model of domestic material consumption, as Habert et al., (2010) developed it for French regions and did not use it in the Australian region. Domestic materials consumption also consisted of quantitative data and exponential equations. This study therefore uses statistics skills, including developing trend of data series for regression models, mean average, seasonality indices and trend line with a fit-to-lines skill to develop the domestic material consumption equation suiting Australian cement feedstock. One of the solutions was to use a linear equation instead of an exponential equation. Additionally, the set of data series also provided a clue to develop seasonality ratio indices, linear equations based on curve characteristics and forecasting for every raw material used in cement production.

B. Step 2: Optimisation

(a) Seek the optimal solution for each single scenario:

The linear programming equations to cover the selected problems were developed for each single tailor-made scenario study to examine the optimal solution. Some linear equations have more than two unknowns in complex linear programming equations. To solve this issue, two types of mathematical methods, including traditional mathematics with statistical and Gaussian-Jordan Elimination methods (Grcar, 2011 and 2012; Khanrel and Cao, 2015) and spreadsheet-based models (e.g., Solver®) were used to calculate the optimisation of each scenario.

(b) Two approaches to solve the linear programming equations problems are:

(i) Statistical and Gaussian-Jordan Elimination methods and the traditional mathematical method (Grcar, 2011 and 2012; Khanrel and Cao, 2015), which are:

- Statistical method. This is one of the traditional methods to calculate linear equations with one to three unknowns and more easily presentable data and information in graphical format. By changing the data in spreadsheet-based equations, an alternative solution is provided for the decision maker. Further discussion is in Chapter 4.
- Gaussian-Jordan Elimination method (Grcar, 2011 and 2012; Khanrel and Cao, 2015). This is easy to follow step-by-step to calculate each unknown through long calculation procedures using matrix skills, and is able to solve more than three unknowns in each equation at a time. By changing the data

in a matrix-based equation, an alternative solution is provided to the decision maker. Further discussion is in Chapter 4.

- Traditional mathematical method: This method is used in the calculation of the abiotic depletion potential of each raw material for ordinary Portland cement and fly ash based geopolymer, as well as life-cycle cost including whole-life-cycle cost calculation. Further discussion is Chapter 5.

(ii) Spreadsheet-based model:

All linear programming equations, in 'subject to function', 'subject to constraints' and expected solution (e.g. either maximisation or minimisation) are put into a spreadsheet-based format. The operation of the spreadsheet-based model was systematically to choose the values of the decision variables that make the objective as large or small as possible and cause all the constraints to be satisfied. Any set of values of the decision variable is called a feasible solution. The set of all feasible solutions is called the feasible regions. In contrast, an infeasible solution is a solution where at least one constraint is not satisfied (e.g., not binding). In this case, a new set of data would be considered for each constraint. However, this study only concerns a feasible solution that provides the best values, which is called an optimal solution.

Two approaches are used because this provides an opportunity to compare which methods are quick and flexible to solve complex mathematical operational problems.

The theoretical development of the linear programming equation was discussed in the previous section. Here, the most important issue of developing the objective function was either in minimisation or maximisation of a scenario, in a spreadsheet-based model. The details are discussed in Chapter 4. Normally, if the expected result is the maximum figure, each object of constraint equation is expressed in mathematical symbols as '$\geq$'. If the expected outcome is the minimum figure, each subject of constraint equation is less than, expressed as '$\leq$'. This conveys to Solver® and objective of function the decision maker's expected outcome.

3.2.3.2 Sensitivity Analysis

One of the outcomes from Solver® is a sensitivity analysis report; this result provides the optimal solution of each scenario and will be discussed in Chapter 4.

3.2.3.3 Linear Programming Equations Models for Scenario

To tailor the linear programming equations to seek optimal solutions in this research, based on the assigned equations under the same production manners and boundary, the relevant factors are:

A. Maximising profit and productivity
(a) Ordinary Portland cement and ordinary Portland cement with supplementary cementitious materials in production.
(b) Fly ash based geopolymer cement and metakaolin-based geopolymer cement in production.

B. Minimising energy cost, carbon dioxide emission and abiotic depletion potential in production
(a) Energy cost.
(b) Carbon dioxide emission in production.
(c) Abiotic depletion potential.

A. Maximising profit and productivity
(a) Ordinary Portland cement and ordinary Portland cement with supplementary cementitious materials in production.
  (i) Expressed in the subject of function of calculating optimal cost of ordinary Portland cement and ordinary Portland cement with supplementary cementitious materials with respect to the equation format as obtained:

$$Max(Z) = \sum_{c}^{z}\sum_{d}^{w}(Q_{opc}C_{opc} + Q_{opc+scm}C_{opc+sucm}) \qquad \ldots\ldots\ldots\ldots \quad (3.11)$$

  (ii) Subject to constraints for ordinary Portland cement and ordinary Portland cement with supplementary cementitious materials in production is expressed as obtained:

$$\sum_{c}^{z}\sum_{d}^{w}(Q_{opc}C_{opc} + Q_{opc+scm}C_{opc+scm}) \leq C \qquad \ldots\ldots\ldots\ldots \quad (3.12)$$

(b) fly ash based geopolymer cement and metakaolin-based geopolymer cement in production.

(i) Expressed the subject of function in a linear programming equation to calculate optimal cost of fly ash based geopolymer cement and metakaolin-based geopolymer cement in cement as obtained:

$$Max(Z) = \sum_{c}^{z}\sum_{d}^{w}(Q_{FA}C_{FA} + Q_{MK}C_{MK}) \quad \ldots\ldots\ldots\ldots\ldots \quad (3.13)$$

(ii) Expressed the subject of constraints in linear programming equation to calculate optimal cost of geopolymer-based cement production as obtained:

$$\sum_{c}^{z}\sum_{d}^{w}Q_{FA}C_{FA} + Q_{MK}C_{MK} \leq C_{FA+MK} \quad \ldots\ldots\ldots\ldots\ldots \quad (3.14)$$

B. Minimising energy cost, carbon dioxide emission and abiotic depletion potential

(a) Energy cost.

Minimising Energy Cost

(i) Subject to function based on equation (3.6) as obtained:

$$Min(E_2) = \sum_{i=0}^{n}\sum_{j=0}^{m}M_iQ_j \quad \ldots\ldots\ldots\ldots\ldots \quad (3.15)$$

(ii) Subject to constraints as obtained:

$$\sum_{i=0}^{n}\sum_{j=0}^{m}M_iQ_j \geq \sum_{k=0}^{o}C_k \quad \ldots\ldots\ldots\ldots\ldots \quad (3.16)$$

In the literature review several methods were identified to calculate carbon dioxide emission in different industries for different nations with the assistance of well-known environmental software. McLellan et al., (2011) used Australian National Greenhouse Accounts Factors (2014) to conduct carbon dioxide emission assessment in the construction industry. This research adapts and extends their Carbon Dioxide Emission Assessment method and uses it for cement production, in particular in transport (Company A). This is because raw materials and cement clients are dispersed throughout Australia (DCC, 2009; DITR, 2006; McLellan et al., 2011) and this leads to the consumption of a large amount of diesel fuel in transport (Companies A and B), resulting in one of the sources of air pollution. Both the Carbon Dioxide Emission Equivalent and Australian National Greenhouse Accounts Factors (2014 to 2015) methods are solutions to measure carbon dioxide emission in transport. To effectively use these equations, a large amount of data are collected to satisfy the calculations, such as how many kilometres are travelled to deliver the raw materials to the cement factories, diesel fuel consumption per each single trip, and so on. The sources of primary and secondary data collection methods are discussed in Chapter 4. The outcomes provide data and information to develop theoretical linear programming equations seeking optimal solutions in Scenarios 4 and 5. It also provides an opportunity to compare their results and determine which method is superior and under which conditions this method should be used.

The next section discusses how to develop theoretical linear programming equations in detail for the minimisation of carbon dioxide emission due to transport.

(b) Minimisation of carbon dioxide emission in the production process.

(i) Using Australian National Greenhouse Accounts Factors (2014 to 2016) as objective of function:

Subject to function based on equation (3.6) as obtained:

$$Min(CO_2) = \sum_{i=0}^{n}\sum_{j=0}^{m}\frac{M_iQ_j}{1000} \qquad \ldots\ldots\ldots\ldots\ldots \quad (3.17)$$

Subject to constraints as obtained:

$$\sum_{i=0}^{n}\sum_{j=0}^{m}M_iQ_j \geq \sum_{k=0}^{o}C_k \qquad \ldots\ldots\ldots\ldots\ldots \quad (3.18)$$

(ii) Using Carbon Dioxide Emission Equivalent method as subject to function as obtained:

$$Min(CO_2) = \sum_{i=0}^{n}\sum_{j=0}^{m}(GWP * EC_i * Q_j) \qquad \ldots\ldots\ldots\ldots\ldots \quad (3.19)$$

Subject to constraints as obtained:

$$\sum_{i=0}^{n}\sum_{j=0}^{m}GWP * EC_iQ_j \geq \sum_{k=0}^{o}C_k \qquad \ldots\ldots\ldots\ldots\ldots \quad (3.20)$$

(c) Minimisation of abiotic depletion potential in the production process.

Natural raw materials in equations (4.19) and (4.20), include limestone, clay, sand, gypsum and by-product fly ash, ground-granulate blast slag (GBBS), metakaolin (MK), slag and fume consumption for cement manufacture. The actual consumption of individual natural resources for cement production is dependent on what kind of cement is manufactured, such as ordinary Portland cement, ordinary Portland cement with supplementary cementitious materials (OPC with SCM), fly ash based geopolymer cement, ground-granulate blast slag-based geopolymer cement and metakaolin-based geopolymer cement, etc. The equations are (3.19) and (4.20) and are also associated with equation (3.14) because of less natural resources depletion. The demand for resources would slow as well.

(i) Objective of function based on equation (3.8) as obtained:

$$Min(ADP) = \sum_{i=0}^{n}\sum_{j=0}^{m}(CF_i * M_j) \quad \text{.............} \quad (3.21)$$

(ii) Objective of constraints as obtained:

$$\sum_{i=0}^{n}\sum_{j=0}^{m} CF_i * M_j \geq \sum_{k=0}^{o} C_k \quad \text{.............} \quad (3.22)$$

3.2.3.4 Life-Cycle Cost Including Whole-Life-Cycle Cost and Cost Estimation Methods

In the literature review, the cost estimation method was identified as the best tool for examining construction projects, including material consumption costs and labour costs in the cement and construction industries. Chan et al., (2015) also developed the extended life-cycle cost method to evaluate fly ash based geopolymer cement and ordinary Portland cement production. This method is used in the Australian business environment and involves a great deal of data collection to calculate the whole life production cost and identified cost drivers, and independent and dependent variables. This research adapts and extends the methods of Horngren et al., (2005) and Chan et al., (2015) for better data collection related to cost and cost identification from dependent and independent variables from primary and secondary data and also the expected outcome. The proposed framework, as shown in Figure 3.1, is:

(a) Step 1: identify the dependent variables from primary and secondary data collection. This set of data includes labour wage, extraction rate, machine-hour cost and so on.

(b) Step 2: identify the independent variable or cost driver from primary and secondary data collection. This includes fly ash, slag, sodium hydroxide (NaOH), brine, sand, gravel, clay, gypsum and others, which will be considered independent variables.

(c) Step 3: design survey questionnaire to collect dependent and independent data. This is the most important and difficult of the steps because it needed approval from the Ethics Committee from USQ and to obtain permission from targeted companies for interviews. The data collection forms are in Appendices A and B.

(d) Step 4: analyse and plot the data based on traditional mathematical methods, including graphical, statistical and so on, determining ordinary Portland cement, ordinary Portland cement with supplementary cementitious materials and fly ash based geopolymer cement production performances with respect to maximising profit, and minimising use of natural resources and carbon dioxide emission.

(e) Step 5: examine time-series for regressive model based on primary and secondary cost data. Seasonality indices were developed for the time-series model and also provide data for future cost prediction, domestic material consumption and so on.

(f) Step 6: examine the whole-life-cycle cost of cement production, including supplementary cementitious material, fly ash based geopolymer cement, etc., based on cost identification.

Further, the methodology will develop linear programming equations for six scenarios based on dependent and independent variable data identification, in particular in scenarios 1 and 2 via the above steps for seeking optimal solutions.

Further investigation of the whole-life-cycle of ordinary Portland cement, supplementary cementitious materials and fly ash based geopolymer cement production also relies on cost data and cost estimation methods. Further discussion of this issue can be found in Chapter 5.

3.3 SUMMARY

This chapter has discussed the proposed methodology which combines various tools to better evaluate three cement options, including:

(a) Carbon footprint calculation methods using the Carbon Dioxide Emission Equivalent method and Australian National Greenhouse Accounts Factors method (2014 to 2016) within the defined boundaries.

(b) Natural resources depletion calculation using the abiotic depletion method to examine natural resources and the depletion rates for the cement industry.

(c) Primary and secondary data collection using cost estimation skills to identify cost drivers, and independent and dependent variables.

(d) Financial effect assessment based on carbon footprint calculation methods, natural resources depletion and production methods within defined boundaries by using linear programming equations. The sensitivity analysis outcome can provide an optimal production of three areas including maximisation and minimisation. Additionally, two approaches are used to perform data analysis. First, using spreadsheet-based models, this can provide flexible ranges of data and graphical interpretation. Second, using matrix skills including Gaussian and Gauss-Jordan elimination methods to solve a series of unknowns. All these calculation skills will be further discussed in Chapter 4.

The main advantages of the proposed framework are that it works compatibly with several assessment tools and can share data, meaning that it can operate and evaluate effectively which assessment tool, such as the Carbon Dioxide Emission Equivalent method, Australian National Greenhouse Accounts Factors method (2014), and so on, is superior to others in the evaluation of the three selected areas.

CHAPTER 4

DATA COLLECTION AND ANALYSIS

CHAPTER 4 DATA COLLECTION AND ANALYSIS

This chapter discusses primary and secondary data collection methods, using a literature review and the questionnaire. The tools used to analyse primary and secondary data are statistical methods, including data series for regression models, mean, average and scenario-based studies, etc. The statistical methods examine the inter-relationships of the data and variables, such as trends of raw materials consumption, behaviour and others. Further, each scenario-based model was developed, providing overall assessment of three areas, including financial effect, carbon dioxide emission and material depletion, based on defined boundaries. Six scenario-based models were built to cover the research questionnaire. This method of analysis consisted of ‘subject to objective’ and ‘subject to constraint.’ The ‘subject to objective’ equation data came from the proposed formulas from Chapter 3 (Methodology). The ‘subject to constraints’ came from primary and secondary data, to develop linear programming equations to examine the three areas of production in the Australian cement business environment, seeking optimisation. The skills of solving linear programming problems were used along with traditional linear algebra, graphical and spreadsheet-based methods. Their outcomes were necessary to determine which methods were superior. They also provided quantitative information to Chapter 5 (Results), probing further each scenario-based performance, and provided an opportunity to compare the proposed equations from Chapter 3 (Methodology) and their advantages and disadvantages.

4.1 INTRODUCTION

Data collection is one the most important parts of this research. This is because the ‘subject to function’ equation and ‘subject to constraint’ equation are the main ways of developing linear programming equations for each scenario study, seeking optimal solutions. To achieve this goal, two sources were collected, using primary and secondary data:

A. Primary data were collected through interviews and plant visits to the targeted companies A to C. The questionnaire contents can be found in Appendices A to B. The purposes of this data collection were to examine production processes, raw materials consumption, material flows of sand, clay, gypsum, slag, limestone, lime, fly ash, sodium hydroxide, fume, silica fume, and energy, including fuel types. These sets of data were either qualitative or quantitative data as follows:

(a) *Qualitative data method*: This was used to collect primary data from case studies using face-to-face interviews based on a questionnaire. The conversations between participants and investigators were recorded and identified as qualitative data. Because of the production of a large volume of qualitative data for storing and analysis, NVivo®, one of the best known tools to analyse qualitative data, was used, as it is faster and easier to organise material, including the production of models, charts and other visualisation techniques.

(b) *Quantitative method*: This was used in secondary data collection, and identified as quantitative data from literature. Excel® with XLMiner Analysis ToolPak® and Solver® are quantitative tools for conducting the analysis of the characteristics of curves, inter-relationships, factors, weight, independent and dependent variables and so on. These data also provided information to build the function and subject of each scenario, which was aimed at examining optimal solutions by using sensitivity analysis; the optimal solutions either maximise profits or minimise carbon dioxide emission and natural resources depletion within the three areas.

B. Secondary data were sourced from literature including the Australian Bureau of Statistics, the Cement Industry Federation (Australian), the Fly Ash Association and the Australian Quarry Institution, etc. Additionally, some financial and operational data were from the targeted companies A to C, which are publicly listed companies and well known in Australia. The objectives of secondary data collection were to find production facilities utilisation rates, costs, factories locations and routes to major clients, quarry sites and suppliers, delivered distances and frequency and cement production methods. These data were used with statistical software, such as SPSS®, Minitab®, Excel® and so on. For further analysis and discussion, see the next section.

Other purposes of primary and secondary data were to provide statistical analysis to assist probing further characteristics, such as time-series models with respect to trend and seasonality. These outcomes also provided a clue to estimate the demand equations and were used to examine minimising carbon dioxide emission and natural resources depletion while maximising profit in the production processes. They also validated the proposed framework, including equations and methods.

A further purpose of primary and secondary data collection was that it also provided a better understanding of which methods would be suitable in measuring production processes performances under the same defined boundaries for ordinary Portland cement, ordinary Portland cement with supplementary cementitious material, and fly ash based geopolymer cement manufacturing.

4.2 METHODS OF DATA COLLECTION

There are two types of data captured in the data collection phase, as discussed in the previous section. The questionnaire below was designed to collect primary data via the targeted company (e.g., Companies A to C), through supervisors and managers. The questions are as follows:

- How many types of cement do you produce?
- How much energy is used in the cement manufacture?
- What is the average operations cost for cement manufacture?
- How much carbon dioxide is emitted in the production processes?
- What percentages of raw materials are imported from overseas?
- What types of fuel are used for producing Portland and geopolymer-based cement?
- What kinds of transport are used to deliver from quarry site to factory and factory to factory?
- What are the cement facility specifications and operational data, including machine cost and labour cost of producing ordinary Portland cement and fly ash based geopolymer-based cement?

The resultant data are both qualitative and quantitative and these are discussed in Section 4.1. Analysis of these data are given in the next section for the purpose of probing further into cement production performances, in particular in minimising carbon dioxide emission, minimising natural resources depletion and maximising profits in production.

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4.2.1 PRIMARY DATA

This set of data considers each of three targeted companies from the cement industry. Because of the protection of the companies' privacy, this study refers to them as 'Companies A to C'. All data concerning the production facilities and capabilities of companies A to C are calculated on the basis of a 300-day year and a 24 hour week. The rest of the time the factories manufacture other types of cement instead of ordinary Portland cement, ordinary Portland cement with supplementary cementitious material and fly ash based geopolymer-based cement, etc. All data, whether obtained directly or indirectly, was kept confidential and used only for the purposes of this research. The research followed appropriate ethical procedures and obtained Human Ethics Clearance from the University of Southern Queensland

4.2.1.1 Company A Factory Profile and Data

Company A is one of the largest cement companies in Australia and has three major cement plants nationwide. There are three factories in different locations instead of one sizable plant in one place in order to be able to produce all types of cement at the same time, and also because of reasons to do with market segments and strategy, in minimising transportation costs and maximising geographical proximity to natural resources for cement manufacture, ensuring less carbon dioxide emission because of short distances for delivery. The three factories' locations are as follows:

- The first cement plant is in Tasmania and has its own limestone facility operation. Its capability is one million tonnes per year.
- The second cement plant is located in North Queensland and can produce over 1.7 million tonnes of cement per year, and 250,000 tonnes of lime, including for cement but also for other industries such as medicinal, internal decoration and so on, depending on quality.
- The third cement plant is located on 'A1 Island', which offers deep water access for vessels up to 25,000 tonnes capable of moving one million tonnes of cement clinker, gypsum, slag and other products. Two mills operate 24 hours a day, 300 days a year. The rest of the year is for repairs and maintenance work. The theoretical output is million tonnes each year.

- The finished cement products are stored in six silos with a shared capability of 46,000 tonnes before being loaded into bulk cement trucks via eight dispatch points by utilising sea, rail and road capabilities. Company A can cover 26 million kilometres each year with 350 pneumatic rail containers, more than 250 prime mover pneumatic tankers and 24 hour operation.

Table 4.1 Summaries of Three Plants Yearly Capabilities of Manufacturing Cement (Cement Industry Federation, 2013 to 2016; Company A, 2015)

Productivity / **Processes**	**Capability (Tonne/year)**	**Machine (24hr/day)**	**300-work days**
Coarse grinding	1,500,000	1 mill	432,000 minutes
Mixer	1,200,000	2 mixers	432,000 minutes
Admixture (SCM)	400,000	1 surveyor	432,000 minutes
Fine grinding	1,500,000	1 mill	432,000 minutes
Clinker (Cement)	1,600,000	1 clinker	432,000 minutes
Packing	1,700,000	bulk bag	432,000 minutes
Silo (Store)	46,000	6 sets	432,000 minutes
Transport including vessel and rail	46,000	300 cycle times	432,000 minutes
Delivered distances	26,000,000km		432,000 minutes

Table 4.1 illustrates the three factories' capabilities and work flows, which are the same as Figure 2.3, Figure 2.6 and Figure 2.9. The major source of carbon emissions was from producing lime from limestone, including transportation and intensive energy use for heat. Table 4.1 provides data to develop linear programming equations problems and also to generate sensitivity analysis reports to examine optimal solutions for production.

4.2.1.2 Company B Factory Profile and Data

Company B is a joint venture company between German and American cement firms. It was established more than 60 years ago and is located at Port of Brisbane. This location provides several advantages to Company B; it is more convenient for importing raw materials and distributing cement to elsewhere in Australia and exporting overseas via ship, by truck and by air. Another advantage is the factory can also function as a grinding, packing and cement distribution centre. The factory capacity is as follows:

- Each year, it produces over 1.5 million tonnes (Company B, 2014) of cement and turnover is around A$150 million (Company B, 2014).
- The majority of the production facilities are imported from America and Germany. It uses wet and semi-wet-dry kilns (see Figure 2.2) instead of dry kilns (see Figures 2.1, Figure 2.3 and Figure 2.6) to mainline dust generation in the production process and extra dust bags to collect dust in the grinding process (Marceau et al., 2006). It is a traditional mill (Atmaca and Kanolglu, 2012) with a capability of 600 tonnes/hour (Cement Industry Federation, 2013). An image of this vertical ball mill and its specifications are given in Figure D.1 and Table C4.1 respectively.

Company B is an ISO 9001 certified factory and accredited laboratory facility for the National Australian Testing Authority. Therefore its products can be tailor-made to clients’ requirements, and a variety product ranges are available. This is one of the major differences between Company A and Company C. Although it can produce a wide range of cements including white and grey cement, this research is only concerned with ordinary Portland cement, Portland cement with supplementary cementitious materials (see Table 2.1 as marked by red box), and fly ash based geopolymer cement (as shown in Figure 2.7 and Table 2.6).

Table 4.2 Plant Capability of Ordinary Portland Cement Production for Company B (2015)

Productivity / Processes	Capability (Tonne/year)	Machine (24hr/day)	300 work days
Coarse grinding	1,700,000	1 mill	432,000 minutes
Mixer	1,200,000	2 mixers	432,000 minutes
Admixture	560,000	1 surveyor	432,000 minutes
Fine grinding	1,700,000	1 mill	432,000 minutes
Clinker (Cement)	1,800,000	1 clinker	432,000 minutes
Silo(Store)	7,000	8 sets	432,000 minutes
Transport including, rail, ship and truck	56,000	300 cycle times	432,000 minutes

The factory capabilities are shown in Table 4.2. The majority (e.g. 80%) of raw materials including coal, limestone, clay, slag and sand etc. are obtained via ship. The average distances are around 300km to 800km.

Coal is commonly used in the clinker process and each year 2000 to 2500 tonnes (Company B, 2014) of brown coal and 1,000 tonnes (Company B, 2014) of diesel fuel and 100GJ/hr electricity are consumed. This factory works 24 hours a day, 7 days a week and has 300 working days. The remaining 65 days are spent producing other types of cement or carrying out repair and maintenance work.

A further breakdown of the factory capabilities of each of the processes including crushing, coarse grinding, mixing, kiln, fine-grinding and packing, etc., is shown in Table 4.3.

Table 4.3 Plant Capability for Ordinary Portland Cement with Supplementary Cementitious Materials for Company B (2015)

Productivity **Process**	**Unit processing capability (tonne/hour)**		**Availability (hour)**
	OPC (tonne/hr)	**OPC with SCM cement (tonne/hr)**	
Crushing	3.1	3.1	3000
Vertical roller mill (coarse grinding)	2.6	2.6	7,200
Additive (SCM)	0	1	7,200
Clinker	3	3	7,200
Additive (gypsum)	1	1	7,200
Ball mill (fine grinding)	2.99	2.99	7,200
Packing	3	3	7,200

This process is only to produce OPC with SCM cement

Table 4.3 illustrates the typical production processes flows to produce ordinary Portland cement and ordinary Portland cement with supplementary cementitious materials cement in Company B. This table is also a clue to develop the appropriate linear equation seeking optimal production and profit. This study will be discussed in the Scenario 1 section further.

A high level of noise is generated in the crushing process and it is normally outdoor work rather than an indoor operation. The gravel must undergo a process ensuring the appropriateness of the sizes of gravel pieces which pass through a defined screen before use for cement production. This also reduces the coarse grinding loading and the service life of the mill ball. The working hours of this are only 10 hours operation per day and 300 days a year because the rest of the time, the cement plant produces other types of cement such as high performance cement, white Portland cement, Portland Pozzolan cement and so on, as shown in Table 2.1. This period of time also serves for condition-based repair and maintenance services.

4.2.1.3 Company C Factory Profile and Data

Company C has been established for more than 30 years and is a small-scale cement company compared with companies A and B. The major business is a grinding factory. This means some upfront processes are carried out overseas and the products imported to this factory, such as coarse grinding, mixing, kilning and so on. The final processes such as adding gypsum, mixing and fine-grinding, packing including bulk bags and distribution processes have been carried out in this Australian factory and the products stored in silos.

This factory also provides a cement production service to an affiliated cement manufacturer. As such, it uses flexible manufacturing methods and acts as a cement distribution centre and concrete manufacturer as well as providing transport services. To analyse the three areas of production, detailed machine capabilities are shown in Table 4.4. Here, there is no geopolymer-based cement production. Each year, the factory can produce 0.6 million tonnes of cement and also provide Australian Standards AS 3972, AS 3582.1, AS 35825.2, AS 3582.3 cement. It has an ISO 9001 accredited National Association Testing Authorised laboratory on site, dealing with both Australian-produced and worldwide-manufactured cementitious materials and providing materials to the Department of Transport and Main Roads (MRTS) 70 and Specification SP 43 cement and cementitious materials for concrete.

Table 4.4 Plant Capability of Company C (2015)

Productivity **Process**	**Capability (Tonne/year)**	**Machine (24hr/day)**	**300 work days**
Fine grinding	500,000	1 mill	432,000 minutes
Clinker (Cement)	600,000	1 clinker	432,000 minutes
Silo (Store)	5,000	8 sets	432,000 minutes
Transport including ship and truck	50,000	300 cycle times	432,000 minutes

There are several limitations of Company C

- Table 4.4 illustrates Company C's production capability. This assumes there are no down times and that all production facilities are always in good conditions.

- The factory works 24 hours a day and 7 days a week for 300 days a year. The remaining days are for repairs and maintenance of the equipment (Australian Bureau of Statistics, 2014 and Cement Industry Federation, 2014).

- One of the scenarios was based on this information to develop the linear equation to calculate carbon dioxide emission, because its material supply chain and feedstock was different from expectations compared with companies A and B. Therefore, this study only took account of the distances from quarry sites to the cement factory and also of the distribution of cement from factory to client within Australia. This is because these sets of secondary data were easily collected from annual financial reports (Company C, 2015).

- The production boundary is based on Figure 2.6 and Table 2.4. This study only considered the last two processes of mixing and grinding gypsum as the cradle-to-function and ordinary Portland cement and supplementary cementitious material with ordinary Portland cement as cradle-to-cradle. This is because this cement plant is classified as a grinding factory and not an integrated cement plant (Cement Industry Federation, 2013).

4.2.2 SECONDARY DATA

This set of data are from the Australian Bureau of Statistics (2014 and 2015), Australian Government (2014 and 2015), Fly Ash Australia (2015), Cement Industry Federation (2014 and 2015), Ash Development Association (2014 and 2015), Environmental Life-cycle Inventory of Portland Cement Concrete, Department of Transport and Main Road, SP 70, AS 3582 Parts 1 and 2, AS 3972 - Cement Performances Parameters, Annual financial reports and released relevant environmental effect in cement production from the literature of targeted companies.

4.2.2.1 *Raw Material Consumption and Costs for Ordinary Portland Cement*

The secondary data concerning raw materials consumption and costs for ordinary Portland cement production was based on 2013 to 2015 as shown in Tables 4.3 and 4.6

including limestone, clay, sand, slag and gypsum. The prices and raw materials consumption as shown in Tables 4.3 and 4.6 for cement industry were the average prices and had 5 to 8% (Companies A to C, 2014) fluctuation as the results some processes or raw materials would been outsourced overseas, as the results it is one of consumption that all raw materials will be outsourced in defined boundaries and also keep an ex-factory in constants for certain period of times. In addition, some small cement factories' have eliminated some front stream processes, in kiln usage, avoiding intensive energy consumption and environmental effect issues, and import semi-cement products from overseas, mixing them with gypsum, grinding them and packing them for the Australian market. Therefore, this study only considers what kinds of raw materials have been consumed in the ordinary Portland cement production. The cost estimation method is one of the solutions to tackle natural resources depletion by using statistical methods.

Table 4.5 Raw Materials Consumption for Ordinary Portland Cement from 2013 to 2015 (Australian Bureau of Statistics, 2013 and 2015; United States Geological Survey (USGS), 2013 to 2014; Cement Industry Federation, 2013 to 2015)

Year **Raw Material Name**	**2013**	**2014**	**2015**	**Subtotal**
	Thousand Metric Tonnes			
Limestone	2,200	2,300	2,350	6,850
Clay	2,000	2,550	2,700	7,250
Sand	2,500	2,450	2,500	7,450
Gypsum	600	650	650	2,350
Gravel	790	810	830	2,430
Silica	500	800	890	2,190
Subtotal (thousand metric tonnes)	8,590	10,010	10,370	28,970

Raw materials consumption, including limestone, clay, sand, gypsum, gravel, silica, etc., from 2013 to 2015, is shown in Table 4.5. The highlighted area in the red box shows that a total of 28,970 thousand tonnes of raw materials were used for cement production. In contrast, 8.1, 9.3 and 9.31 million tonnes of ordinary Portland cement were made in Australia in 2012 to 2015 respectively (Cement Industry Federation, 2016). Some raw materials became dust and were collected by dust bags, in the milling or grinding production processes (Marceau et al., 2006; Cement Industry Federation, 2014).

The total amount of raw materials consumption was discussed in Table 4.5. Based on its outcomes and multiple raw materials costs, the subtotal amount is shown in Table 4.6. The average turnover was 2.3 billion Australian dollars from 2012 to 2015 (Cement Industry Federation, 2013). It occupied $\frac{74022000}{230000000} * 100 = 32.183\%$ of the total expenditure. Bulk cement prices also increased in New South Wales, Tasmania and South Australia by A$15 per tonne for white cement and A$10 per tonne for grey cement, effective 1 April 2017 (Australian Government, 2017). Therefore, cost control for cement production is one of the issues.

Table 4.6 Raw Material Cost of Producing Ordinary Portland Cement from 2013 to 2015 (Australian Bureau of Statistics, 2014; McLellan et al., 2011; Habert et al., 2013; Companies A to C, 2015; Alibaba, 2015; Bunnings Warehouse, 2015)

Price **Raw Material**	**Cost (A$/tonne)**	**Three Years Raw Material Consumption based on Table 4.5 Results** **(Thousand Metric Tonnes)**	**Subtotal (A$)**
Limestone	1.8	6,850	12,330,000
Clay	1.2	7,250	8,700,000
Sand	1.1	7,450	8,195,000
Gravel	1.4	1,900	3,290,000
Gypsum	1.3	2,430	5,159,000
Slag	1.0	2,190	2,190,000
Subtotal (A$)	7.8	28,070	74,022,000

This table illustrates production of ordinary Portland cement in different ratios of limestone (lime), clay, sand, slag and gypsum; therefore the prices are considered by proportion mix ratio with respect to quantities per kilogram as shown in Table 4.6.

4.2.2.2 Raw Material Consumption and Costs for Fly Ash Based Geopolymer Cement

The raw materials and costs for fly ash based geopolymer cement, ground-granulate blast slag-based geopolymer cement, metakaolin (MK) based geopolymer cement and supplementary cementitious materials are shown in Tables 4.6 to 4.7 respectively.

Table 4.7 Raw Material Consumption for Fly Ash Based Geopolymer Cement Production from 2013 to 2015 (Cement Industry Federation, 2014 and 2015; Company A, 2015)

Year Raw Material Name	**2013**	**2014**	**2015**	**Subtotal**
	Thousand Metric Tonnes			
Fly ash	802	890	900	2,992
Sodium hydroxide (NaOH)	1,100	1,100	1,100	3,300
Sand	2,500	2,450	2,500	7,450
Slag	730	730	6,500	7,960
Subtotal (Thousand Metric Tonnes)	5,132	5,170	11,000	21,302

Table 4.7 identifies trends of the raw materials, including sand, sodium hydroxide (NaOH) liquid, by-product fly ash and slag consumption from 2012 to 2015. One of the fly ash based geopolymer cements (Davidovits, 1991; Duxson et al., 2007) is called Zeolite, known as one of the green cements, which emits 0.675 CO_2 kg/kg in production. However, its price is higher than ordinary Portland cement (Chan et al., 2015; Company A, 2015) and further discussion is in Table 4.8 and item (d) (see page 105). One of the solutions is optimal use of materials in manufacturing. Further, fly ash and slag also serve as supplementary cementitious materials to cut carbon dioxide emissions. These kinds of materials are also very expensive and increased in cost by 2% in 2014 (Australian Bureau of Statistics, 2014). The Liddell coal-fired power station will be closed in 2022 (Parliament of Australia, 2017), and this is expected to push up the fly ash price as well.

Table 4.8 Raw Material Cost of Producing Fly Ash based Geopolymer Cement (Australian Bureau of Statistics, 2014 and 2015 and McLellan et al., 2013)

Price Raw Material	**Cost (A$/tonne)**	**Three Years Raw Material Consumption based on Table 4.7 Results (Thousand Metric Tonnes)**	**Subtotal (A$)**
Fly ash	3.7	2,592	9590,400
Sodium hydroxide	3.3	3,300	10,890,000
Sand	1.1	7,400	8,195,000
Slag	1	7,940	7,960,000
Subtotal (A$)	9.1	21,302	36,635,400

The theoretical fundamental contents and basic quantity (McLellan et al., 2011) as shown in Table 4.8 are to produce one kilogram of fly ash based geopolymer cement. However, this does not take account of significant dust particles suspension (Gani, 1997) in the production process (Peray, 1979). Several items are identified in Table 4.8.

(a) Fly ash is one of the major contents in fly ash based geopolymer cement production. The fly ash is one of the most expensive raw materials.

(b) Sodium hydroxide (NaOH) is used in fly ash based geopolymer cement for its chemical reaction with fly ash. The majority of the sodium hydroxide (NaOH) solution is imported from overseas (McLellan et al., 2011) and it is not cheap (Cement Industry Federation, 2013). Its substitution is potassium hydroxide (KOH) solution, which is cheaper, but the production method is more complex than when using a sodium hydroxide (NaOH) solution.

(c) The sand used is a special sand from rivers. The purity of it contains fewer silicate substitutes (Australian Bureau of Statistics, 2014) for fly ash based geopolymer cement production, ensuring good quality outcomes.

(d) The raw materials costs of fly ash based geoplymer cement is higher than ordinary Portland cement, as shown in Table 4.6 and Table 4.8, material cost per tonnes outcomes results as obtained:

$$\frac{9.10-7.8}{7.8}*100\%=17\%$$

This means the raw materials of fly ash based geopolymer cement are 17% higher than ordinary Portland cement in terms of cost. Normally, supplementary cementitious material is a small portion of an ordinary Portland cement - less than 2% in composition (Potter, 1991; Cement Industry Federation, 2014; Company A, 2015). Its material cost is cheaper than fly ash based geopolymer cement. In the mass of ordinary Portland cement and fly ash based geopolymer cement production, if the quantities in terms of kilogram are changed to tonnes or kilo-tonnes, the price per unit item is changed to Australian dollar per thousand million tonnes instead of kilograms. This data were collected from Bunnings warehouse. In contrast, in developing a linear programming equation seeking optimal profits, all units involved in Tables 4.5 to 4.6 for ordinary Portland cement and Tables 4.7 to 4.8 for fly ash based geopolymer cement, would be at the same level, eliminating unnecessary calculation errors.

Table 4.9 Domestic Material Consumption in the Asia-Pacific Region Over Three Decades (Schandl and West, 2010)

	1975	1985	1995	2005
Fossil Energy carriers(Mt)	1,283	1,884	3,184	4,762
Coal	60%	67%	63%	65%
Petroleum products	37%	29%	29%	26%
Natural gas	3%	4%	8%	9%
Metal ores and concentrates, processed metals(Mt)	514	658	1,156	2,267
Iron ores and concentrates, iron and steel	41%	42%	37%	39%
Non-ferrous metals and processed metals	59%	58%	63%	61%
Construction minerals(Mt)	2,054	3,948	9,255	16,184
Cement related	60%	64%	69%	74%
Non-cement related	40%	36%	31%	26%

Table 4.9 shows three decades of domestic material consumption time-series data including trend and seasonality. This provides data to develop the time-series for regression models, such as indices and forecasts, etc., and is discussed in the next section.

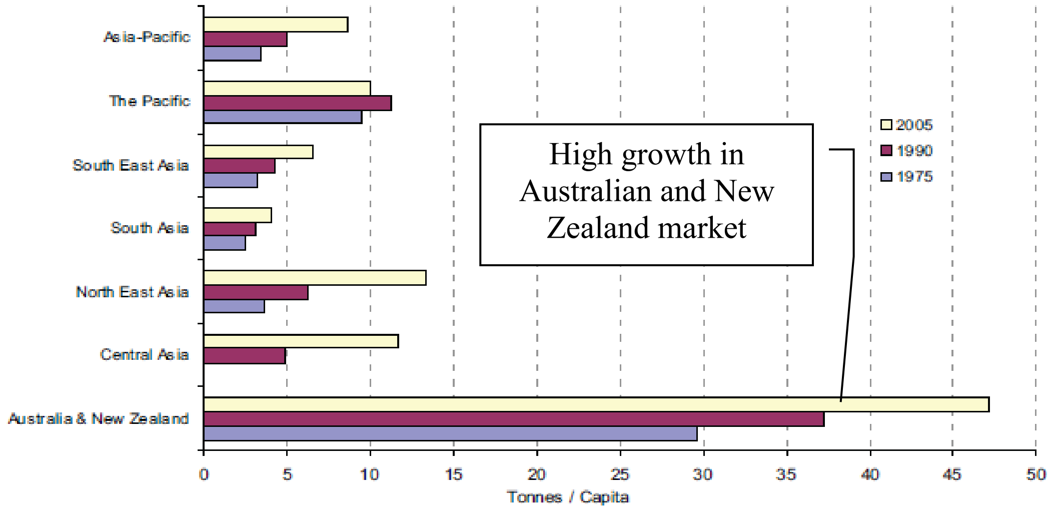


Figure 4.1 Domestic Materials Consumption per Capita for Asia-Pacific Region (Image Courtesy of Schandl and West, 2010)

Figures 4.1 and 4.2 provide information about the huge growth of domestic material consumption in the Asia-Pacific market. Raw materials resources companies and quarry firms took this opportunity to export large quantities of raw materials overseas.

This was significant enough to cause potential abiotic depletion problems and environmental effects. To quantitatively measure this kind of effect, statistical tools are one solution.

In the next section, XLMiner Analysis ToolPak® in a spreadsheet-based format will be used to discuss this issue, using a time-series for regressive model method. One of the expected outcomes is seasonality indices for domestic materials consumption in an Asia-Pacific demand market and also the abiotic depletion potential in the coming year.

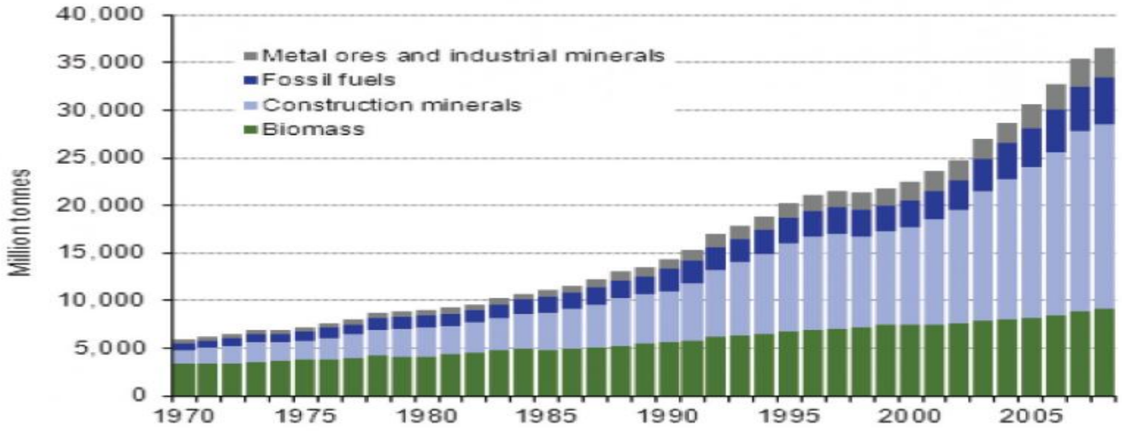
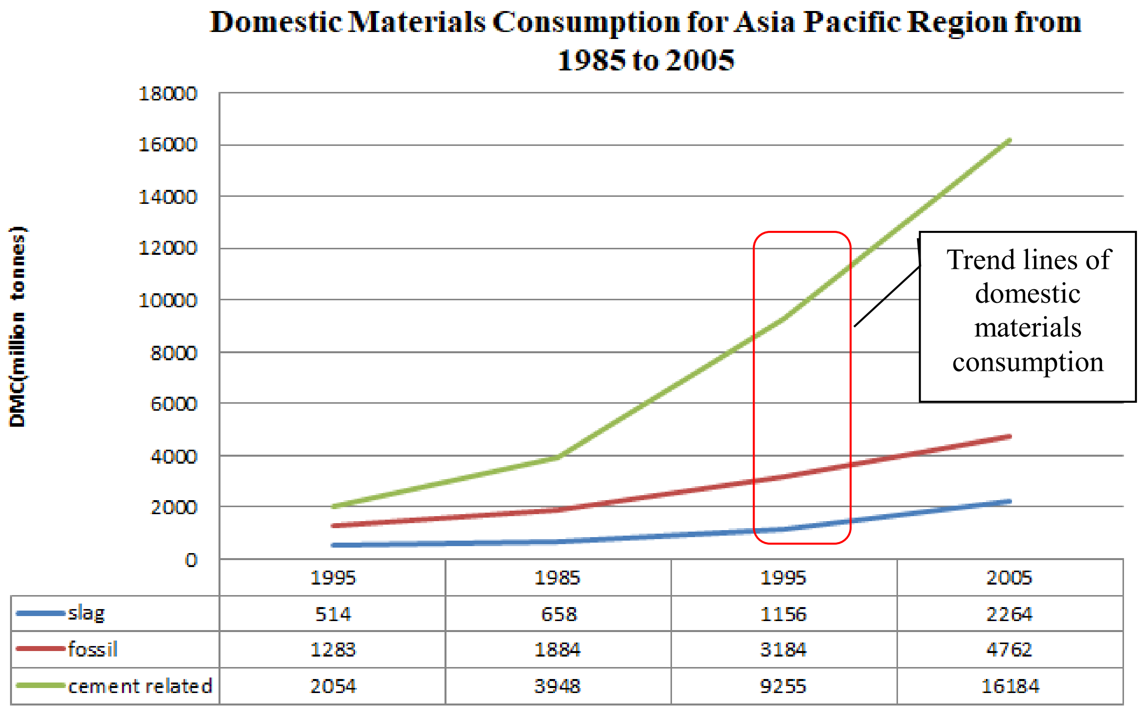


Figure 4.2 Domestic Materials Extraction in the Asia-Pacific Region from 1970 to 2005 (Image Courtesy of Visually, 2016)

Additionally, the data sources for time-series were based on Figure 4.1 and 4.2 respectively. This data were used to plot a curve by using spreadsheet program Excel® to analyse what type of curve fits, such as polynomial curves, including quadratic and linear curves, exponential curves and so on. The domestic material consumption equation is found based on the curve characteristics. Further discussion is in the next section.



	1995	1985	1995	2005
slag	514	658	1156	2264
fossil	1283	1884	3184	4762
cement related	2054	3948	9255	16184

Figure 4.3 The Trend lines of Domestic Materials Consumption Including Fossil Fuel Carrier, Slag and Cement Related per Capita for Asia-Pacific Region (Schandl and West, 2010)

Figures 4.1 to 4.2 show the domestic material consumption and extraction status from 1970 to 2005 (Visually, 2016; Schandl and West, 2010). To better analyse this set of data Excel's Chart wizard was used, adding a trend line, by selecting the options under trend/regression, the trend lines of regressive model times were found for series data including fossil fuel, slag and cement from 1975 to 2005, as shown in Figure 4.3. This method adapted and extended by Habert et al., (2010), who used it in examining reserves and abiotic depletion potential in French regions. The equation for domestic material consumption uses an exponential equation with the assistance of well-known environmental software. In contrast, this study uses fundamental theory to find out the curve characteristics by using statistical methods (e.g., Excel), which provide a good fit to the historical data and the most likely accurate description of the future values of the time-series (Lafare et al., 2016). The seasonality index was developed based on the time-series for a regressive model and curve shape. The outcome, as shown in Figure 4.3 in the trend lines, are polynomial lines including quadratic and linear equations based on curve characteristics. Here, a domestic material consumption equation was solved and further discussion is provided in Chapter 5 as to how to calculate the 'reserve' values based on the assigned equation in Chapter 3. Curve identification can be:

(a) An exponential equation with respect to $y = ae^{bx}$. This type of equation is used when the dependent variable is changing by a constant per cent (Harris and Fraser, 2002; Habert et al., 2013; Lawrence, 2014).

(b) A power equation with respect to $y = ax^b$. This type of equation is commonly used in business problems, in learning curves as the manufacturer took time to learn the best ways to produce cheaper cement over time (Reilly and Brown, 2003; Leepsa and Mishra, 2013).

(c) A polynomial equation with respect to $y = a + bx + cx^2$ in degree of 2 including linear and quadratic equations. These types of equation are often used for linear programming and cost modelling curves (Copeland, 2013; Gass, 2002; Lasher, 2013; Lawrence, 2014; Lafare et al., 2016).

These lines, as shown in Figure 4.3, are linear equations based on curve characteristics. These sets of time-series data and regressive model equations are a good tool to analyse the trend by using seasoning or de-seasoning indices (Copeland, 2013; Lafare et al., 2016) as obtained:

$$index = \frac{S_{n+1}}{S_n} \qquad \text{………..........} \quad (4.1)$$

where

S_{n+1} = frontal data of S_n
S_n = backward data of S_{n+1}

(d) Considered 'fossil fuel carrier row' for three decades seasonality indices ratios using equation (4.1) as follows:

$$\frac{1884}{1283} = 1.47; \frac{3184}{1884} = 1.69; \frac{4762}{3184} = 1.5 \qquad \text{....................} \quad (4.2)$$

The variation of fossil fuel in three decades was 0.22 as the result of $1.69 - 1.47$ and the average index ratio is 1.55.

(e) Considered 'slag including iron ore and steel row' for three decades seasonality indices ratios are as follows:

$$\frac{658}{514} = 1.28; \frac{1156}{658} = 1.76; \frac{2264}{1156} = 1.96 \qquad \text{....................} \quad (4.3)$$

The variation of slag including iron ore and steel in three decades was 0.68 as the result of $1.96-1.28$ and the average index ratio is 1.67.

(f) Considered ‘cement related row’ for three decades seasonality indices ratios are as follows:

$$\frac{3948}{2054}=1.94;\frac{9255}{3948}=2.34;\frac{16184}{9255}=1.75 \qquad \ldots\ldots\ldots\ldots\ldots \qquad (4.4)$$

The variation of cement related in three decades is 0.59 as the result of $2.34-1.75$ and the average index ratio is 2.01. Additionally, this provides clues to forecast domestic material consumption in the next decades, 2015 or 2035 based on trend lines equations and expressed as:

Forecast DMC = seasonality index * forecast using trend line equation ….(4.5)

Table 4.10 Seasonality Indices for Fossil Fuel, Slag, Cement Related Products for Three Decades (Copeland, 2013 and Lafare et al., 2016)

Index / Year	1975	1985	1995	Average
Fossil fuel	1.47	1.69	1.5	1.55
Slag	1.28	1.74	1.96	1.67
Cement related	1.94	2.34	1.75	2.01

Three forecast trend line equations are identified as polynomial equations based on Figure 4.1. The three year seasonality index of the slag, cement related product and fossil fuel is in Table 4.10 (red box), which can be used in a forecast.

Taking cement related data in Table 4.10 as forecast domestic material consumption (DMC) as it consumed a large quantity of raw materials to make cement and as obtained:

Forecast DMC in terms of ‘n’ year $\Rightarrow y_n = 1.75*(a+bx_n+cx_n{}^2)$ …… (4.6)

where

a, b and c are constants

The aim of this work was earlier stated as being to examine domestic material consumption in 2015 to 2025 and provide theoretical information concerning raw materials stock and send a clear message to the cement industry's material suppliers as to when raw materials will be exhausted; thus new sources would be explored at the right time based on the fact that Australia is rich in abiotic and biotic resources. It will also ensure the continued boom of the cement export business. In addition, these figures also provide a clue as to carbon dioxide emission based on the Carbon Dioxide Emission Equivalent method or the Australian National Greenhouse Factors Accounts (2014 to 2016) method as discussed in Chapter 3.

Further, from Tables 4.9 to 4.10 and Figures 4.1 to 4.2, we can see that growth rates were nearly 60% in cement related products for the Asia-Pacific region, causing natural resources depletion issues. To better understand this issue, equations (3.8) to (3.10), Table 4.8 and Figure 4.1 are used to evaluate how much abiotic depletion and reserve would occur in order to meet market demand. It also provides information to calculate how much carbon dioxide emission occurs over 30 years of the cement industry by using the Carbon Dioxide Emission Equivalent method and Australian National Greenhouse Accounts Factors (2014) method. From equations (3.4) and (3.5), this study also provides more data related to kiln dust and the degree of calcinations of cement kiln dust produced in preparing limestone to lime. Equation (3.6) is most suitable for calculating carbon dioxide emission in past cement production. Based on outcome forecast DMC results, it can also calculate carbon dioxide emission in 2025 respectively.

In the collection of primary data processes, raw materials costs can be found on Australian Government websites, including the Australian Bureau of Statistics, Department of Manufacturing and Commerce and so on. Such data are classified as secondary data and this study did not consider collecting them using surveys.

4.2.2.3 Fuel Cost and Energy Distribution for Cement Production

Several types of fuels and energy cost, including petrol, diesel, LPG and electricity (as shown in Table 4.11 and Figures 4.3 to 4.4) are identified in cement production and transport based on the defined boundaries for companies A to C. Coal and diesel oil are the major energy providers to cement production.

(a) Fuel Costs

Four types of fuel costs are used in the cement industry as shown in Table 4.11 based on literature, Company A, survey data and electricity fees in Queensland from 2014 to 2016. This study took the average of each item from different sources using statistical methods with the assistance of Excel®. The average values of each category of fuel are considered to formulate linear programming equations for seeking optimal operational cost solutions over the three areas.

Table 4.11 Fuel Typed Used of OPC Manufacture (Collins, 2013; Huntzinger and Eatmon, 2009; Australian Bureau of Statistics, 2014 and 2015; World Bank, 2014)

Year / **Fuel typed cost**	**2013**	**2014**	**2015**	**Unit**
Petrol	1.62	1.35	1.5	A$/litre
Diesel	1.78	1.71	1.5	A$/litre
Coal	79.7	66.2	57.5	US/Mt
LPG	1.1	1.1	1	A$/litre
Electricity	1.55	1.32	1.3	Kw/hr

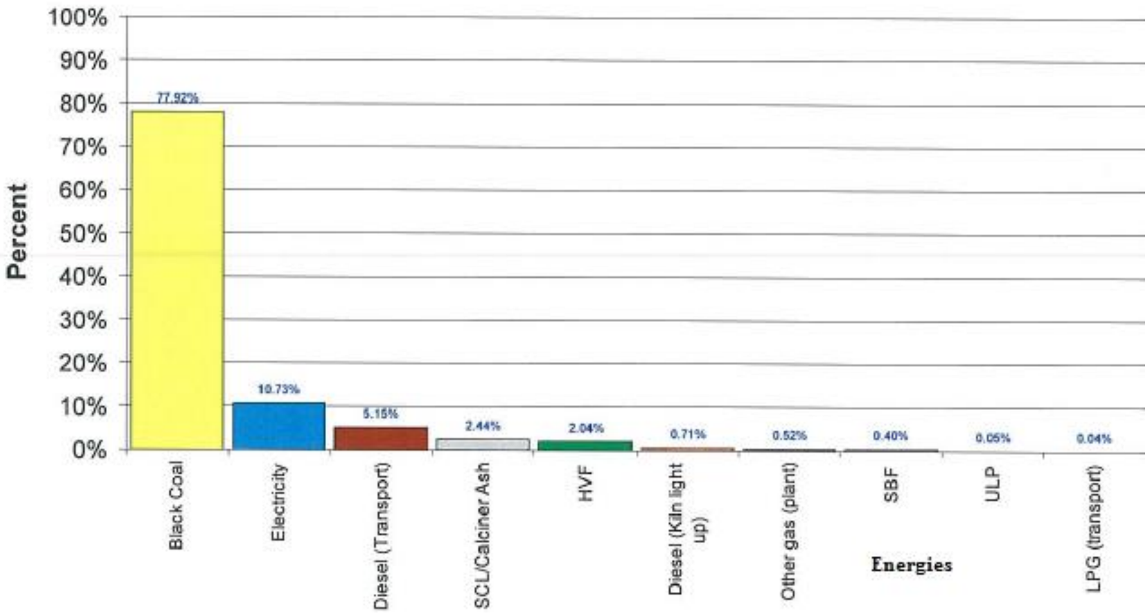


Figure 4.4 Classical Fuel Types Distribution in Cement Production (Company A, 2015)

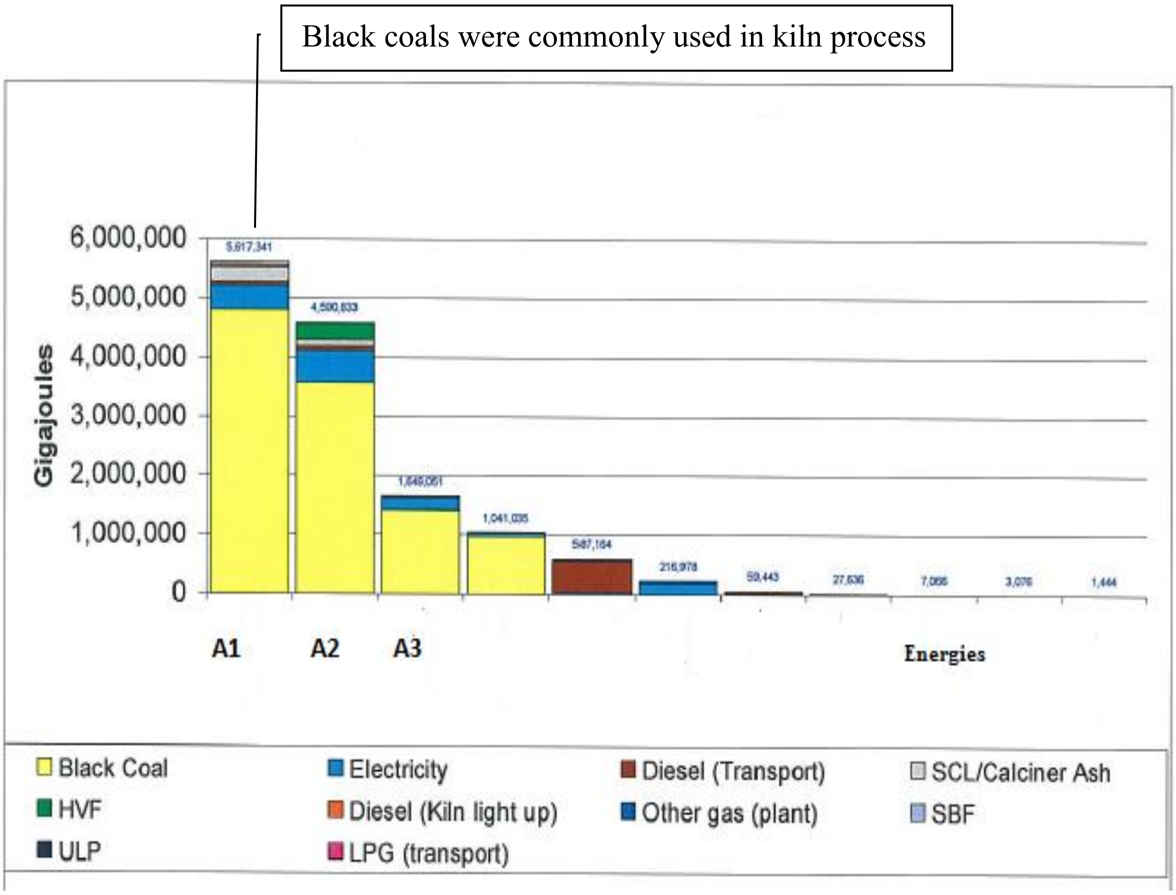

Black coals were commonly used in kiln process

Figure 4.5 Classical Energy Distributions in Cement Production (Company A, 2015)

(b) Fuel Types and Energy Distribution

Figures 4.4 to 4.5 concern Company A and illustrate the distribution of classical fuel types and energy consumption in cement production. Black coal is commonly used as the fuel in the kiln process. It supplies around 5,000,000GJ of power to cement production, as shown in Figure 4.4, and produces 1.6 million tonnes of cement per year (Company A, 2015). This means 1 tonne of cement consumes 3.21GJ, because dry-type kilns prepare clinker by elevating the temperature to 1,450˚C, and consequently a chemical reaction takes place to form cement after fine-grinding. To produce such heat, coal is one of the solutions, as a result of ranking number one in energy used in cement manufacturing. Consequently, carbon dioxide emissions are also increasing. This information is useful to formulate linear programming equations in ‘subject to constraints’ to seek optimal solutions.

4.2.2.4 Distance Measure

Distances are measured from quarry site to cement factories - Companies A to C, based on a DITR (2006) map and domestic feedstock sources map, as shown in Figures 4.5 to 4.6, by using global position system and manual calculation via scale. The distance results are shown in Table 4.10. All primary data collected from targeted factories were used for scenario studies. The major cement factories are located Queensland.

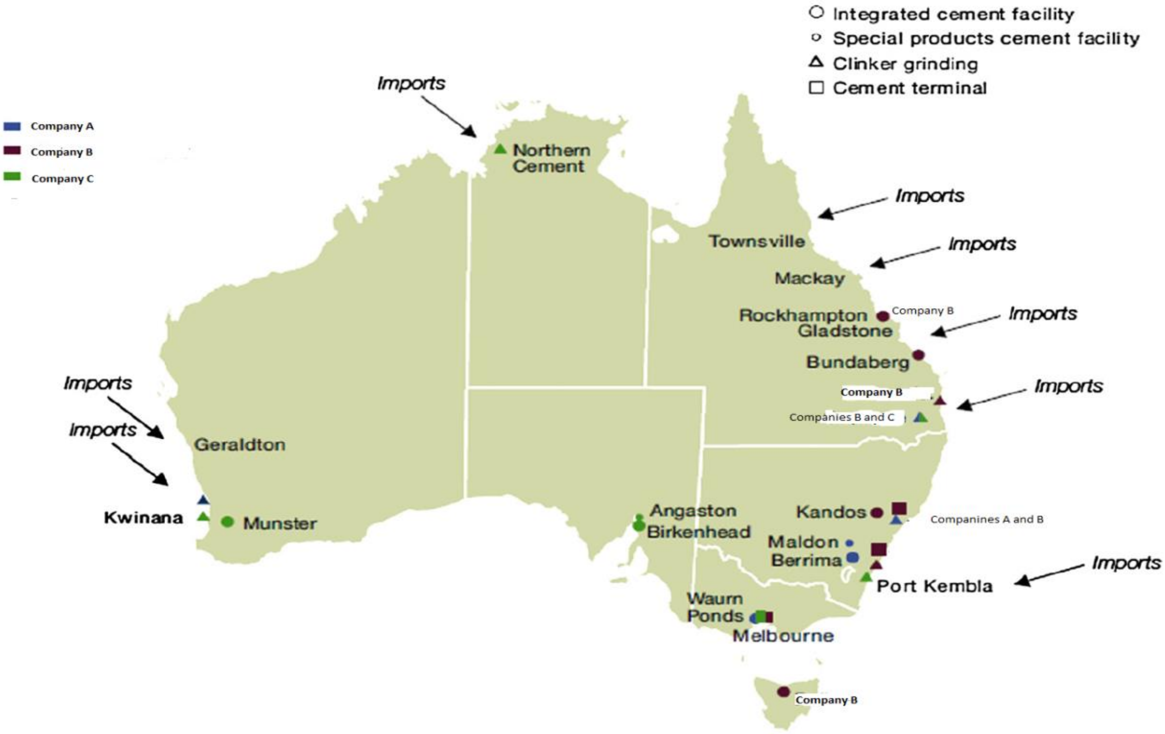
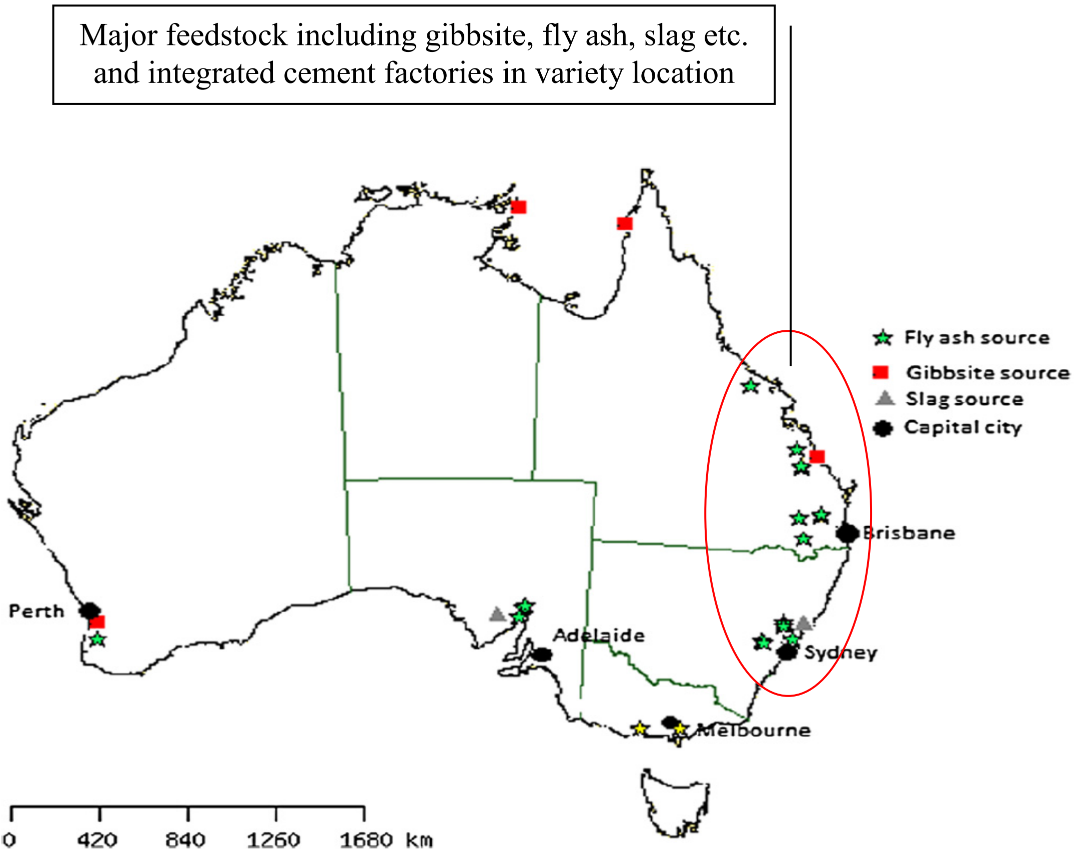


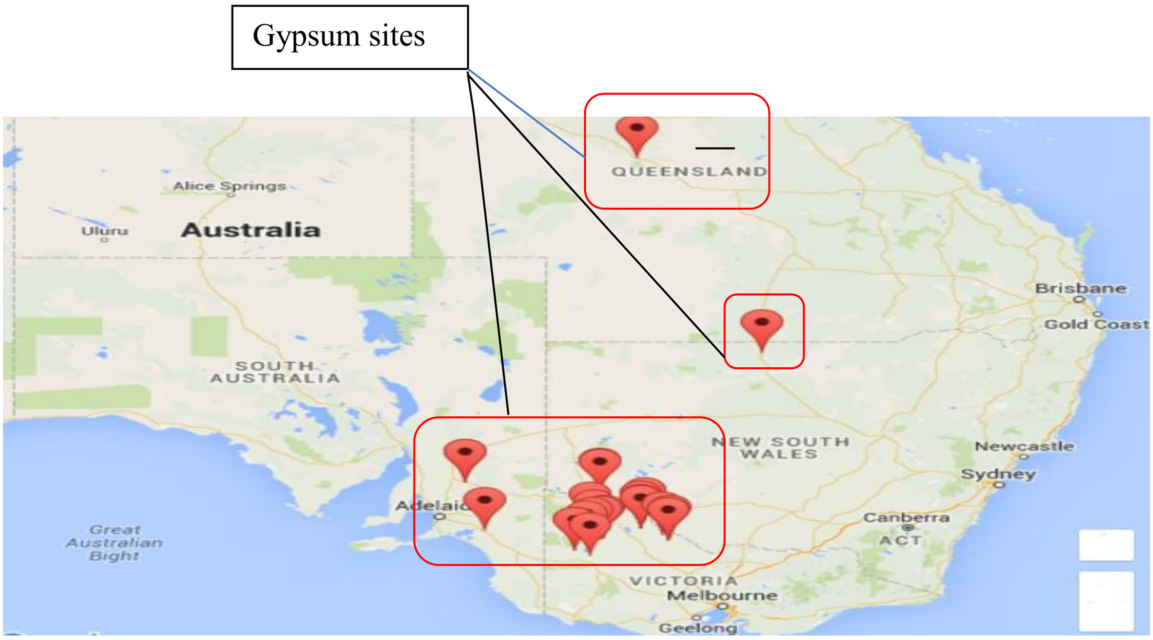
Figure 4.6 Map of OPC Cement Production and Import Centre (Image Courtesy of DITR, 2006 - Adapted and Extended with Respect to Cement Factory Location)

Figure 4.6 is a general map illustrating the integrated cement facilities, special product cement facilities, clinker grinding and cement terminal as well as the import centres, which are in the major harbours. Compared with other states in Australia, Queensland has more integrated cement facilities and clinker grinding factories; it produces 40% of the total cement capability (Cement Industry Federation, 2014) of Australia. North Queensland is one of the richest sources of raw materials for supplying ordinary Portland cement and fly ash based geopolymer cement production. Because of this, one of the major fly ash based geopolymer cement factories of Company A is in North Queensland; ensuring raw material feedstock is healthy. Clinker grinding factories are also more numerous in Queensland than in other states; they are energy intensive and produce a lot of carbon dioxide. Therefore, one of the scenarios is how to minimise carbon dioxide emission and cause less natural resources depletion while maximising profit.



Major feedstock including gibbsite, fly ash, slag etc. and integrated cement factories in variety location

Figure 4.7 Maps of Domestic Feedstock Sources (Image Courtesy of McLellan et al., 2011)



Gypsum sites

Figure 4.8 Known Gypsum Sites in Australia (Google Map, 2016; National Gypsum Miners Association, 2017)

Many coal mining sites are located in Northern Queensland and as a result there are many major coal-fired power stations located close to them in order to shorten coal delivery times; consequently there is a lot of fly ash produced in Queensland compared with other states in Australia, as shown in Figures 4.7 to 4.8. These are one of the key suppliers providing raw materials, including slag, calcium sulfate dehydrates (gypsum-$CaSO.2H_2O$), basic aluminium hydroxide (gibbsite)-$Al(OH)_3$, limestone, lime, sodium hydroxide, etc., to cement factories.

Raw materials from quarry sites, including gypsum (as shown in Table 4.8), are generally located in the southern part of Australia. Gypsum is used in the cement industry by adding it at the rate of between two and five per cent to cement clinker as it is ground. This slows its setting rate when used to make concrete. The main gibbsite (bauxite) sites are located at Weipa in Queensland (Australian Government, 2017; McLellan et al., 2011). Because of these geographical locations, sea freight is commonly used to transport materials from quarry sites to cement factories.

Table 4.12 Quarry Sites Away from Companies A to C

Vessel	From quarry-to-factory	Unit
By ship	1050	km
By heavy dump truck	1125	km
By air	980	km

One finding is that ordinary Portland cement and geopolymer-based factories are located close to waterways, as shown in Figures 4.6 to 4.8, providing an alternative for delivering cement nationally and internationally. Thus, Scenario 6 is based on Table 4.12, developing one of the ‘subject to constraints’ linear programming equations.

Raw materials delivered by air were transported over shorter distances than those transported by ship and heavy truck, but fuel consumption by air is significantly higher than by ship or truck. Consequently, the carbon dioxide emissions and operational costs are expected to be higher.

4.2.2.5 Secondary Data from Typical American Cement Production

Sections 4.2.2.1 to 4.2.2.2 discussed raw materials, fuel types and energy consumption in Australian cement production. Some production data are from American cement factories. Company C is one kind of cement plant that produces cement on a small scale. This provides an opportunity to compare energy performances under the same type of production in American and Australian cement factories.

Coal is a major fuel and energy provider in cement manufacturing (Company A). Coal itself contains carbon. Once coal is burnt and mixed with sufficient oxygen, carbon dioxide is emitted to the atmosphere. In kiln processes in Australian-owned cement production brown coal is often used (USGS, 2012; Parliament of Australia, 2017), which means that more carbon dioxide is emitted than that by American cement plants. This is based on an average energy consumption of about 0.5 million Btu (119KWh per tonne) of cement production in rotary kilns in American cement plants (Peray, 1979), using kiln processes, which are recognised as very energy intensive. Nisbet et al., (2002) also highlighted that cement manufacturing accounts for about 70% of the total energy of the 20MPa (3,000psi) mix and transportation contributed 7.5% of embodied energy. Additionally, the weighted average energy consumption, including fuel and electricity, is 4.8 GJ/metric tonne (4.1 MBtu/tonne) of cement. Fossil fuels account for about 80% of the total, and waste fuels and electricity account for about 10% each (Company C, 2014).

One of the solutions to measure the carbon footprint is the Carbon Dioxide Emission Equivalent method, based on the values in Table 4.12, to calculate how much carbon dioxide is emitted. One specific equation from Australian National Greenhouse Accounts Factors (2014 to 2016) is also able to calculate carbon footprint in kiln (limestone) production, but it requires more dust data to complete the calculation. Marceau et al., (2006) also highlighted that each tonne of cement production would collect 0.02 tonnes of dust in filter bags in the process of cement production, as shown in Table 4.13. Although the milling process uses electrical power to operate grinding facilities in Companies A to C, the dust outcome results (Marceau et al., 2006) are same as with the kiln process.

To make one tonne of cement, each raw material should be calculated proportionally to add up 1.02 tonnes, because of the dust issue, to find the effect on natural resources depletion. Appendices C and D also provide one of the typical features of vertical mill and electricity energy consumption general specification information.

Table 4.13 Ancillary Materials Input by Process Type (SI Units) (Marceau et al., 2006)

Ancillary **Material**	**Wet**	**Long Dry**	**Pre-heater**	**Pro-claimer**	**Average**	**Unit**
Grinding	0.14	0.14	0.14	0.14	0.14	tonne
Filter bag	0.02	0.02	0.02	0.02	0.02	tonne

Average 7% of dust caught in filter bag

Table 4.14 Energy Input by Process Type (SI Unit) (Marceau et al., 2006)

Ancillary **Energy**	**Wet**	**Long Dry**	**Pre-heater**	**Pro-clainer**	**Average**	**Unit**
Coal	3,165	2,780	3,064	2,658	2,823	GJ/tonne
Gasoline	0.0121	0.0017	0.0037	0.0034	0.0046	GJ/tonne
LPG	0	0.001	0.0001	0.0004	0.0004	GJ/tonne
Electricity	0.495	0.541	0.541	0.517	0.520	GJ/tonne

LPG used in pre-heated process at the rate of 0.0001 Gigajoules (GJ)/tonnes consumption

Energy intensive

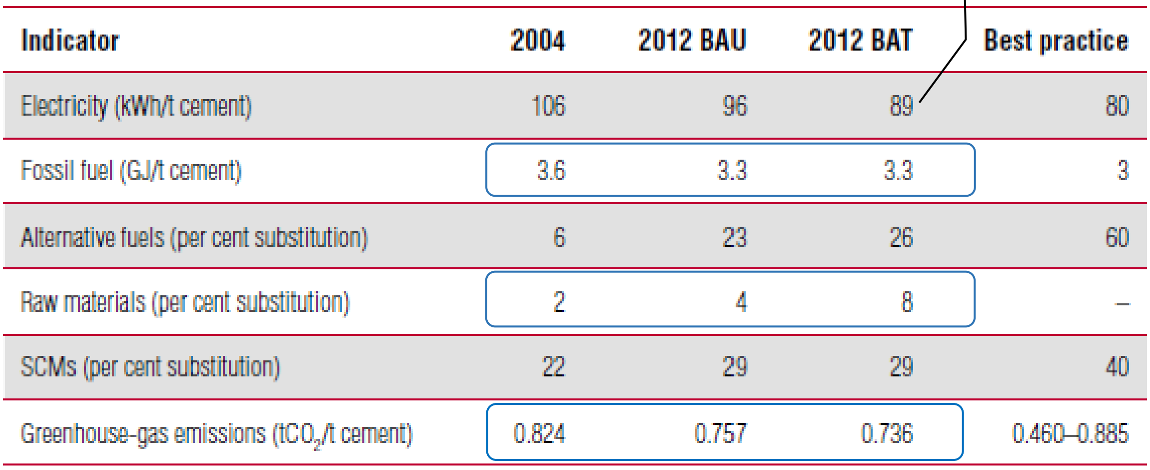
Table 4.14 clearly indicates that LPG emits less carbon dioxide through the grinding process in American types of cement factories. In other words, LPG uses less energy; consequently, there is less carbon dioxide emission. However, the investment and production facilities costs were higher than when using coal. Company A is in Northern Queensland and can easily obtain coal feedstock, so the costs of logistics and supply are lower than they would be if using alternatives.

Table 4.15 Theoretical Heat Output from Cement Kilns (Peray, 1979)

Ancillary **Theoretical heat**	**Wet**	**Long Dry**	**Pre-heater**	**Pre-clainer**	**Average**	**Unit**
Clinker	5,844	4,999	3,615	3,615	4,181	GJ/tonne
Cement	5,493	4,699	3,398	3,398	3,931	GJ/tonne

It is significant that the theoretical heat output in Table 4.15 (red box) from each long dry-type kiln uses less energy than wet-type kilns, because of wet-type kilns using extra energy to dry cement. This theoretical heat only considers making an ordinary Portland cement or ordinary Portland cement with supplementary cementitious materials using traditional fuel types - coal and diesel oil (Peray, 1979, Companies A and B, 2015). Based on this information, Carbon Dioxide Emission Equivalent methods and Australian National Greenhouse Accounts Factors (2015) can calculate how much carbon dioxide is released into the atmosphere. It also provides an opportunity to compare wet-type and dry-type kilns to find which type of kiln releases less carbon dioxide into the atmosphere.

4.2.2.6 Energies, Raw Material, Supplementary Cementitious Materials and CO_2 Emission



Significant reduction in CO_2 using electricity

Indicator	2004	2012 BAU	2012 BAT	Best practice
Electricity (kWh/t cement)	106	96	89	80
Fossil fuel (GJ/t cement)	3.6	3.3	3.3	3
Alternative fuels (per cent substitution)	6	23	26	60
Raw materials (per cent substitution)	2	4	8	–
SCMs (per cent substitution)	22	29	29	40
Greenhouse-gas emissions (tCO_2/t cement)	0.824	0.757	0.736	0.460–0.885

Figure 4.9 Energy, Raw Material Including Supplementary Cementitious Materials (SCM) Consumption and Australian Greenhouse Gas Emission in Cement Industries (Cement Industry Federation, 2015)

where

GJ = gigajoules
$CO_{2\text{-e}}$t/t = one tonnes of carbon dioxide emission tonne per tonne

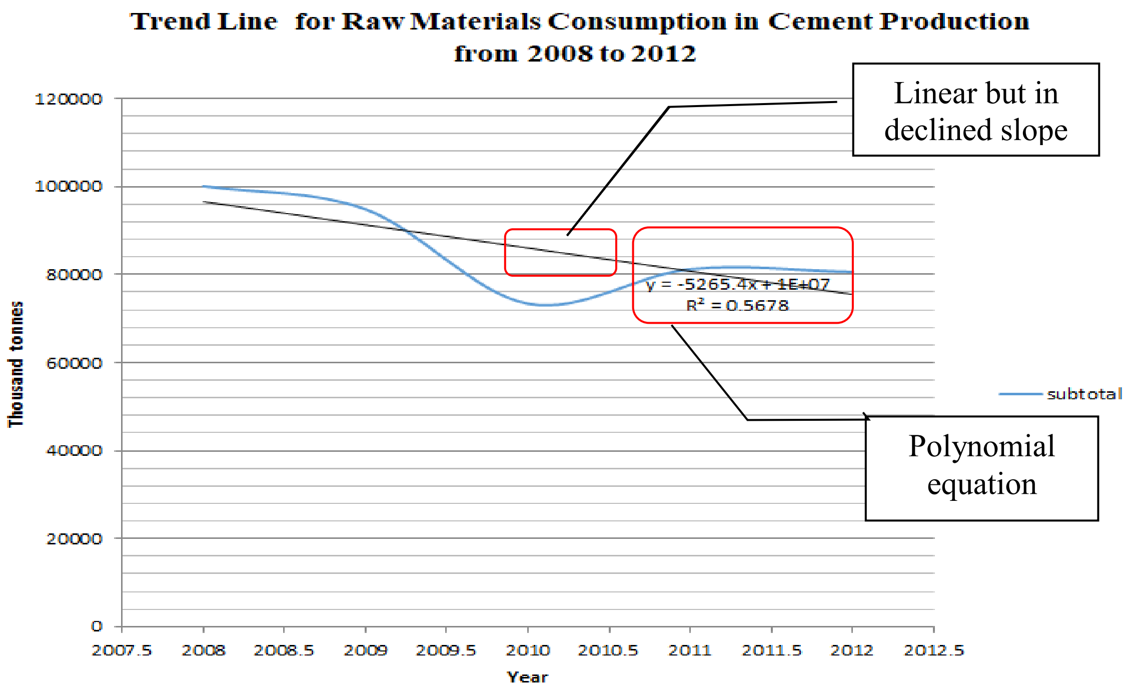
There are six sets of statistical information in Figure 4.9 including electricity, fossil fuel, alternative fuel, raw materials, supplementary cementitious materials and greenhouse gas emission for the cement industry in 2004 and 2012 (Cement Industry Federation, 2015). There was a significant reduction in carbon dioxide emissions and energy consumption when adding more supplementary cementitious materials in the production of ordinary Portland cement. This is a good option to drive down the carbon footprint, but the process did not consider optimal production costs. By using linear programming equations, it is possible to find the optimal mix proportion of ordinary Portland with supplementary cementitious materials in terms of cost.

4.2.2.7 Natural Resources Depletion for Ordinary Portland Cement and Fly Ash Based Geopolymer Cement

The data from 2008 to 2012 concerning raw materials, including gypsum, sand, gravel, limestone (lime), silicate and clay consumed for ordinary Portland cement production in Australia, are shown in Table 4.16. To better understand total raw materials consumption, natural resources depletion and seasonality indices it is necessary to develop a regression model, by added up the previous year’s consumption values, as seen in Table 4.17, which provides data to examine the trend of data series for regression models, curve characters and forecast the future materials used for cement production.

Table 4.16 The Trend of Raw Materials Consumption for Ordinary Portland Cement Industry in Australia (USGS Mineral Yearbook, 2012 to 2015 and Cement Industry Federation, 2013)

Yr **RM**	**2008**	**2009**	**2010**	**2011**	**2012**	**unit**
Gypsum	3,734	3,436	3,300	3,250	3,500	thousand tonnes
Sand	37,000	34,000	21,000	24,000	25,000	thousand tonnes
Gravel	12,000	12,000	6,000	8,000	8,000	thousand tonnes
Limes	18,400	16,800	17,000	18,000	18,000	thousand tonnes
Silica	5,000	4,000	3,100	3,500	3,500	thousand tonnes
Clay	24,000	24,600	23,000	24,500	22,600	thousand tonnes
Subtotal	100,134	94,836	73,400	81,250	80,600	thousand tonnes



Linear but in declined slope

Polynomial equation

Figure 4.10 The Trend of Raw Materials Consumption Including Gypsum, Sand, Clay, Limestone, etc., Based on Table 4.16

Figure 4.10 was developed based on Table 4.16. The blue curve, as shown in Figure 4.10, was identified as a polynomial equation, and the straight grey line is declined downward. This means the demand for raw materials would decline gradually from the overseas market and there would be a slowdown in the natural resources depletion in Australia as well.

Table 4.17 Accumulated Yearly Natural Resources Depletion from 2008 to 2012

Yr **RM**	**2008**	**2009**	**2010**	**2011**	**2012**	**Unit**
Gypsum	3,734	7,170	10,470	13,720	16,920	thousand tonnes
Sand	37,000	71,000	95,000	119,000	144,000	thousand tonnes
Gravel	12,000	24,000	32,000	40,000	48,000	thousand tonnes
Lime	18,400	35,200	53,200	71,200	89,200	thousand tonnes
Silica	5,000	9,000	12,500	16,000	19,500	thousand tonnes
Clay	24,000	48,600	72,100	97,600	120,200	thousand tonnes

A Table 4.16 shows the trend of raw material consumption and natural resources depletion status from 2008 to 2012 for cement production. However, this research is only interested in the trend for raw material consumption for the past five years, by using a time data series for regression model. To achieve this, one of the solutions was to use seasonality ratio indices to analyse time-series data including gypsum, sand, gravel, limes, silica and clay, as shown in Table 4.18. The outcomes of these indices can be used to develop the forecast equation in 2017 or later.

Table 4.18 The Trend of Gypsum Data Series for Regression Model

Year **Seasonality Ratio Indices** $\left[\frac{S_{n+1}}{S_n}\right]$	**2008**	**2009**	**2010**	**2012**	**Average** $\frac{1}{n}\sum\frac{S_{n+1}}{S_n}$
Gypsum	0.92	0.96	0.96	1.08	0.99
Sand	1.09	0.62	1.14	1.04	0.97
Gravel	1	0.5	1.33	1	0.89
Lime	0.91	1.01	0.16	1	1
Silica	1.03	0.93	1.04	0.94	0.98
Clay	1.03	0.96	1.07	0.92	1.02

The red box in Table 4.18 shows the average value seasonality of each raw material for cement production. This time-series data were used to estimate future raw material consumption which is illustrated in the next section.

Based on the average seasonality indices from Table 4.18 (red box), is the outcome of each raw material consumption and curve characteristics. The forecast of each raw material for cement production in 2017 based equation (4.2) as obtained:

(a) Forecast gypsum

$$y_n = 0.99 * (a + bx_n + cx^2{}_n) \qquad \text{..................} \qquad (4.7)$$

(b) Forecast sand

$$y_n = 0.97 * (a + bx_n + cx^2{}_n) \qquad \text{..................} \qquad (4.8)$$

(c) Forecast gravel

$$y_n = 0.96 * (a + bx_n + cx^2{}_n) \qquad \text{..................} \qquad (4.9)$$

(d) Forecast limes

$$y_n = 1 * (a + bx_n + cx^2{}_n) \qquad \text{..................} \qquad (4.10)$$

(e) Forecast silica

$$y_n = 0.98 * (a + bx_n + cx^2{}_n) \qquad \text{..................} \qquad (4.11)$$

(f) Forecast clay

$$y_n = 1.02 * (a + bx_n + cx^2{}_n) \qquad \text{..................} \qquad (4.12)$$

The prediction calculation for 2017, including gypsum, sand, lime, gravel and clay, etc., based on equations (4.1) and (4.2), were discussed in the previous section. Their results provide vital information to the quarry industry to examine the current reserve, and whether it is the right time to explore a new quarry site to satisfy the civil and construction industries. Cement industries entrepreneurs can also re-think their feedstock status, avoiding surprises in pricing.

Table 4.19 Raw Materials Consumption for Fly Ash Based Geopolymer Cement Industry in Australia (USGS, 2014)

Materials	Quantities	Units
Fly ash	1.25	million tonnes
SCM-GGBS	1.82	million tonnes
Slag	7.3	million tonnes
Sodium hydroxide (NaOH)	Imported 1.2 million tonnes but	million tonnes
	0.25 million tonnes for domestic application	million tonnes
Silica fume	Imported 10,000 to 15,000 but	thousands tonnes
SCM-silica fume	2,500 to 37,500 produced in Australia	thousands tonnes

The characteristics of this data series, trend of raw materials and results for ordinary Portland cement were discussed in Tables 4.17 to 4.18. The major raw materials to produce fly ash based geopolymer cement are shown in Table 4.19, in which the highlighted red box shows one of main findings, which is that the sodium hydroxide (NaOH) solution is imported from overseas. The production of sodium hydroxide (NaOH) solution is performed by using an electrolysis process to convert brine into sodium hydroxide (NaOH) liquid; consequently, it emits large quantities of carbon dioxide, while complying with the Carbon Tax Scheme in 2012 (this ended in 2013) (Australian Bureau of Statistics, 2012 and 2014). The cost of this tax was part of the cost of cement production (Company A, 2015). The cement manufacturers tried to drive down costs elsewhere in order to pay this extra charge, including transport costs from supply sites to cement factories, by contracting them to overseas companies, in order to maintain profits. The main advantage of this business consideration was that it slowed down natural resources depletion and caused less financial effect on the three areas of production. However, when developing the linear programming equations for scenario studies, this research only considered the sodium hydroxide (NaOH) cost, whether imported from overseas or Australian-made

Table 4.20 Limestone, Silica Fume, Slag, Sand and Cement Production Rate in South Australia, Gypsum Production Rate (Operating Mines and Quarries of South Australia, 2015)

Material and Rates **Operator**	**Industrial Materials**	**Production Rate** **(tonnes/six month)**
GRA Company	Gypsum	Less than 100
AM Company	Limestone	1,000 to 10,000
OT Company	Slag	10,000 to 100,000
MH Company	Sand	10,000 to 100,000
H Company	Sand	Less than 100
CM Company	Clay	1,000 to 10,000
AB Company	Ordinary Portland cement	100 to 1,000

Not in full capability

Table 4.21 Compared Ordinary Portland Cement Factories Capability from Companies from A to C

Material **Companies**	**Industrial materials**	**Capability (million tonnes)**
A	OPC	5.5
B	OPC	4.8
C	OPC	1.5

Table 4.22 Cement Price from Distributors (Bunnings Warehouse, 2015; Mitre 10, 2015; Masters, 2015)

Cost Warehouse	Industrial Material	Price (A$)
Bunnings Warehouse	General purposed cement, 20kg	7 to 9
Mitre 10	General purposed cement, 20kg	7 to 10
Masters	General purposed cement, 20kg	7 to 11

Table 4.20 shows statistical information concerning the major well-known quarries and cement companies which supply raw materials, including clay, sand, slag and ordinary Portland cement in South Australia in 2013. One of the findings is that these kinds of quarry sites are located close to cement factories. This minimises transport issues, ensuring the unique quality of the raw materials. Another finding in Table 4.20 (red rectangle) is that the AB company only produced 100 to 1000 tonnes of cement within six months; this figure is lower than Company A consumption in 2013 (Company A, 2015) and also the capabilities of Companies' A to C as shown in Table 4.21. Thus, the basic operation of cement production was subcontracted to overseas cement factories and shipped back as semi-cement to Australia, which only focused on downstream processes such as grinding, packing and distribution. This operation causes a certain degree of difficulty in defining the boundary and cost breakdown in sink tax (e.g. environmental tax). This study only considered how much they provided in Australian cement factories within the defined boundary production events.

This study also identified that the selling prices were quite variable, from A$7 to A$9 per 20 kilograms of ordinary Portland cement, despite the brand names as shown in Table 4.22. This means the cement and retail industries maintain their profit at a reasonable level. In addition, this set of costs provides data to develop 'functions and constraints' by using linear programming equation methods.

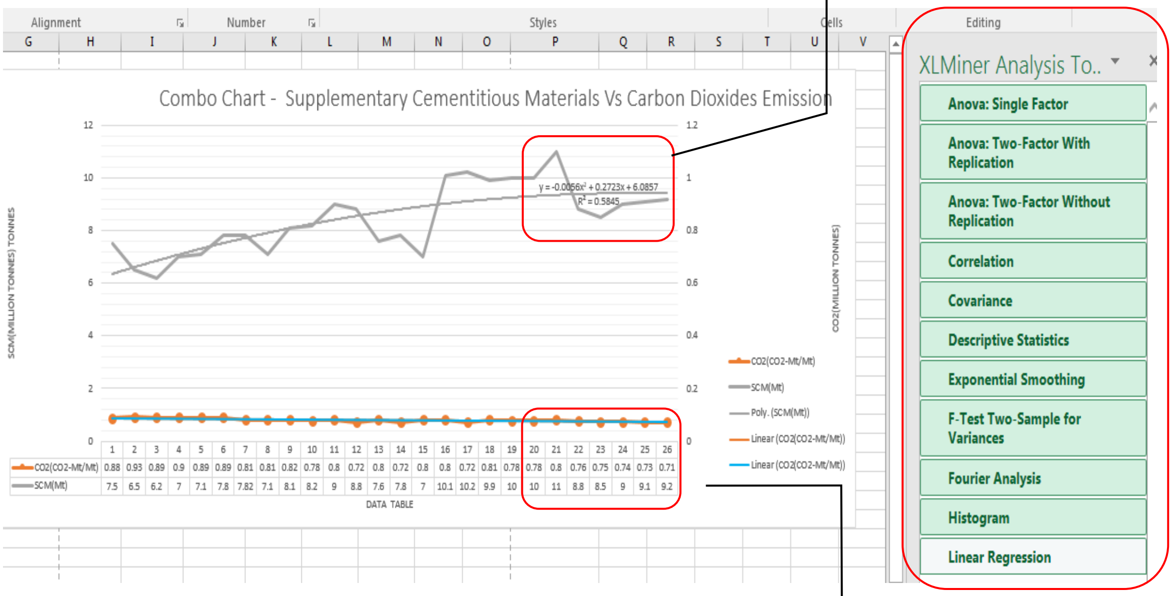
4.2.2.8 Carbon Dioxides Emission from Cement Manufacture

Table 4.23 Adding Supplementary Cementitious Materials to Ordinary Portland Cement Production to Reduce Carbon Dioxides Emission (Cement Industry Federation, 2013)

Year	**CO_2 ($CO_{2\text{-}e}$ Mt/Mt)**	**Used Supplementary Cementitious Materials (Mt)**
1989	0.88	7.7
1990	0.93	6.5
1991	0.89	6.2
1992	0.9	7
1993	0.89	7.1
1994	0.89	7.8
1995	0.81	7.82
1996	0.81	7.1
1997	0.82	8.1
1998	0.78	8.2
1999	0.8	9
2000	0.72	8.8
2001	0.8	7.6
2002	0.72	7.8
2003	0.8	7
2004	0.8	10.1
2005	0.72	10.2
2006	0.81	9.9
2007	0.78	10
2008	0.78	10
2009	0.8	11
2010	0.76	8.8
2011	0.75	8.5
2012	0.74	9
2013	0.73	9.1
2014	0.71	9.2

The Cement Industry Federation (2013) has recorded data about carbon dioxide released from 1989 to 2014 by adding certain supplementary cementitious material to ordinary Portland cement production, as shown in Figure 4.11. Maximum and minimum carbon dioxide emissions data are shown in the three red boxes. All-in-all, it did not optimise production to add supplementary cementitious material to ordinary Portland cement in order to reduce carbon dioxide emission. Supplementary cementitious materials, including fly ash, slag etc., and incur costs, which have a financial effect on the cement companies. The building of regression models for time-series data are one method to find out the curve characteristics and seasonality to forecast by using one of the built in functions of Excel® ('XLMiner Analysis ToolPak®'), to assist data analysis, as shown in Figure 4.11.

Data series model for quantities of supplementary cementitious materials most likely polynomial equations



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
CO2(CO2-Mt/Mt)	0.88	0.93	0.89	0.9	0.89	0.89	0.81	0.81	0.82	0.78	0.8	0.72	0.8	0.72	0.8	0.8	0.72	0.81	0.78	0.78	0.8	0.76	0.75	0.74	0.73	0.71
SCM(Mt)	7.5	6.5	6.2	7	7.1	7.8	7.82	7.1	8.1	8.2	9	8.8	7.6	7.8	7	10.1	10.2	9.9	10	10	11	8.8	8.5	9	9.1	9.2

Linear equation for CO_2 emission

Figure 4.11 The Time-Series Models and Trend of Supplementary Cementitious Material, Carbon Dioxides Emission, Expected Line-in-fit with Equations Using Excel® with XLMiner Analysis ToolPak®

The supplementary cementitious material seasonality indices based on equation (4.1) and Table 4.24 and the outcome results are listed in Table 4.23.

Table 4.24 The Supplementary Cementitious Material Seasonality Indices

SCM Year	**Supplementary Cementitious Material (Mt)**	**Indices** $\left(\frac{S_{n+1}}{S_n}\right)$	**Average** $\left(\frac{1}{n}\sum\frac{S_{n+1}}{S_n}\right)$
1989	7.7	0.87	
1990	6.5	0.95	
1991	6.2	1.12	
1992	7	1.01	
1993	7.1	1.09	
1994	7.8	1	
1995	7.82	1.1	
1996	7.1	1	
1997	8.1	0.91	
1998	8.2	1.14	
1999	9	1.01	
2000	8.8	1.1	
2001	7.6	0.98	
2002	7.8	0.86	
2003	7	1.44	
2004	10.1	1	
2005	10.2	0.97	
2006	9.9	1.01	
2007	10	1	
2008	10	1.1	
2009	11	0.8	
2010	8.8	1	
2011	8.5	1.02	
2012	9	1.01	
2013	9.1	1.01	
2014	9.2	0	
Average			0.975

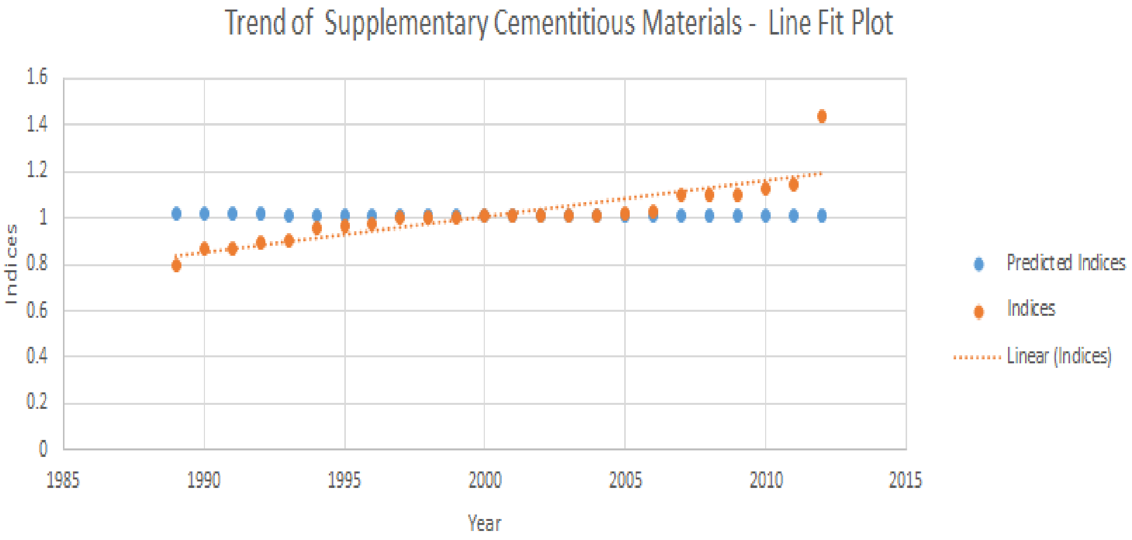


Figure 4.12 The Trend of Supplementary Cementitious Materials Indices from 1989 to 2014

The orange dotted line for supplementary cementitious materials indices in Figure 4.12 was identified by using the XLMiner Analysis ToolPak®. Based on this analysed outcome, the cement manufacturer can understand how much supplementary cementitious materials should be added to ordinary Portland cement production to reduce levels to the target carbon dioxide emission in cement production, as expressed:

$$y_n = 0.975 * (a + bx_n + cx_n^2) \qquad \ldots\ldots\ldots\ldots\ldots \quad (4.13)$$

Table 4.25 The Indices for Carbon Dioxides Emission

Emission Year	Carbon Dioxides Emission ($CO_{2\text{-}e}$ Mt/Mt)	Indices $\left(\frac{S_{n+1}}{S_n}\right)$	Average $\left(\frac{1}{n}\sum\frac{S_{n+1}}{S_n}\right)$
1989	0.88	1.06	
1990	0.93	0.96	
1991	0.89	1.01	
1992	0.9	0.99	
1993	0.89	1	
1994	0.89	0.91	
1995	0.81	1	
1996	0.81	1.01	
1997	0.82	0.95	
1998	0.78	1.03	
1999	0.8	0.9	
2000	0.72	1.11	
2001	0.8	0.9	
2002	0.72	1.11	
2003	0.8	1	
2004	0.8	0.9	
2005	0.72	1.13	
2006	0.81	0.96	
2007	0.78	1	
2008	0.78	1.03	
2009	0.8	0.95	
2010	0.76	0.99	
2011	0.75	0.99	
2012	0.74	0.99	
2013	0.73	0.99	
2014	0.71		0.95

The average value is 0.95 as shown in Table 4.25 (red box), using this result as the slope of the linear equation illustrated in equation (4.14).

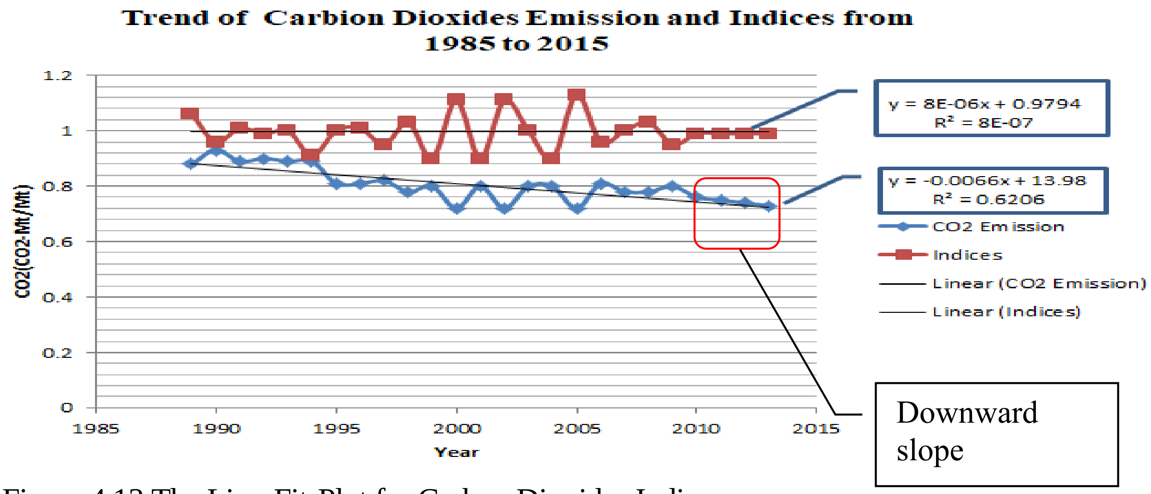


Figure 4.13 The Line-Fit-Plot for Carbon Dioxides Indices

This is the outcome result from the XLMiner Analysis ToolPak® to analyse the trend of carbon dioxide emission from 1989 to 2014, as shown in Figure 4.12 in blue, based on Table 4.25 data. It is a significant polynomial curve, including a linear line of carbon dioxide emission. It declines downward in the coming years by adding supplementary cementitious material in ordinary Portland cement production. The forecast equation of carbon dioxide emission is expressed as:

$$y_n = 0.95*(a+bx_n) \qquad \ldots\ldots\ldots\ldots\ldots \qquad (4.14)$$

The result provides clues to optimising how many supplementary cementitious materials should be added to ordinary Portland cement production for further reduction of carbon dioxide without affecting the general functions of ordinary Portland cement, and adding more raw materials by using seasonality or de-seasonality data characteristics.

4.3 DATA COLLECTION AND SENSITIVITY ANALYSIS

4.3.1 DATA COLLECTION

Data collection was discussed in the previous section. Several types of data were identified including fuel types, distance to deliver, operational cost, machinery capability, production rates and natural resources consumption, for ordinary Portland cement and fly ash based geopolymer cement, energy used, etc. This is used to develop a scenario for evaluation of cement options manufacture by using a spreadsheet-based model for optimal solutions (Shih, 1999; Lai and Chen, 1996; Lawrence, 2014) with the assistance of the Gaussian-Jordan Elimination Method (Grcar, 2011 and 2012; Copeland, 2013; Lafare et al., 2016) to solve multiple unknown variables.

4.3.2 SENSITIVITY ANALYSIS

In chapter 3, this study identified that one of the best tools to evaluate the three areas is linear programming with sensitivity analysis (Loijos et al., 2012; Lawrence et al., 2014), which can formulate assigned equations from the Methodology as 'subject to function' equation, seeking maximisation of profit and minimisation of costs, natural resources depletion and carbon dioxide emission. Primary and secondary data are treated as 'subject of constraints' to assist 'subject to function' to evaluate cement options performances. When the 'subject to function' and 'subject to constraint' are established in an linear programming equations, the best way to interpret the calculation and matrices is with the assistance of spreadsheet-based Solver® in which combinations are effectively analysed to provide solutions to each scenario outcome. Additionally, a wide ranges of data sets in 'subject to constraints' will provide a variety of outcomes until optimal results are found that meet the dynamic manufacturing environment.

4.3.2.1 Spreadsheet-Based Model

One issue of spreadsheet-based modelling is to provide optimal solutions through a flexible method of quantitative analysis by using the linear programming models with a simplex method. The modelling process is to:

(a) Identify the function or objective; the objective of this research is minimising carbon dioxide emission and natural resources depletion and maximising profit for manufacturers.

(b) Identify variables including their definitions in terms that are quantifiable; examples are raw material consumption each year, including limestone (lime), clay, sand, gravel, coal (fly ash), steel (slag), sodium hydroxide (NaOH) (brine), factory operational costs including machine rate, salaries (A$/hr), quarry rate, cement output etc.

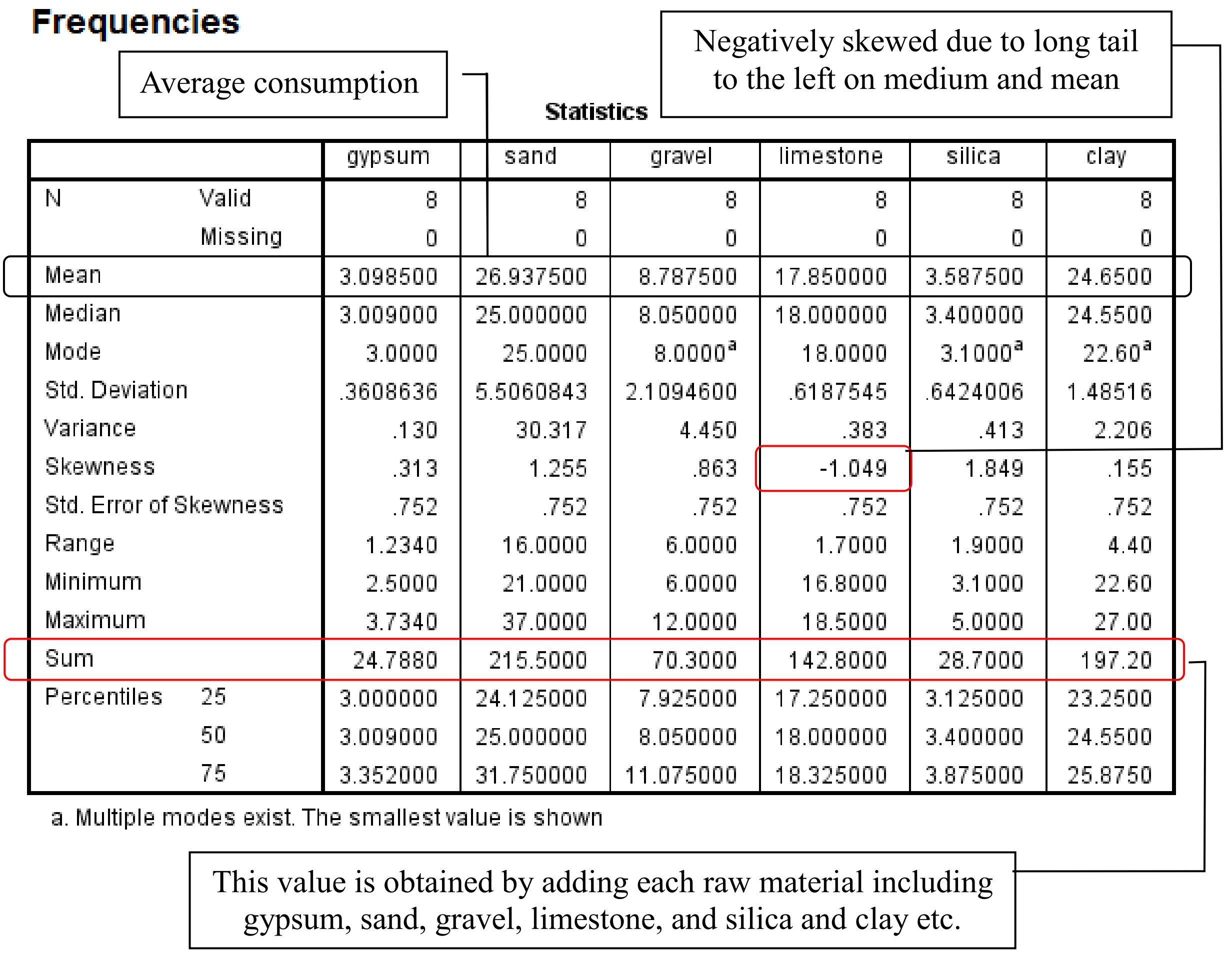
This is one of the best tools to perform optimal calculations by using Solver. The advantages of Solver are that it produces several options - answer, sensitivity and limits reports - based on linear equations with respect to Excel format equations. It can solve a sequence of constraints and function at the same time. However, in the literature review, no researchers used this method. Therefore, this research adapted Excel characteristics and built a model based on scenarios solving linear equation problems to produce optimal

Spreadsheet-based models do not only solve linear programming problems but are also able to calculate the mean, mode, medium, standard deviation and skew. This provides information on the trend of raw material flow of natural resources depletion, providing earlier warning as to what kinds of raw materials will become scarce soon. Based on this kind of information, cement engineers can tailor their cement manufacturing strategy, capability planning and feedstock

4.3.2.1.1 Prototypes of Natural Resources Depletion Including Limestone, Clay, Sand, Slag, Gravel, Silica and Gypsum Depletion for Ordinary Portland Cement Manufacture in Australia

The summary of mean, median, mode, minimum and maximum values for frequency distribution is shown in Table 4.26. The average consumption of gypsum, sand, crushed stone, gravel, limestone; silica and clay are 3.0985, 26.9375, 8.7865, 17.85, 3.5875 and 24.65 million tonnes each year in Australia. Additionally, the overall relationship among the three mean, mode and medium are skewed to the right, or positively skewed. These extreme values pull the medium to the left. Based on the information in equations 4.1 and 4.2, it is possible to calculate how many resources will be needed in the next 20 years or 50 years to satisfy the ordinary Portland cement market. However, while many kinds of forecasting techniques and methods are available, no single technique works best in every situation. When selecting a technique, the most important factors are cost, accuracy and availability of historical data, the availability of statistical software like SPSS® or Excel©, and the time needed to gather and analyse data to prepare the forecast. This research, based on the discussion in Chapter 3, has identified the importance of work by Guinée (2002), Habert et al., (2013) and Yellishetty et al., (2011), to determine trickle depletion using abiotic depletion potential and domestic material consumption methods of equations (3.8) to (3.10). This study uses statistical methods, including mean, mode, minimum and maximum, sum and medium to analyse the historical data regarding gypsum, clay, sand, slag and gravel for the cement industry, and then uses seasonality indices methods to forecast future consumption of raw materials.

Table 4.26 The Mean, Median, Mode, Minimum, Maximum, Sum, Limestone, Clay, Sand, Gravel, Silica and Gypsum Consumption from 2008 to 2015



Frequencies

Statistics

		gypsum	sand	gravel	limestone	silica	clay
N	Valid	8	8	8	8	8	8
	Missing	0	0	0	0	0	0
Mean		3.098500	26.937500	8.787500	17.850000	3.587500	24.6500
Median		3.009000	25.000000	8.050000	18.000000	3.400000	24.5500
Mode		3.0000	25.0000	8.0000[a]	18.0000	3.1000[a]	22.60[a]
Std. Deviation		.3608636	5.5060843	2.1094600	.6187545	.6424006	1.48516
Variance		.130	30.317	4.450	.383	.413	2.206
Skewness		.313	1.255	.863	-1.049	1.849	.155
Std. Error of Skewness		.752	.752	.752	.752	.752	.752
Range		1.2340	16.0000	6.0000	1.7000	1.9000	4.40
Minimum		2.5000	21.0000	6.0000	16.8000	3.1000	22.60
Maximum		3.7340	37.0000	12.0000	18.5000	5.0000	27.00
Sum		24.7880	215.5000	70.3000	142.8000	28.7000	197.20
Percentiles	25	3.000000	24.125000	7.925000	17.250000	3.125000	23.2500
	50	3.009000	25.000000	8.050000	18.000000	3.400000	24.5500
	75	3.352000	31.750000	11.075000	18.325000	3.875000	25.8750

a. Multiple modes exist. The smallest value is shown

Average consumption

Negatively skewed due to long tail to the left on medium and mean

This value is obtained by adding each raw material including gypsum, sand, gravel, limestone, and silica and clay etc.

The ‘sum’ row of Table 4.25 also provides a clue to the relationship with respect of ratio to produce ordinary Portland cement or ordinary Portland cement with supplementary cementitious materials as defined limestone as denominator and gypsum, sand, gravel, silica and clay as numerators. The results are that:

$$\frac{\text{clay}}{\text{limestone}} = 1.37,\ \frac{\text{sand}}{\text{limestone}} = 1.511,\ \frac{\text{gravel}}{\text{limestone}} = 2,\ \frac{\text{silica}}{\text{limestone}} = 0.2 \text{ and } \frac{\text{gypsum}}{\text{limestone}} = 0.2$$

Based on this finding, it is pre-requisite to examine the material and operational costs of producing ordinary Portland cement and ordinary Portland cement with supplementary cementitious materials. Additionally, this study also uses accumulated data from each year of raw material consumption for cement production against time such as limestone against time, clay against time and so on to analyse the trend of each material’s curve characteristics using time-series model method. Further discussion is in next section.

4.3.2.1.1.1 Curve Characteristic of Limestone, Clay, Gravel and Sand

Curves of limestone, clay, gravel and sand were identified as linear lines in Australia domestic material consumption (see Figure 4.14) by using statistical methods. Further discussion is in next section.

4.3.2.1.1.2 Linear Curves

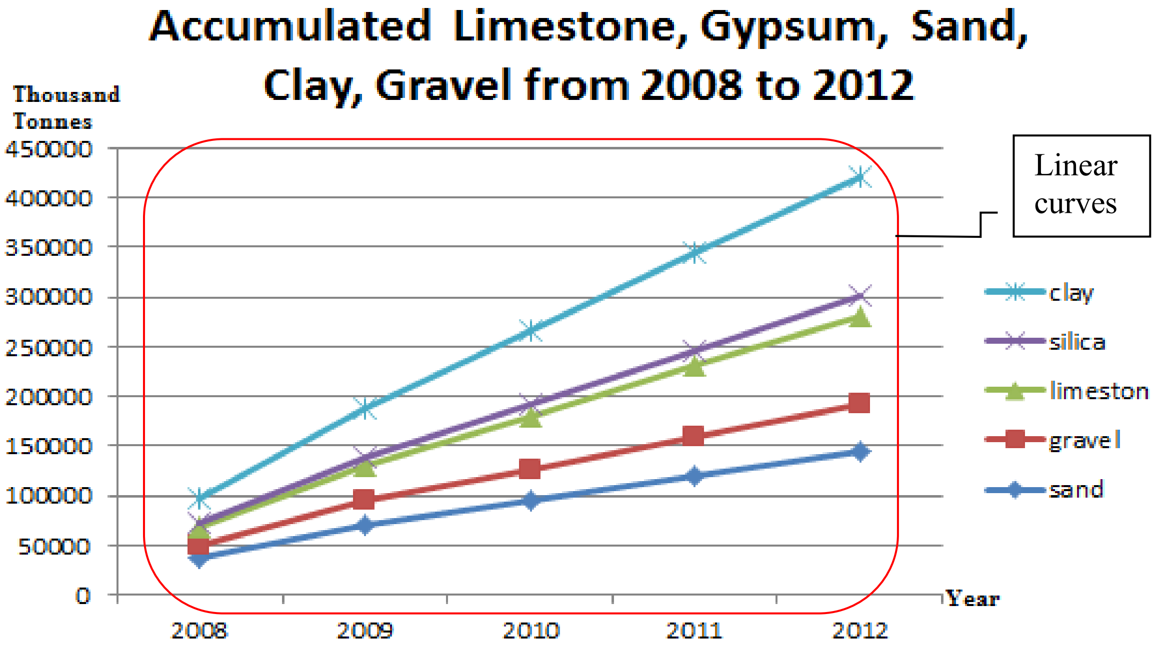


Figure 4.14 Accumulated Domestic Material Consumption (DMC) Including Clay, Silica, Limestone, Gravel and Sand Consumption from 2008 to 2012 for Cement Industry in Australia

The equation for DMC calculation for the cement industry in the French regions was normally in an exponential curve shape (Habert et al., 2010). Therefore, the aim was to adapt Habert et al.,'s (2010) method and extended this equation to an Australian cement business environment. The curves, as shown in Figure 4.14, are in linear equations, which used statistical skills to examine raw materials consumption data from 2008 to 2012 in the Australia region.

One finding was that linear equations could interpret the curve behaviours, so this was considered the most suitable approach in this study. The findings were different from those of Habert et al., (2010), because of Australia being one of the major sources of raw material in the world (USGS, 2014), so this is not the same as the situation in France which imported more materials from overseas.

4.3.2.1.2 Phototypes of Sub-Natural Resources Depletion Including Fly Ash, Sodium, Hydroxide, Sand and Slag for Geopolymer-Based Cement Manufacture in Australia

To better analyse the secondary data concerning the past several years of raw materials consumption for fly ash based geopolymer cement industry, statistical methods were used, including mean, mode and medium, etc., seeking out the trend of each item, as shown in Table 4.27. The mean of fly ash, sodium hydroxide (NaOH), slag and sand are 18.05, 26.1667, 7.0333 and 24.833 respectively. The relationship among the three measures (mode, mean medium) of fly ash is smoothed relative frequency figures as the result of being symmetrical and unmodal; the three measures coincide.

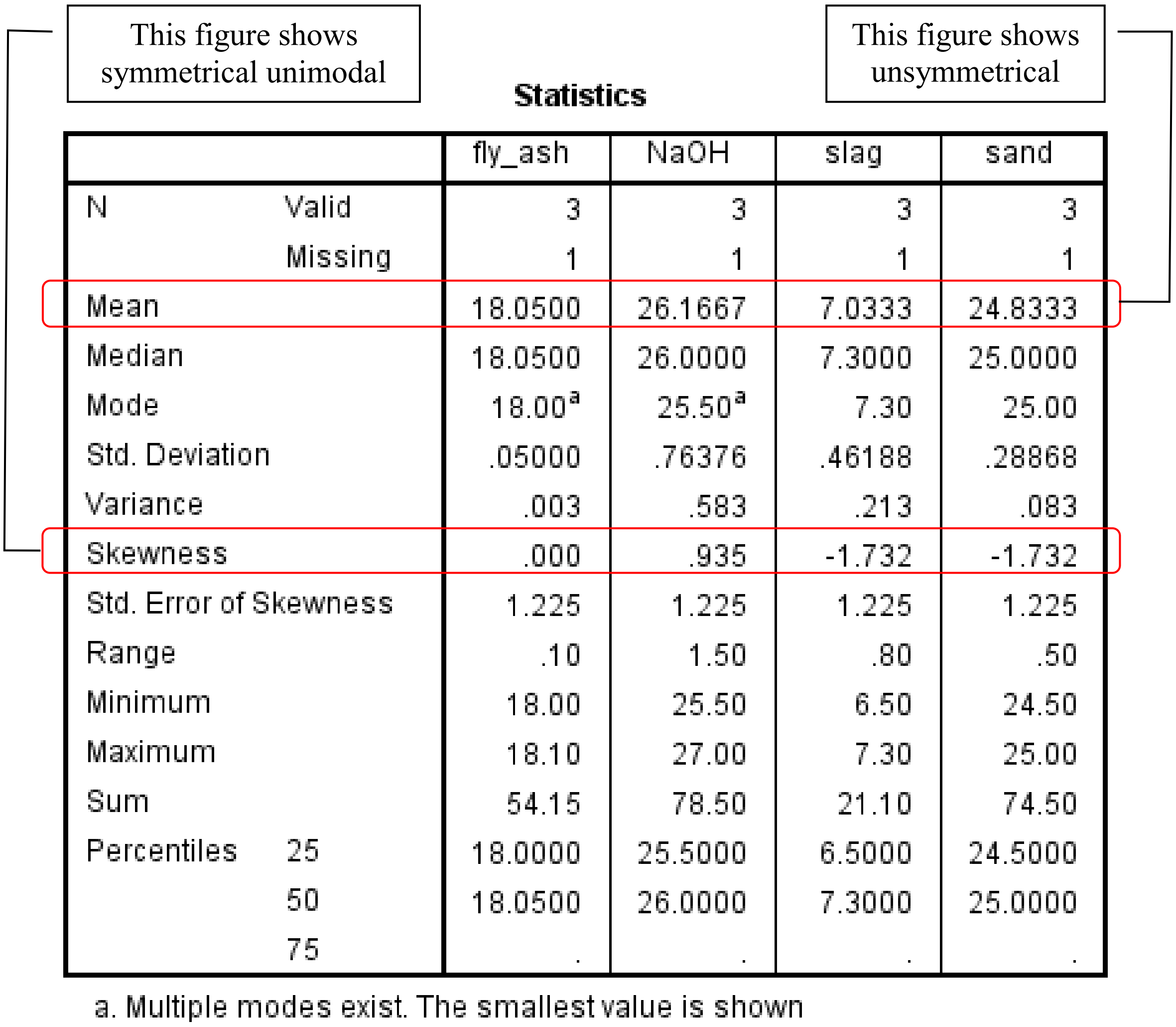
Because fly ash is not a raw material but a by-product from coal-fired power stations, there is a certain degree of difficulty in evaluating depletion. Therefore, an indirect method was employed, by using the ratio method. Because fly ash is a by-product of coal, it is necessary to consider how many tonnes were burnt in the coal-fired plant, based on coal characteristics, to multiply a percentage to obtain the fly ash quantities. This is one of the solutions to close the gap. Additionally, 4% to 6% (Fly Ash Association, 2015) of fly ash would be produced if the coal-fired power station used supplied coal from North Queensland, but 5% to 7% (Fly Ash Association, 2015) of fly ash would be collected if the coal-fired power station used coal from Western Australia.

Each year, a total of around 1.2 million tonnes (Fly Ash Association, 2013; Cement Industry Federation, 2013) of fly ash is produced by coal-fired power stations in Australia. This is a temporary reserve. The location of these kinds of sites were distant fly ash based geopolymer cement factories, in particular the Hazelwood Brown Coal-fired Power Station in Victoria, which was decommissioned starting from early 2017, and the Leddell Coal-fired Power Station, which is also due in 2022 to cease generating electricity (Parliament of Australia, 2017). The fly ash supply chain hastened better transport infrastructure. Based on this situation, companies A to C are located in convenient areas to operate cement production but the sales and marketing departments are in major cities such as Brisbane, Sydney and Melbourne. Company A (2015) is one example of a company using these strategies. Another advantage is less environmental effect. An alternative way is to build a factory with relevant industries in one industrial or quarry precinct. Company B (2015) is one example of this.

The ‘consumption ratio’ is also shown in Figure 4.15, which examines what percentages of raw materials are taken to produce traditional fly ash based geopolymer cement, by using the ratio method based on fly ash as denominator to divide each individual raw material to discover the relationship. This gives a clue to better control of raw material and sub-material costs, such as the stock level, transport issues and so on. It also provides guidelines to seeking a substitution for these expenditure items.

Regarding iron slag, Australia is one the major iron ore and slag exporters of the world. From 2011 to 2012, it exported 4,747 thousand tonnes to India (India Minerals Yearbook 2012). The world produces about 300 million tonnes of iron blast slag each year, and 60% is shipped to China. Australia only used 2.613 million tonnes from major steel makers nationally or imported from overseas sources and used in various industry sectors. Compared with 2013, there was a decrease of approximately 260,000 metric tonnes of total slag available on the market (ASA, 2014). This means that natural resources depletion has had a chance to slow down in Australia. Additionally, slag is the by-product of refining steel, and this process saves generating carbon dioxide emission as well. Another finding was that the world economy had not yet fully recovered from the global financial recession; domestic materials consumption from 2013 to 2015 also significantly dropped.

Table 4.27 The Mean, Median, Mode, Minimum, Maximum and Sum of Raw Materials Considering Sand and Sub-Materials, Including Fly Ash, Sodium Hydroxide, Slag for Geopolymer Cement Production from 2013 to 2015



This figure shows symmetrical unimodal

This figure shows unsymmetrical

Statistics

		fly_ash	NaOH	slag	sand
N	Valid	3	3	3	3
	Missing	1	1	1	1
Mean		18.0500	26.1667	7.0333	24.8333
Median		18.0500	26.0000	7.3000	25.0000
Mode		18.00[a]	25.50[a]	7.30	25.00
Std. Deviation		.05000	.76376	.46188	.28868
Variance		.003	.583	.213	.083
Skewness		.000	.935	-1.732	-1.732
Std. Error of Skewness		1.225	1.225	1.225	1.225
Range		.10	1.50	.80	.50
Minimum		18.00	25.50	6.50	24.50
Maximum		18.10	27.00	7.30	25.00
Sum		54.15	78.50	21.10	74.50
Percentiles	25	18.0000	25.5000	6.5000	24.5000
	50	18.0500	26.0000	7.3000	25.0000
	75	.	.	.	.

a. Multiple modes exist. The smallest value is shown

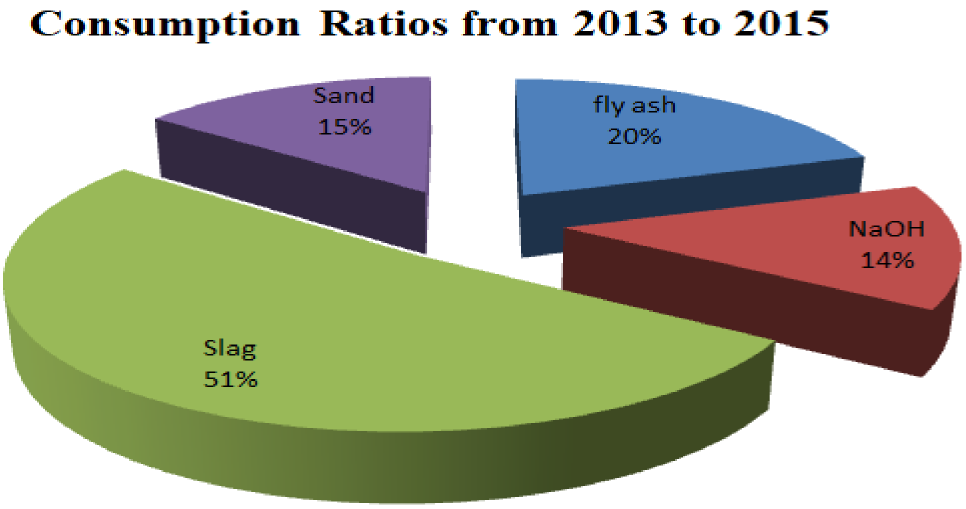


Figure 4.15 Consumption Ratios from 2013 to 2015 Based on Table 4.27 Mean Data

4.3.2.1.3 Prototypes of Abiotic Depletion and Abiotic Depletion Potential Calculation

Chapter 3 proposed that abiotic depletion calculations are equal to characteristic factors for abiotic depletion of resources multiple mass of resources consumed in the process. Therefore, abiotic depletion potential is based on equation (3.9) as obtained:

$$CF_i = ADP_i = \frac{DR_i}{(R_i)^2} * \frac{(R_{Sb})^2}{DR_{Sb}} \qquad \text{…..………} \quad (3.9)$$

where

R_i and DR_{Sb} are extraction rate (kg/year) for resources i and antimony
But DR_{Sb} = 6.06 $*10^{7\ kg}$ (60.6 MT)
R_{Sb} = 4.63 $*10^{15}$kg (4.62$*10^{9}$MT$^{)}$

Substituted their known values of DR_{sb} and R_{sb} as mentioned above into $\frac{(R_{Sb})^2}{DR_{Sb}}$ as obtained:

$$\frac{(4.62*10^9)^2}{60.6} = \frac{21.623*10^{81}}{60.6} = 0.3568*10^{81} \qquad \text{….…………} \quad (4.15)$$

So, abiotic depletion potential of **l**imestone based on the equation (3.9) as obtained:

$$ADP_{limestone} = \frac{DR_{i\_limestone}}{(R_{i\_limestone})^2} * 0.3568*10^{81} \qquad \text{…….………} \quad (4.16)$$

Abiotic depletion potential of gypsum based on the equation (3.9) as obtained:

$$ADP_{gypsum} = \frac{DR_{i\_gypsum}}{(R_{i\_gypsum})^2} * 0.3568*10^{81} \qquad \text{….….………} \quad (4.17)$$

Abiotic depletion potential of clay based on the equation (3.9) as obtained:

$$ADP_{clay} = \frac{DR_{i\_clay}}{(R_{i\_clay})^2} * 0.3568*10^{81} \qquad \text{……..………} \quad (4.18)$$

Abiotic depletion potential of sand based on the equation (3.9) as obtained:

$$ADP_{sand} = \frac{DR_{i\_sand}}{(R_{i\_sand})^2} * 0.3568*10^{81} \qquad \text{…….………} \quad (4.19)$$

Abiotic depletion potential of gravel based on the equation (3.9) as obtained:

$$ADP_{gravel} = \frac{DR_{i\_gravel}}{(R_{i\_gravel})^2} * 0.3568 * 10^{81} \qquad \text{…..………} \quad (4.20)$$

Additionally, equations (4.13) to (4.18) are derived from equation (3.9), providing the abiotic depletion potential of raw materials because of cement production in Australia. The cement engineers and raw materials suppliers, purchasers and cement entrepreneurs can use this information to develop earlier intervention strategies in their material supply chain.

4.4 PROTOTYPES OF LINEAR PROGRAMMING EQUATIONS BASED ON SIX SCENARIO STUDIES FOR CEMENT MANUFACTURE IN AUSTRALIA

Primary and secondary data collection was discussed in the previous sections. This provides an opportunity to recognise objective and constraints in linear programming problems, expressed in terms of linear equations or inequalities. Six scenarios were developed to further examine each cement manufacture to validate the methodology and see which is the best alternative for minimising carbon dioxide emission, slowing down natural resources depletion, maximising profits. There are several limitations to this:

(a) The evolution of the three areas including ordinary Portland cement, supplementary cementitious material with ordinary Portland cement and geopolymer-based cement within the defined boundaries, which are identified in Chapter 2 and shown in Figure 2.6, Figure 2.9, Table 2.4 and Table 2.6.

(b) These boundaries include cradle-to-function and cradle-to-cradle.

(c) Two types of factories were considered in the study. One type only produces ordinary Portland cement and supplementary cementitious materials with ordinary Portland cement, and type produces fly ash based geopolymer and metakaolin-based geopolymer cement. This is because the production facilities differ and this distinction provides fair conditions for evaluation.

(d) All data are from primary and secondary data in Chapter 4 and equations are from Chapter 3.

The outcomes of these six scenarios are expected to provide optimal solutions in cement production. The purposes of each scenario are as below:

(a) Scenario 1 seeks an optimal solution in the maximisation of the production of ordinary Portland cement and ordinary Portland cement with supplementary cementitious material.

(b) Scenario 2 seeks an optimal solution in the maximisation of the production of fly ash based geopolymer cement and metakaolin-based geopolymer cement.

(c) Scenario 3 seeks an optimal solution in the maximisation of the production of fly ash based geopolymer cement and ordinary Portland cement.

(d) Scenario 4 seeks an optimal solution in the minimisation of carbon dioxide emission in the production processes, particularly in transport, by using Australian National Greenhouse Accounts Factors (2014 to 2016) as 'subject to function' and 'subject to constraint' to develop a linear programming equation.

(e) Scenario 5 seeks an optimal solution in the minimisation of carbon dioxide emission in the production processes, in particular in transport, by using the Carbon Dioxide Emission Equivalent method as 'subject to function' to develop a linear programming equation. The rest of the data and 'subject to constraints' equations are the same as for Scenario 4. Results are used to compare which is the superior of the two methods.

(f) Scenario 6 seeks an optimal solution in the minimisation of natural resources depletion in cement production.

4.4.1 SCENARIO 1

This study is based on Figure 2.6 and Table 2.4 and the defined boundary to produce ordinary Portland cement with supplementary cementitious material and ordinary Portland cement in an integrated cement factory (Company A and Company B, 2015). This is a typical cement production factory in Australia (cement Industry Federation, 2014) including processes and material flow. The major difference in the production of ordinary Portland cement and ordinary Portland cement with supplementary cementitious material is the additive process (Table 5.24) for mixing supplementary cementitious materials before the kiln process. The purpose of this process is to reduce carbon dioxide emission (Company A, 2013 and Company B, 2014) and have less effect on the current production environment (Yang et al., 2014). To calculate optimal profits of these products, the conditions for evaluation are that:

(a) It is a 24-hour and 300-day operation, non-stop process cement factory (Companies A and B, 2013 to 2014). The remaining days of the year are to produce other types of cement and also conduct repair and maintenance tasks, as shown in Table 2.1. The vertical mill is for coarse grinding and the large horizontal ball mill is for fine grinding (Company A, 2014).

(b) The vertical mill can process 2.1 tonne / hr. coarse grinding material and the large ball is able to produce 2.99 tonne / hr. The kiln is able to process 120 tonnes per 24 hours. The materials cost is based on Tables 4.6 and 4.8 respectively.

(c) It is assumed that there is no down time of the machines and no union strike in the working period.

(d) It uses an one-piece-flow manufacturing (Chan and Yung, 2008) production method.

(e) This study does not consider dust generation in the grinding and extraction processes.

(f) There are two products manufactured in one factory in the same manner, as utilisation of machines and workforce within the defined boundary.

(g) Operating expenses including transport, labour costs and machine costs were the same, so other operating expense figures were not considered in this assessment.

(h) All data are from literature and case studies and relevant reports from Companies A to C from 2013 to 2015.

Table 4.28 Scenario 1 Based on Table 4.3 to Examine Total Processes Time to Produce Ordinary Portland Cement (OPC) and Ordinary Portland Cement with Supplementary Cementitious Materials (OPC with SCM) (Company A, 2014)

Machines **Process**	**Unit processing capability(tonne/hr)**		**Availability (hr)**
	OPC (tonne/hr)	**OPC with SCM cement (tonne/hr)**	
Crushing	3.1	3.1	930
Vertical roller mill (coarse grinding)	3	3	7,200
Clinker	3	3	7,200
Additive (gypsum and SCM)	1	3	900
Ball mill (fine grinding)	3.1	3.2	7,200
Packing	3	3	7,200
One-piece-flow manufacturing (Chan and Yung, 2008)	15.2	18.30	7,200

Based on these values to develop one of the subjects to constraints equations

To better analyse the cement plants' capabilities, this study considered one-piece-flow processes (Chan and Yung, 2008) that follow a cement batch through the whole production process to the finished product. There are several considerations:

(a) This study considers only two processes because the production of ordinary Portland cement and ordinary Portland cement with supplementary cementitious materials are carried out in the same facilities. The major difference is the additive process as marked in red rectangular boxes in Table 4.28.

(b) This study has identified several cost drivers variables (indicated in the two red rectangular boxes) that provide data to develop equations (4.19) and (4.20) respectively. Further discussion is in Section 4.4.1.1.

Table 4.29 Machine, Material and Energy Costs Distribution for Ordinary Portland Cement (OPC) and Ordinary Portland cement (OPC) with Supplementary Cementitious Material (SCM) in Traditional Cement Plant Production (Australian Bureau of Statistics, 2015; Cement Industry Federation, 2014; United States Geological Centre (USGC), 2012; Company A, 2015)

Item **Cost**	**OPC**	**OPC with SCM Cement**	**Unit (A$ / tonne)**
Total machine cost	150	155	A$/tonne
Total material cost	106.9	111.5	A$/tonne
Total energy cost	43.1	23.5	A$/tonne
Subtotal total cost	300	290	A$/tonne
Revenue	345	348	A$/tonne
Profit	45	58	A$/tonne

Based on these values to develop the function of seeking for maximising profit

Table 4.29 shows the distribution of cost performances including total machine cost, total material cost, total energy cost, revenue and profit of the traditional cement factory within the defined boundary in an Australian business environment. This study identified two cost drivers in the profit row against ordinary Portland cement and ordinary Portland cement with supplementary cementitious material column to develop ‘subject to function’ equation as shown in equation (4.19). The profit as shown in Table 2.29 was before tax.

CHAPTER 4 DATA COLLECTION AND ANALYSIS

In the literature review, this study identified two methods to solve the linear equations. Considerations when seeking the best alternative using a comparison method are that:

(a) The first method uses traditional methodology, including 'Gaussian-Jordan Elimination' (Grcar, 2011 and 2012) for matrix and 'graphical' methods to solve the linear programming equations with sensitivity analysis with a wide range of parameters upon seeking optimal solutions. The general procedures are that:

    (i) Outcome from tables 4.27 to 4.29 are used to develop 'subject to function' and 'subject to constraint' for linear programming equations based on the methodology chapter.
    (ii) A graph is constructed to solve two unknowns.
    (iii) The parameters are changed within the matrix seeking the optimal solution.

(b) The second method is a spreadsheet-based model method, which is a more flexible method and can provide a solution (set cell) by setting a wide range of parameters into the function equation or subject to constraints all at once. With this method it is very important to design the cell position for 'cell formulas'; otherwise it will provide unexpected solutions. The general procedures are to:

    (i) Formulate function and subject to constraints from primary and secondary data with respect to linear programming equations by using 'Solver® Parameters to solve them.
    (ii) Changed parameters seeking optimal solution or alternatives including sensitivity analysis of linear programming.

(c) The two approaches are compared to find which alternative is better.

4.4.1.1 Identified Cost Drivers, Function, Constraints, Related Information from Primary and Secondary Data Using Linear Programming Equation Method Seeking Optimisation

This scenario considers the production of ordinary Portland cement and ordinary Portland cement with supplementary cementitious materials in one factory because the majority of the processes are the same, unless the additive supplementary cementitious materials process is the main difference. As the labour and operational costs are the same, they are not considered in this event. The linear programming equations are based on Tables 4.28 and 4.29 to develop as obtained:

Let

Q_{opc} is the amount of quantities of OPC producing per year
$Q_{OPC+SCM}$ is the amount of quantities of OPC with SCM producing per year

Subject to function equation based to Table 4.29 as obtained:

$$Max(Z) = 45Q_{opc} + 58Q_{opc+scm} \quad \text{………………} \quad (4.21)$$

Subject to Constraints

For total machine operational cost including all process cost as shown in Table 4.28 as obtained:

$$15.2Q_{opc} + 18.3Q_{opc+scm} \leq 7200 \quad \text{………………} \quad (4.22)$$

For mixed gypsum and supplementary cementitious materials (SCM) process:

$$(1Q_{opc}) + (3Q_{OPC+SCM}) \leq 900 \quad \text{………………} \quad (4.23)$$

Non-negativity constraints:

$Q_{OPC} \geq 0$ and $Q_{OPC+SCM} \geq 0$

4.4.1.2 Traditional Mathematical Method for Scenario 1

Rewritten equations (4.20) to (4.21) into matrix format:

$$\left(\begin{array}{cc|c} 15.2 & 18.3 & 7200 \\ 1 & 3 & 900 \end{array}\right)$$

Using Gaussian-Jordan elimination (Grcar, 2011 and 2012) method:

$$r_2 \rightarrow 15.2 * r_2 - r_1$$

where

r1 = row number 1

and

r2 = row number 2

$$\Rightarrow \left(\begin{array}{cc|c} 15.2 & 18.3 & 7200 \\ 15.2 & 45.6 & 13680 \end{array}\right)$$

$$\Rightarrow \left(\begin{array}{cc|c} 15.2 & 18.3 & 7200 \\ 0 & 27.3 & 6480 \end{array}\right)$$

$$Q_{opc+scm} = 237.657$$

Substituted back to equation (4.20) and $Q_{opc} = 187.915$; consequently the result became $Q_{opc} = 187.915$ and $Q_{opc+scm} = 237.657$. The optimal solution as obtained:

Max (Z) = $45 * 187.95 + 58 * 237.36 = 22{,}224.63$ …………... (4.22)

This scenario illustrates how to use traditional calculation methods to find optimal cement production in one cement factory with one-piece-flow manufacturing (Chan and Yung, 2008) method. This method is commonly suitable for a trial run batch operation. In the case of mass customisation production, each process is automatically fed raw materials for the next batch's operation and fed out when the individual process is complete, and then it flows to the next process until the packing process, ensuring that the factory is in full output manufacturing mode. Another traditional method is called the graphical method. The inequality is represented graphically by every point on or above the plotted line. The easiest way to plot these lines is to find the points of intersection with both axes. The points of intersection with these axes are summarised in Table 4.30, which produces the information necessary to construct the lines.

4.4.1.3 Graphical Method for Scenario 1

Table 4.30 Cut-Points at X and Y Axis, Seeking Optimal Solution Using Graphical Method for Scenario 1

Item Cost	Equation of Line	Cut Q_{opc}-axis when $Q_{opc+scm}= 0$	Cut $Q_{opc+scm}$-axis when $Q_{opc}= 0$
Total machine cost based on equation (4.22)	$(15.2Q_{opc})+(18.3Q_{OPC+SCM}) = 7200$	$15.2Q_{opc}=7200 \rightarrow Q_{opc} = 473.3$	$18.3Q_{opc+scm}=7200 \rightarrow Q_{opc+scm} = 393.4$
Mix SCM and gypsum based on equation (4.23)	$(Q_{opc})+(3Q_{OPC+SCM}) = 900$	$1Q_{opc}=900 \rightarrow Q_{opc} = 900$	$3Q_{opc+scm}=900 \rightarrow Q_{opc+scm} = 300$
Expected outcome based on equation (4.21)	$Max\ (Z)=45Q_{opc}+58Q_{opc+scm}$		

The purpose of Table 4.30 is to find out the points of intersection with the axes:

(a) Treat each inequality as an equation as shown in 'equation of line' column.

(b) Set either $Q_{opc+scm}$ is equal to zero and find out Q_{opc} values as shown in cut 'Q_{opc}-axis' column.

(c) Set either Q_{opc} is equal to zero and find out Q_{opc} values as shown in cut '$Q_{opc+scm}$ axis' column.

Table 4.31 Trial-and-Error Method Seeking Optimal Solution for Scenario 1

TR Item	Corner point	OPC	OPC with SCM	Total Contribution Margin
1	(473.3, 0)	473.3	0	45 (473.3) + 58 (0) = 21,298.5
2	(0, 393.4)	0	393.3	45 (0) + 58 (393.3) =22,811.4
3	(900,0)	900	0	45 (900) + 58 (0) = 40,500
4	(0, 300)	0	300	45 (0) + 58 (300) = 13,500
5	(187.975, 237.675)	187.975	237.675	45 (187.975) + 58 (237.675) = 22,244.025

The purposes of Table 4.31 are summarised two lines, equations (4.22) and (4.23) intersection results, which provide data to plot the linear lines for the next section. This is the first step in developing the graphical method seeking optimal solution.

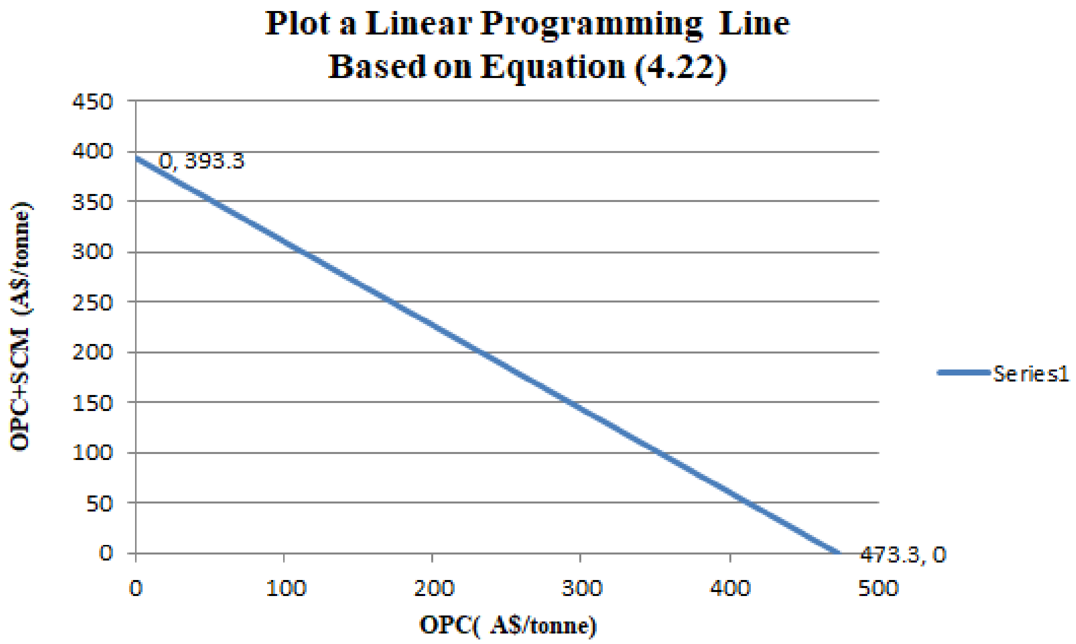


Figure 4.16 Linear Programming Equation Based on Equation (4.22), Tables 4.30 and 4.31 for Scenario1

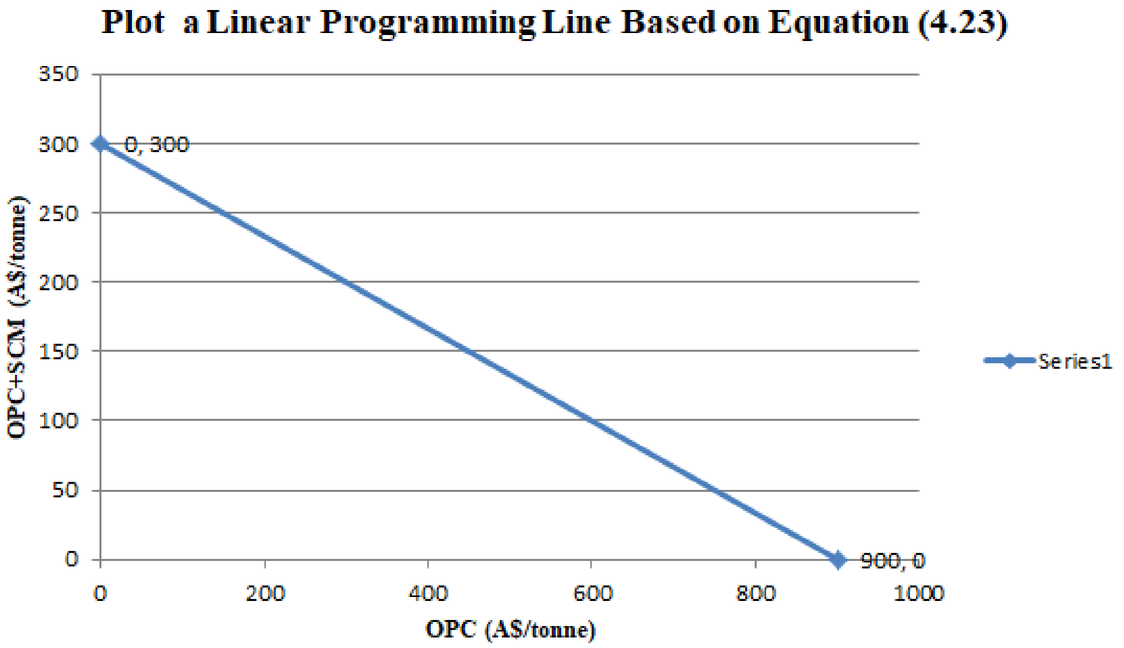


Figure 4.17 Linear Programming Equation Based on Equation (4.23), Tables 4.30 and 4.31 for Scenario1

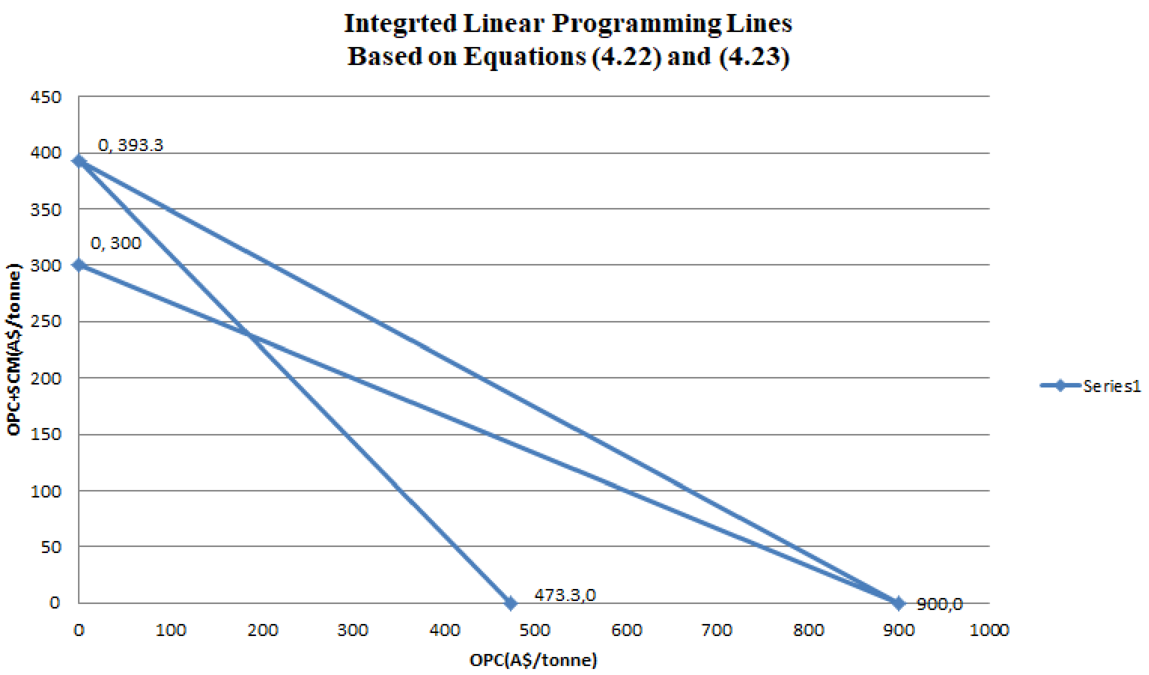


Figure 4.18 Integrated Linear Programming Equation Based on Equations (4.22) to (4.23), Tables 4.30 and 4.31 for Scenario 1

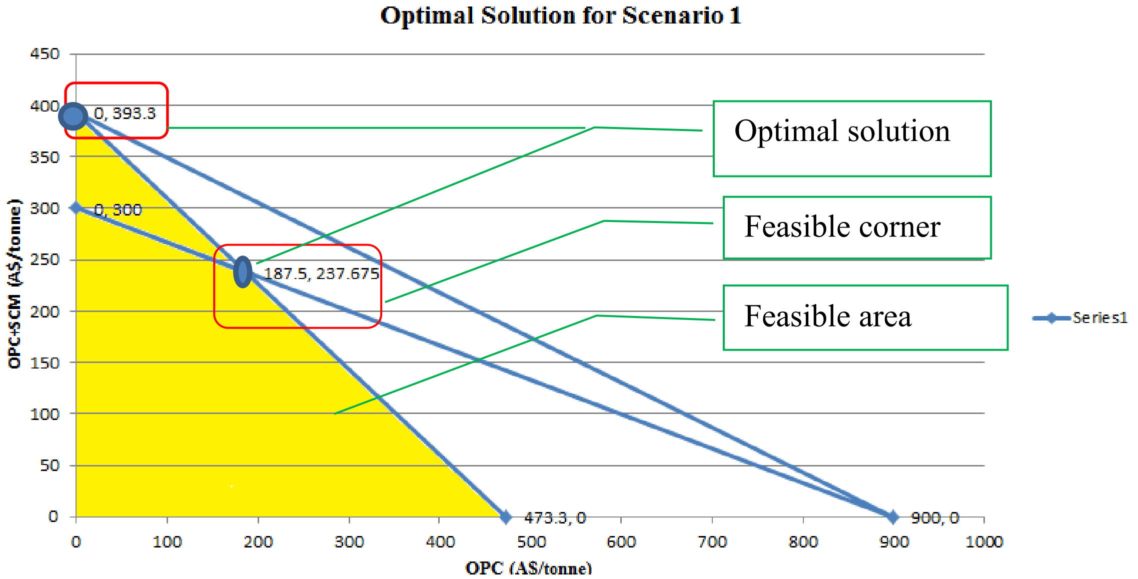


Figure 4.19 Integration Linear Programming Equations Seeking Optimal Solution for Scenario 1

Figures 4.16 to 4.19 are based on Tables 4.30 and 4.31 to construct graphs as the result of each line intercepting with x and y axis and providing the opportunity to use the graphical method of solving the optimal profit of mix production of ordinary Portland cement and ordinary Portland cement with supplementary cementitious materials based on the one-piece-flow manufacturing (Chan and Yung, 2008) method.

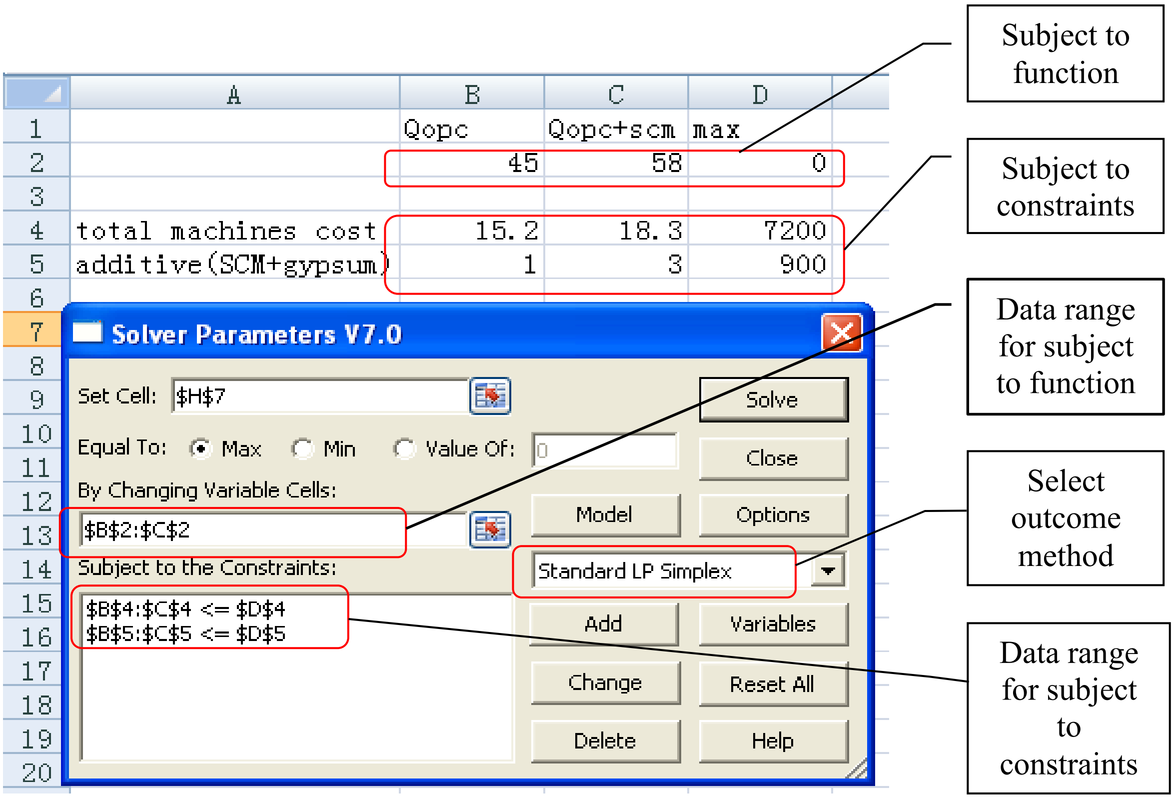
Figure 4.19 is the outcomes result to solve the linear programming equations problem using the graphical method. The yellow area is the feasible area and the red rectangle is the feasible corner. The intersection points are within two separate red rectangles. Two possible optimal solutions are found, as marked in blue circles:

(a) $\{0 \quad 393.3\}$

(b) $\{187.5 \quad 237.675\}$

Substituting (a) and (b) results into equation (4.21) and using the calculation procedures in Table 4.31, the optimal solution is (b). This result is the same as Table 4.31 line 5, and also the traditional matrix method outcomes. However, this method is more flexible by changing the parameters from 'subject of constraints' seeking alternative optimal solutions. This method does not comprehensively study each linear programming equation slick. The spreadsheet-based (Excel) model is to bridge the gap.

4.4.1.4 Spreadsheet-Based Method for Scenario 1



	A	B	C	D
1		Qopc	Qopc+scm	max
2		45	58	0
3				
4	total machines cost	15.2	18.3	7200
5	additive(SCM+gypsum)	1	3	900

Solver Parameters V7.0

Set Cell: $H$7

Equal To: ● Max ○ Min ○ Value Of: 0

By Changing Variable Cells: $B$2:$C$2

Subject to the Constraints:

$B$4:$C$4 <= $D$4
$B$5:$C$5 <= $D$5

Standard LP Simplex

Subject to function

Subject to constraints

Data range for subject to function

Select outcome method

Data range for subject to constraints

Figure 4.20 Establish Spreadsheet-based Model to Solve Scenario 1 Linear Programming Equations Using Solver®

Figure 4.20 illustrates the method of establishing a spreadsheet-based model using Solver®. The procedures are set cell including maximising, data ranges for ‘subject to function’ and ‘subject to constraints’, selecting linear programming equation method to solve optimal solution and changing the variable and subject to constraints of ‘trial-and-error’ seeking alternative optimal solutions. The results of the answer, sensitivity and limit reports are shown in Tables 4.28 to 4.30 respectively. Each report has its own purpose as below:

(a) Answer report: this report summarises the solution to the problems, and is self-explanatory. The first section of the report summarises the original and final (optimal) value of the set cell. The next section summarises the original and final (optimal) values of the adjustable (changing) cells reports, representing the decision variables as shown in Table 4.32.

(b) Sensitivity report: this report summarises information about the objective (target cell), the variable (adjustable cells), and constraints for the model. This information is useful in evaluating how sensitive the optimal solution is to changes in various coefficients in the model as shown in Table 4.33.

(c) Limit report: this report lists the optimal value of the set cell. It then summarises the optimal values of each variable cell and indicates what values the set cell assumes of each variable cell is set to its upper or lower limits as shown in Table 4.34.

4.4.1.4.1 Answer Report for Scenario 1

The results based on spreadsheet use were discussed in the previous section. The results as obtained:

Table 4.32 Outcome of the Answer Report for Scenario 1

Target Cell (Max)					
Cell	**Name**	**Original Value**	**Final Value**		
$D$2	Max	**0**	**0**		
Adjustable Cells					
Cell	**Name**	**Original Value**	**Final Value**		
$B$2	Qopc	**45**	**0**		
$C$2	Qopc+scm	**58**	**0**		
Constraints					
Cell	**Name**	**Cell Value**	**Formula**	**Status**	**Slack**
$B$4	Qopc total machines cost	**15.2**	**$B$4<=$D$4**	Not binding	7,184.8
$C$4	Qopc+scm total machines cost	**18.3**	**$C$4<=$D$4**	Not binding	7,181.7
$B$5	Qopc additive (SCM+gypsum)	**1**	**$B$5<=$D$5**	Not binding	899
$C$5	Qopc+scm additive (SCM+gypsum)	**3**	**$C$5<=$D$5**	Not binding	897

The sources of data location

Not binding but adjusted any constraint values and complied Solver® again would have binding status

The answer report is illustrated in Table 4.32, and provides the constraints which are ‘not binding.’ This means it is not an optimal solution. The data would have a use until the optimal solution was found by using slack values, which are in the right-hand column showing the amount of time that a task in a production can be delayed without causing a delay to subsequent tasks.

The sensitivity report also showed that there is not a wide range of ‘allowable increase’ and ‘allowable decrease’ as shown in Table 4.33. This is because the bottle neck is in a slack status in production facilities, in particular in mixer and grinding processes. Data in Table 4.34 is within upper, lower and target limits. This means the calculation is within the defined boundary.

4.4.1.4.2 Sensitivity Report for Scenario 1

Table 4.33 Outcome Result of the Sensitivity Report for Scenario 1

Cell	**Name**					
$D$2	Max	0				
Cell	**Name**	**Value**	**Reduced Cost**	**Objective Coefficient**	**Allowable Increase**	**Allowable Decrease**
$B$2	Qopc	0	0	0	1E+30	0
$C$2	Qopc+scm	0	0	0	1E+30	0
Cell	**Name**	**Final Value**	**Shadow Price**	**Constraint R.H. Side**	**Allowable Increase**	**Allowable Decrease**
$B$4	Qopc total machines cost	15.2	0	7,200	1E+30	7,184.8
$C$4	Qopc+scm total machines cost	18.3	0	7,200	1E+30	7,181.7
$B$5	Qopc Additive (SCM+gypsum)	1	0	900	1E+30	899
$C$5	Qopc+scm additive (SCM+gypsum)	3	0	900	1E+30	897

4.4.1.4.3 Limit Report for Scenario 1

Table 4.34 Limit Report for Scenario 1

Cell	**Target Value**	**Result**				
$D$2	Max	0				
Cell	**Adjustable Name**	**Value**	**Lower Limit**	**Target Result**	**Upper Limit**	**Target Result**
$B$2	Qopc	0	0	0	0	0
$C$2	Qopc+scm	0	0	0	0	0

(a) Answer Report for Scenario 1. Table 4.32 shows the answer report of Scenario 1. This report summarises the solutions to the problems. The first section of the report gives the original and final (optimal) values of the set cell. The next section summarises the original and final (optimal) values of the adjustable for changing cells representing the decision variables. These constraints prevent scenarios from achieving a higher level of profits. Finally, the values in the 'slack' column indicate the difference between the left-hand side and right-hand side of each constraint. Binding constraints have zero slack and non-binding constraints have a positive level of slack. The value in the slack column indicates whether this solution is implemented. The slack values for non-negative conditions indicate the amount by which the decision variables exceed their respective lower boundary.

(b) Sensitivity Report for Scenario 1. Regarding the sensitivity report as shown in Table 4.33, the 'cell value' column shows the final (optimal) value assumed by each constraints cell. Note that these values correspond to the final value assumed by the left-hand side formula of each constraint. The formula column indicates the upper or lower boundaries that the upper and lower boundaries that apply to each constraints cell. The status indicates which constraints are binding and which are non-binding. A 'subject to constraint' is binding if it is satisfied as a strict equality in the optimal solution; otherwise it is non-binding, as shown in Table 4.33.

(c) Limit Report for Scenario 1. Table 4.34 shows the 'limit report' of Scenario 1 problems. This report summarises information about the objective (or target cell), the variable (or adjustable cells), and constraints for the model. This information is useful in evaluating how sensitive the optimal solution is to changes in the various coefficients in the model. It summarises the optimal values for each variable cell and indicates what values the set cell assumes if each variable cell is set to its upper or lower limits. The values in the lower limits column indicate the smallest value that each variable cell can assume while the values of all other variable cells remain constant and all constraints are satisfied. The values in the 'upper limit' column indicate the largest value that each variable cell can assume while the values of all other variable cells remain constant and all the constraints are satisfied.

4.4.1.4.4 Compendium for Scenario 1

This Scenario uses mathematical and spreadsheet-based models to illustrate how to seek optimisation of the production of ordinary Portland cement and ordinary Portland cement with supplementary cementitious material within one factory, based on the boundary in Figure 2.6.

These three reports showed that Scenario 1 was not binding and in ‘slack’ status based on the ‘answer report’ and towards ‘allowable decrease’ values, but towards ‘allowable increase’ remained ‘1E+20’ values in the ‘sensitivity report.’ This means some production facilities would not be fully used yet to reach their target outcome based on this production situation. It also provides a message that the production yield could be set at the best values without extra production costs and facilities, as the result of improvements in production efficiency and better material flows in cement production.

To evaluate graphical information, Gaussian-Jordan Elimination and spreadsheet-based methods are suitable in this calculation, based on Table 4.35 outcomes, and also illustrated by the previous calculation procedures of each method. The Gaussian-Jordan Elimination method is considered one of the fastest methods to solve a set of linear equations problems. However, it cannot generate comprehensive analysis reports, including sensitivity reports, to further examine which set of ‘subject to constraint’ values are able be to be justified upon finding a binding solution.

Table 4.35 Advantages and Disadvantages of Three Methods

	Advantages	**Disadvantages**
Graphical method	More presentable and can easily trace back data	Can only solve up to three unknowns in one linear equation
Gaussian-Jordan Elimination method	Provides the optimal solution answer	Need to establish a matrix and use algebra approach to solve equation
Spreadsheet-based method	More flexible and provides a space to justify parameters up to the optimal solution. The answer, sensitivity and limit reports would be generated based on spreadsheet-based models (Solver®)	The ‘cell’ where data are located must be carefully designed; otherwise wrong assumptions may occur

4.4.2 SCENARIO 2

Geopolymer-based cement, including fly ash based and metakaolin-based geopolymer cement, production is arranged in a separate production line in Company A, because the production facilities are different from those used to manufacture ordinary Portland cement or ordinary Portland cement (OPC) with supplementary cementitious materials (SCM) and this avoids quality issues in manufacture. This factory produces three types of geopolymer-based cement, which are fly ash based geopolymer cement, metakaolin-based geopolymer cement and ground granulated blast furnace slag based geopolymer cement. For fair evaluation of the geopolymer-based cement production, and seeking optimisation, all the production facilities treated the same within the defined boundaries, which are:

(a) Fly ash and metakaolin and other raw materials, including sand, gravel, sodium hydroxide (NaOH) or potassium hydroxide (KOH) are supplied from nearby feedstock.

(b) Working hours are considered 300 days a year and 24 hours per day. This means 7,200 hours are available. It uses the one-piece-flow manufacturing method (Chan and Yung, 2008) to make geopolymer-based cement, based on Table 4.36 to 4.37.

(c) Fly ash, and metakaolin-based geopolymer cement production is examined, and energy consumption considered along with dust loss in the production process. An automatic process control method is used to collect fly ash and metakaolin materials.

(d) Two mixers are considered: one for sodium hydroxide (NaOH) with fly ash or metakaolin (MK) and another one for sand. There is one set of vertical milling machines for fine-grinding and packing facilities or pneumatic bulk tanker, etc.

Table 4.36 Scenario 2 for Machine Standard Time and Availability of a Classical Geopolymer-based Cement Plant (Australian Bureau of Statistics, 2014 and 2015; Cement Industry Federation 2013 to 2015; Fly Ash Australia Association, 2014; Peray, 1979)

	Unit processing time (tonne / hour)		**Availability (hour)**
	FA	**MK**	
Chemical reaction of sodium hydroxide (NaOH) with either fly ash or metakaolin (mixer)	3	3.3	2400
Mixed with sand	3.3	3.3	2400
Pack (pneumatic bulk tanker)	3	3	2400
Total processes yield	9.3	9.6	7200

‘subject to constraints’ equation was developed based on these outcomes values

Adding up the chemical reaction of sodium hydroxide with either fly ash or metakaolin and mixing with sand processes data are as the result of total process yield values becoming one of the ‘subject to constraints’ equation. Another equation is from the chemical reaction process. This is because the chemical reaction process time is different between metakaolin and fly ash (Company A, 2015). Mixing with sand was not considered because of its having the same timing.

Table 4.37 Revenue, Material Cost, Profit and Sales Data for Fly Ash Based Geopolymer Cement and Metakaolin-based Geopolymer Cement Plant (Australian Bureau of Statistics, 2015; Cement Industry Federation, 2014; USGS, 2014)

Item	**Description**		**Unit**
	Fly Ash Based Geopolymer Cement	**Metakaolin-based Geopolymer Cement**	
Revenue	1500	1500	A$/tonne
Material cost tonne	1464	1462	A$/tonne
Profit per tonne	36	38	A$/tonne

The profit per tonne values comes from revenue minus material cost per tonne as shown in Table 4.37.

Based on this outcome, this study could develop the ‘subject to function’ equation with respect to maximising profit.

The optimal fly ash based geopolymer-based and metakaolin-based geopolymer cement productions were found by using traditional mathematical methods and spreadsheet-based models using Solver®. This method was illustrated in Scenario1.

4.4.2.1 Identified Cost Drivers as Variables Building Linear Programming Equation

A linear programming model for Scenario 2 was based on equations from Chapter 3, Methodology. Their cost drivers are that:

Let

Q_{FA} is the amount of quantities of FA-based geopolymer cement to produce
Q_{MK} is the amount of quantities of MK-based geopolymer cement to produce

Choosing the Objective

Subject to function based on Table (4.37) red box as obtained:

$$Max(Z) = 36Q_{FA} + 38Q_{MK} \quad \text{……….……...} \quad (4.24)$$

Identifying the subject to constraints parameters as obtained:

The processing times for each machine are identified in Table 4.36. The corresponding constraints can be written as linear inequalities as below:

Subject to constraints

For total processes yield based on Table (4.36)

$$9.3Q_{FA} + 9.6(Q_{MK} \leq 7200 \quad \text{…………...} \quad (4.25)$$

Mixed with sand either fly ash or metakaolin-based on Table (4.36)

$$3Q_{FA} + 3.3Q_{Mk} \leq 2400 \quad \text{…………...} \quad (4.26)$$

Non-negativity constraints

$$Q_{FA} \geq 0 \ , Q_{GBBS} \geq 0 \text{ and } Q_{MK} \geq 0$$

4.4.2.2 Traditional Mathematical Method for Scenario 2

The linear programming equations were developed based on equations (4.25) and (4.26). Transforming them into matrix format for calculation purposes as obtained:

Q_{FA} is the amount of quantities of FA-based geopolymer cement to produce
Q_{MK} is the amount of quantities of MK-based geopolymer cement to produce

This is only to solve two unknown and relocated parameters from equations (4.25) and (4.26) into the 2 * 2 matrix as obtained:

Established the matrix:

$$\left(\begin{array}{cc|c} 9.3 & 9.6 & 7200 \\ 3 & 3.3 & 2400 \end{array}\right)$$

Using Gaussian-Jordan Elimination method (Grcar, 2011 and 2012) as obtained:

$$r_2 \rightarrow 3.1r_2 - r_1$$

$$\left(\begin{array}{cc|c} 9.3 & 9.6 & 7200 \\ 0 & 0.63 & 240 \end{array}\right)$$

$Q_{mk} = 380.95$ and substituted back into subject to constraints equation and as obtained:

$Q_{FA} = 380.95$

Substitution back again of ‘subject to function’ into equation (4.23) again and as obtained:

$$Max(Z) = 36*380.95 + 38*380.95 = 28190.3 \quad \text{……….……...} \quad (4.27)$$

4.4.2.3 Graphical Method for Scenario 2

Table 4.38 Cut-Points at X and Y Axis, Seeking Optimal Solution Using a Graphical Method for Scenario 2

Process	**Equation of Line**	**Cut Q_{FA}-axis when $Q_{Mk}=0$**	**Cut Q_{Mk}-axis when $Q_{FA}=0$**
Total processes based on equation (4.25)	$(9.3Q_{FA}+9.6Q_{Mk})=7200$	$9.3Q_{FA}=7200\rightarrow Q_{FA}=774.2$	$9.6Q_{MK}=7200\rightarrow Q_{Mk}=750$
Mixed sand based on equation (4.26)	$(3Q_{FA}+3.3Q_{MK})=2400$	$3Q_{FA}=2400\rightarrow Q_{FA}=800$	$3.3Q_{Mk}=2400\rightarrow Q_{Mk}=727.27$
Expected outcome based on equation (4.24)	$Max\ (Z)=36Q_{FA}+38Q_{MK}$		

The purpose of Table 4.38 is to find out the points of intersection with the axes by:

(a) Treating each inequality as an equation as shown in 'equation of line' column.

(b) Setting either Q_{MK} equal to zero and finding out Q_{FA} values as shown in 'cut Q_{FA}-axis' column.

(c) Setting either Q_{FA} is equal to zero and finding out Q_{MK} values as shown in 'cut Q_{MK}-axis' column.

Table 4.39 Trial-and-Error Method Seeking Optimal Solution for Scenario 2

Trial	**Corner point**	**Metakaolin**	**Fly Ash**	**Total Contribution Margin**
1	(774.2, 0)	774.2	0	36 (774.2) +38 (0) = 27,871.2
2	(0, 750)	0	750	36 (0) + 38 (750) = 28,500
3	(800,0)	800	0	36 (800) + 38 (0) = 28,800
4	(0, 727.27)	0	727.27	36 (0)+38 (727.27) = 27,636.26
5	(741.85,0)	741.85	0	36 (741.85) + 0 = 26,706.6
6	(0, 783.05)	0	783.05	0 + 38 (783.05) = 29,755.9

Table 4.39 provides data for the next section to develop the linear programming line graph and uses a graphical method to solve linear programming equations problems, seeking the optimal solution, as shown in Figures 4.21 to 4.24.

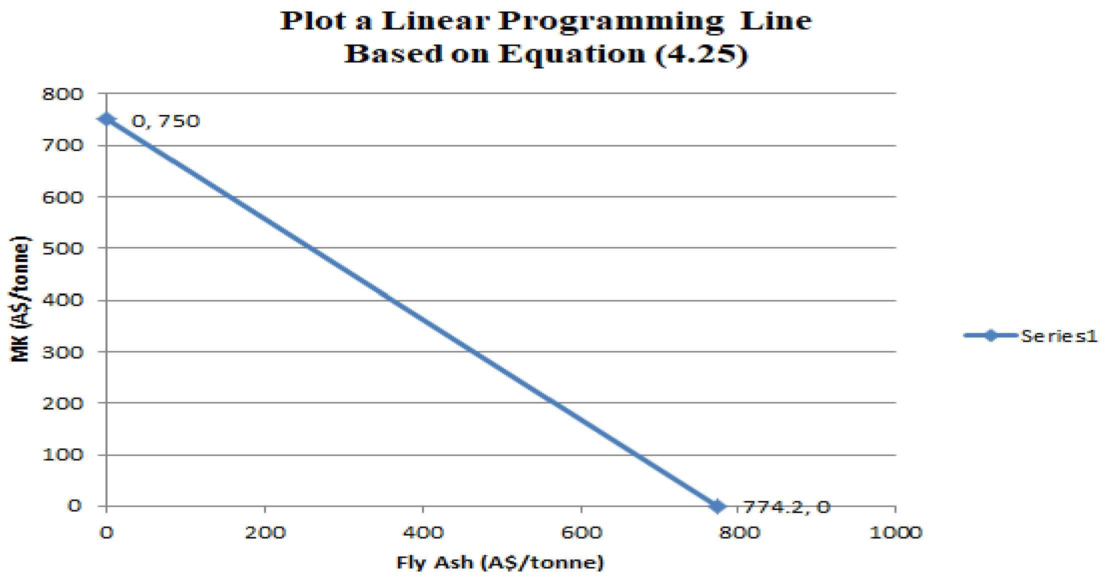


Figure 4.21 Graphical Method Representing Total Processes Based on Equation (4.25) for Scenario 2

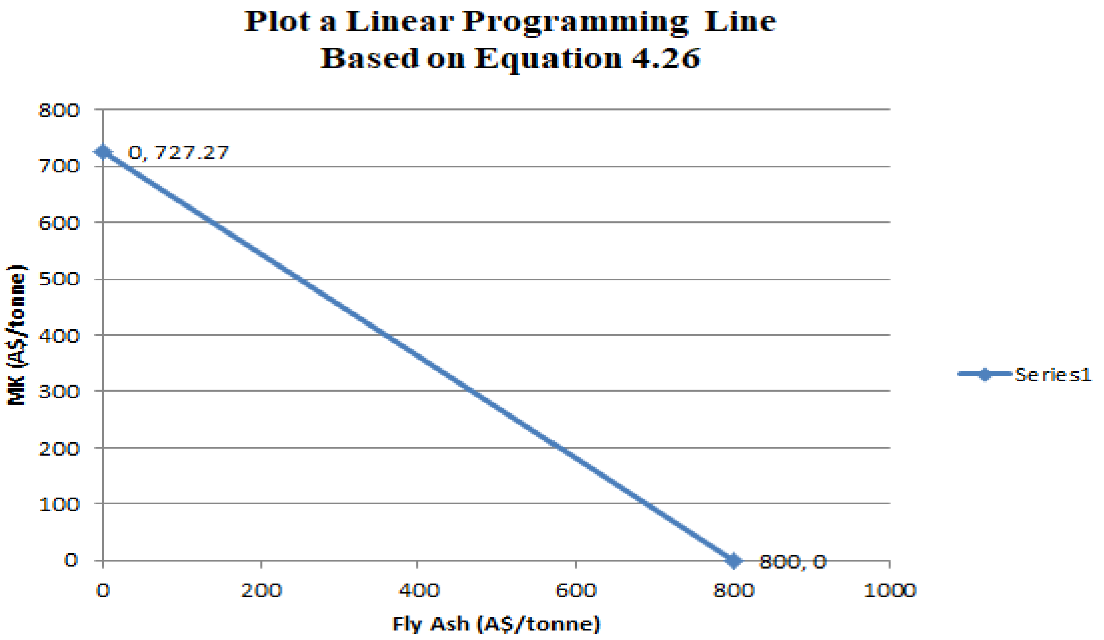


Figure 4.22 Graphical Method Representing Mixer Process Based on Equation (4.26) for Scenario 2

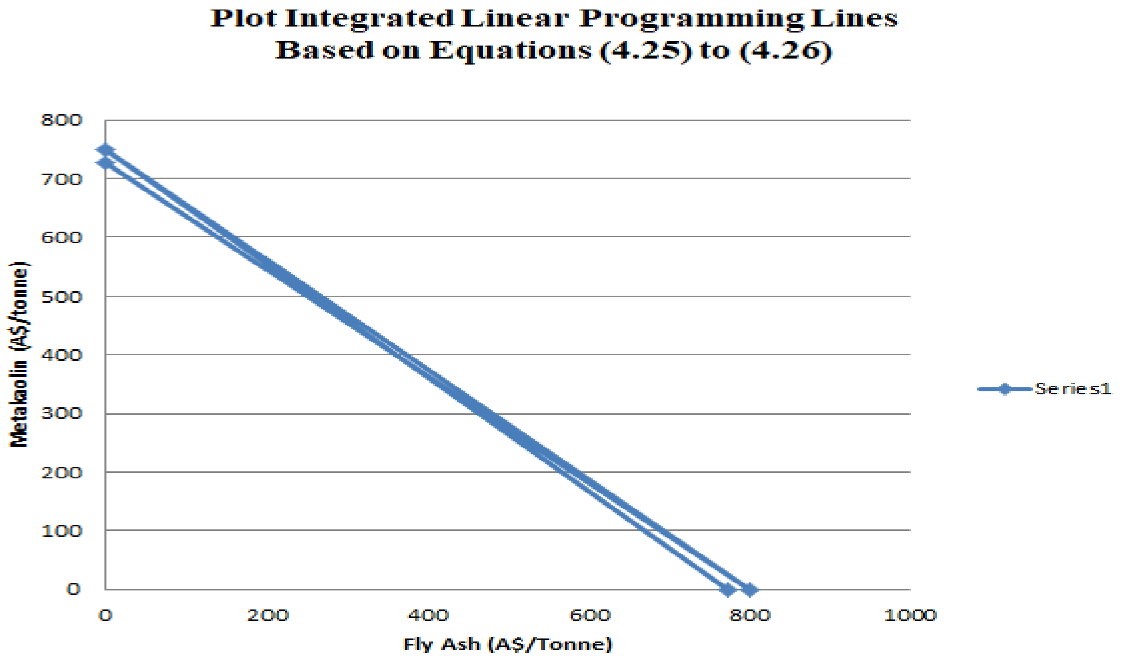


Figure 4.23 Integrated Linear Programming Equations Based on Equations (4.25) to (4.26) Seeking Optimal Solution for Scenario 2

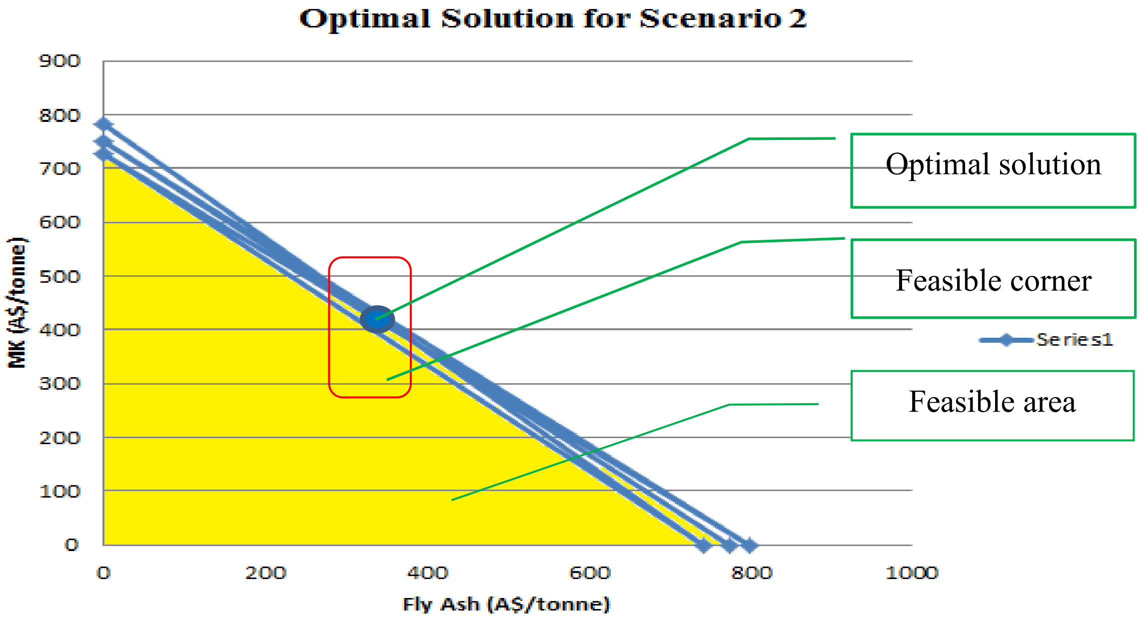
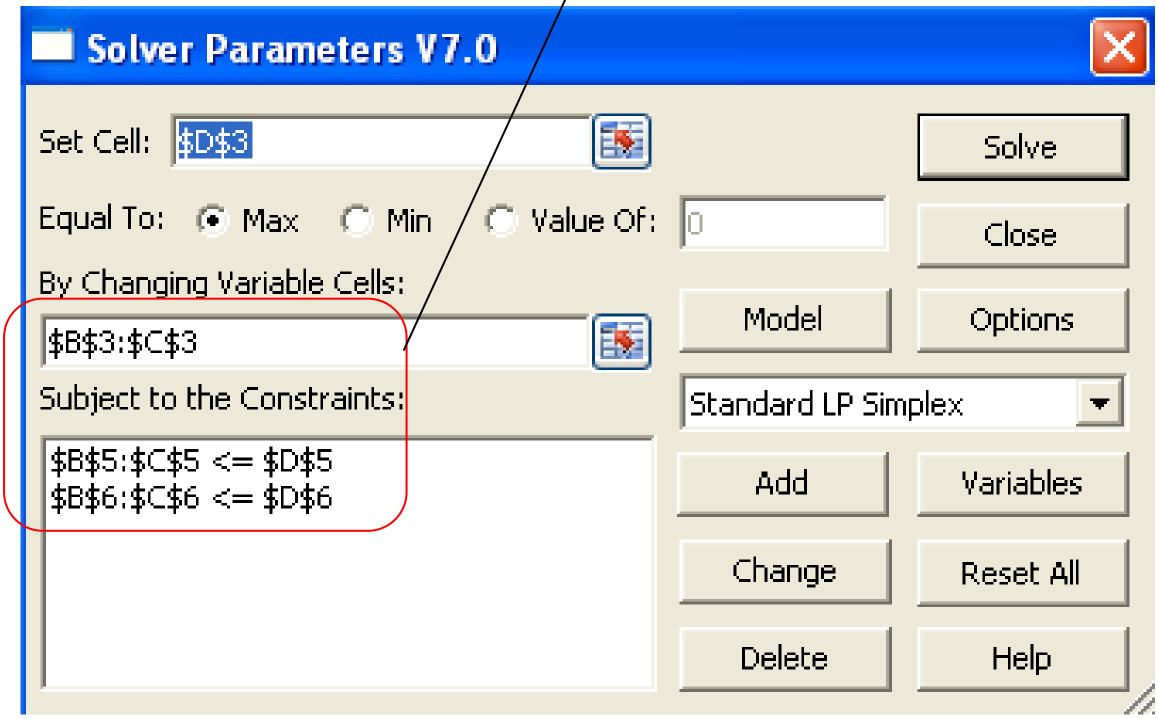


Figure 4.24 Optimal Solution for Scenario 2

Three lines were constructed seeking the optimal solution for Scenario 2. To find the optimal solution for Scenario 2, one moves up the line until it meets another line, as shown in Figure 4.24. Here the optimal solutions are indicated by red dots within the feasible area (in yellow) and feasible corner (in the red rectangle). The optimal solution is found as marked by the blue circles: $\{Q_{FA} \quad Q_{Mk}\} = \{380.952 \quad 380.952\}$.

4.4.2.4 Spreadsheet - Based Model Method for Scenario 2

To probe further the Scenario 2 linear programming problem with a wide range of parameters, a spreadsheet-based model is one of the solutions. There was pre-requisite to properly set cell or set ranges and formulas, which play an active role, meaning the outcome is based on these settings and will change based on the new manufacturing parameters, as shown in Figure 4.25 seeking optimal solution for linear programming equation of Scenario 2.



Changed parameters in the spreadsheet would have different LP outcomes

Solver Parameters V7.0

Set Cell: $D$3

Equal To: ● Max ○ Min ○ Value Of: 0

By Changing Variable Cells:

$B$3:$C$3

Subject to the Constraints:

$B$5:$C$5 <= $D$5
$B$6:$C$6 <= $D$6

Standard LP Simplex

Figure 4.25 Using Solver$^{©}$ in Excel® to Calculate the Linear Programming Equations Problems Seeking Optimal Solution for Scenario 2

The mathematical approach of Scenario 2 was same as for Scenario 1; the ‘subject to function’ and ‘subject of constraints’ equations were formulated into a spreadsheet-based model and careful design was implemented for the ‘set cell’, variable cells (subject to function), ‘subject to constraints’ ranges. ‘max’ and ‘standard LP simplex’ were selected and finally the ‘solve’ icon was used. Solver$^{©}$ was used to seek the optimal solution as shown in Figure 4.25. Three reports, ‘answer’, ‘sensitivity’ and ‘limit’, are quantitatively measured for the Scenario 2 mix production performances, seeking the optimal solution.

4.4.2.4.1 Answer Report for Scenario 2

Table 4.40 Answer Report from Solver© for Scenario 2

Target Cell (Max)					
Cell	**Name**	**Original Value**	**Final Value**		
$D$3		0	0		
Adjustable Cells					
Cell	**Name**	**Original Value**	**Final Value**		
$B$3	Q_{FA}	36	0		
$C$3	Q_{MK}	38	0		
Constraints					
Cell	**Name**	**Cell Value**	**Formula**	**Status**	**Slack**
$B$5	Q_{FA}	9.3	$B$5<=$D$5	Not binding	7,190.7
$C$5	Q_{MK}	9.6	$C$5<=$D$5	Not binding	7,190.4
$B$6	Q_{FA}	3	$B$6<=$D$6	Not binding	2,397
$C$6	Q_{MK}	3.3	$C$6<=$D$6	Not binding	2,396.7

The answer report of Scenario 2 as shown in Table 4.40 was calculated using Solver©. This report was divided into three parts:

(a) The first part is called the target cell (max), which is used to determine the original and final (optimal) values of the set cell. Here, the result is zero both in original and final value. This means the current operation was optimal based on current data.

(b) The second part is called the adjustable cell, which provides the conditions as to how to seek maximum values on the left-hand side. Here, the result was also zero and it is not necessary to bias values by using changing cell values until the optimal solution is reached. This case shows that the system was at optimal operation.

(c) The final part is subject to constraints. The outcome shown on the left-hand side was based on the formula and the cell value column. The outcome status was ‘not binding’ and provided an opportunity to further justify value within constraints to find an alternative optimal operation.

The ‘sensitivity report’ of Scenario 2 for the linear programming equation problem is shown in Table 4.41. The purpose of this report is to summarise information about the objective (or target cell), the variable (or adjustable cells), and constraints for the Scenario 2 model. Based on the result, it can evaluate sensitivity status by changing various coefficients of each equation in the model. The outcome was only minor ‘allowable increase or decrease’ values as shown in the left-hand column in the ‘constraints’ paragraph.

4.4.2.4.2 Sensitivity Report for Scenario 2

Table 4.41 Sensitivity Report from Solver© for Scenario 2

Target Cell (Max)						
Cell	**Name**	**Final Value**				
$D$3		0				
Adjustable Cells						
Cell	**Name**	**Final Value**	**Reduced Cost**	**Objective Coefficient**	**Allowable Increase**	**Allowable Decrease**
$B$3	Q_{FA}	0	0	0	1E+30	0
$C$3	Q_{Mk}	0	0	0	1E+30	0
Constraints						
Cell	**Name**	**Final Value**	**Shadow Price**	**Constraint R.H. Side**	**Allowable Increase**	**Allowable Decrease**
$B$5	Q_{FA}	9.3	0	7200	1E+30	7190.7
$C$5	Q_{MK}	9.6	0	7200	1E+30	7190.4
$B$6	Q_{FA}	3	0	2400	1E+30	2397
$C$6	Q_{MK}	3.3	0	2400	1E+30	2396.7

4.4.2.4.3 Limit Report for Scenario 2

Table 4.42 Limit Report from Solver© for Scenario 2

Cell	**Target Value**					
$D$3		0				
Cell	**Adjustable Name**	**Value**	**Lower Limit**	**Target Result**	**Upper Limit**	**Target Result**
$B$3	Q_{FA}	0	0	0	0	0
$C$3	Q_{Mk}	0	0	0	0	0

The 'limit report' for the Scenario 2 linear programming equations problem outcome is shown in Table 4.42. This report summarises the optimal values for each variable cell and indicates what values the set cell assumes if each variable cell is set to its upper or lower limit for Scenario 2. It showed that:

(a) The values in the lower limits column indicate the smallest value that each variable cell can assume while the values of all other variable cells remain constant and all constraints are satisfied. The result was a zero value and within boundary operation.

(b) The values in the upper limits column indicate the largest value that each variable cell can assume while the values of all other variable cells remain constant and all the constraints are satisfied. Here, the result was a zero value and within boundary operation.

4.4.2.4.4 Compendium for Scenario 2

Traditional mathematical and spreadsheet-based model outcomes for Scenario 2 illustrate how to effectively find the optimal solution of the linear programming problems in the previous section of Scenario 2.

The linear programming problem of Scenario 2 has only two unknowns, namely fly ash based geopolymer and MK-based geopolymer cement, and seeks optimal production operation based on the boundary in Figure 2.6. To effectively solve the 'objective function' and two 'subject of constraints' equations by using the Gaussian-Jordan Elimination (Grcar, 2011) method, the optimal solution from this method is that:

$$\{Q_{FA} \quad Q_{Mk}\} = \{380.952 \quad 380.952\}$$

Based on this outcome, the alternative solution is also is found using a 'graphical' method with ranges of parameters set to further validate the model. The Solver$^{©}$ further examines 'answer', 'sensitivity' and 'limit' status and provides an alternative optimal solution to solve Scenario 2 linear equations problems. This shows that Company A's geopolymer-based cement production took time to improve production capacity and production efficiency.

4.4.3 SCENARIO 3

The purpose of Scenario 3 is to minimise energy costs without affecting the cement production services, and to achieve a better profit margin. In the literature review and survey, energy costs are a major expenditure in cement production (Company A, 2014; Australian Bureau of Statistics, 2014 and 2015; Peray, 1986; Cement Industry Federation, 2013). Two major types of energy were identified in cement production, as shown in tables 4.10 and 4.11 and Figure 4.9 (Cement Industry Federation, 2013; Company A, 2014). There are:

(a) Fossil fuel, including diesel, petrol, LPG and coal.
(b) Electricity.

4.4.3.1 Identified Cost Drivers as Variables Building Linear Programming Equation

let

Q_{petrol} = quantities of petrol used
Q_{diesel} = quantities of diesel used
Q_{LPG} = quantities of LPG used
Q_{coal} = quantities of coal used
t_{petrol} = feed rate of diesel per hours
t_{diesel} = feed rate of diesel per hours
t_{LPG} = feed rate of LPG per hours
t_{coal} = feed rate of coal per hours

Formulating equation (3.16) into ‘subject to function’ equation as obtained:

Subject to Function

$$Min(Z) = 1.5Q_{petrol} + 1.5Q_{diesel} + 1Q_{LPG} + 1.3Q_{electrciity} + 1.1Q_{coal} \quad \ldots\ldots \quad (4.28)$$

But

$$Q_{fossil}t_{fossil} = Q_{petrol}t_{petrol} + Q_{diesel}t_{diesel} + Q_{LPG}t_{LPG} + Q_{coal}t_{coal}$$

Based on Table 4.11, Companies A to C (2015) and Cement Industry Federation (2014 to 2016), the major energy types used are coal and diesel. The price of coal was equal to diesel fuel. The equation (4.28) is below:

$$Min(Z) = 1.5Q_{fossil}t_{fossil} + 1.3Q_{electrciity}t_{electrciity} \quad \text{..............} \quad (4.29)$$

Subject of Constraints

$$5000Q_{fossil} + 7200Q_{electrciity} \geq 650{,}000 \quad \text{..............} \quad (4.30)$$

$$7200Q_{fossil} + 3600Q_{electrciity} \geq 350{,}000 \quad \text{..............} \quad (4.31)$$

4.4.3.2 Traditional Mathematical Method for Scenario 3

Several variables were identified in equations (4.29) to (4.31) and formulated into matrix format as below:

Using Gaussian-Jordan Elimination (Grcar, 2011 and 2012) method as obtained:

$$\left(\begin{array}{cc|c} 5000 & 7200 & 650000 \\ 7200 & 3600 & 350000 \end{array}\right)$$

$$r_2 \rightarrow r_1 - 0.69r_{21}$$

where

r1 is the first-row number and r2 is the second row

$$\left(\begin{array}{cc|c} 5000 & 7200 & 650000 \\ 0 & 4716 & 241500 \end{array}\right)$$

$Q_{electriciy} = 51.21$ and substituted back into subject to constraints equations as obtained:

$$Q_{fossil} = 56.26$$

The minimisation of energy including diesel and electricity used by substituted back into subject to function equation (4.26) as obtained:

$$Min(Z) = (1.5 * 51.21 * 5000) + (1.3 * 56.26 * 7200) = 910668 \quad \text{.........…….} \quad (4.32)$$

4.4.3.3 Graphical Method for Scenario 3

Table 4.43 Cut-Points at X and Y Axis, Seeking Optimal Solution Using Graphical Method for Scenario 3

	Equation of Line	**Cut E$_{lectricity}$-axis when Q$_{fossil}$= 0**	**Cut Q$_{fossil}$-axis when Q$_{electricity}$= 0**
Fossil	$5000\dot{Q}_{fossil}+7200\dot{Q}_{electrcity}$ $= 650000$	$\dot{Q}_{electricty}=90.28$	$\dot{Q}_{fossil}=130$
Electricity	$7200\dot{Q}_{fossil}+3600\dot{Q}_{electriciy}$ $=350000$	$\dot{Q}_{electriciy}=97.22$	$\dot{Q}_{fossil}=48.61$
Minimising	$Min(Z)=1.5*\dot{Q}_{fossil}*t_{fossil}+1.3*\dot{Q}_{electriciy}*t_{electriciy}$		

The purpose of Table 4.43 is to find out the points of intersection with the axes by:

(a) Treating each inequality as an equation as shown in 'equation of line' column.

(b) Setting either Q$_{fossil}$ equal to zero and finding out Q$_{FA}$ values as shown in 'cut Q$_{electrity-}$axis' column.

(c) Setting either Q$_{fossil}$ equal to zero and finding out Q$_{electricity}$ values as shown in 'cut Q$_{electricity}$ axis' column.

Table 4.44 Trial-and-Error Method Seeking Optimal Solution for Scenario 3

Trial	**Corner point**	**Fossil**	**Electricity**	**Total Contribution Margin**
1	(90.28, 0)	90.28	0	1.5(90.28)5000+0 = 677,100
2	(0, 130)	0	130	0+1.3(130) 7200 = 121,680
3	(97.22,0)	97.22	0	1.5(97.22)5000+0 = 729,150
4	(0, 48.61)	0	48.41	0+1.3(48.41)7200 = 453,118
5	(97.22,0)	97.22	0	1.5(97.22)5000 +0 = 729,150
6	(0,121,42)	0	121.42	0+1.3(121.42)7200 = 2,072,491

Table 4.44 was used a trial-and-error method seeking the contribution margin. Results were given to Figures (4.26) to (4.29) step-by-step to develop linear programming lines based on Tables (4.43) to (4.44).

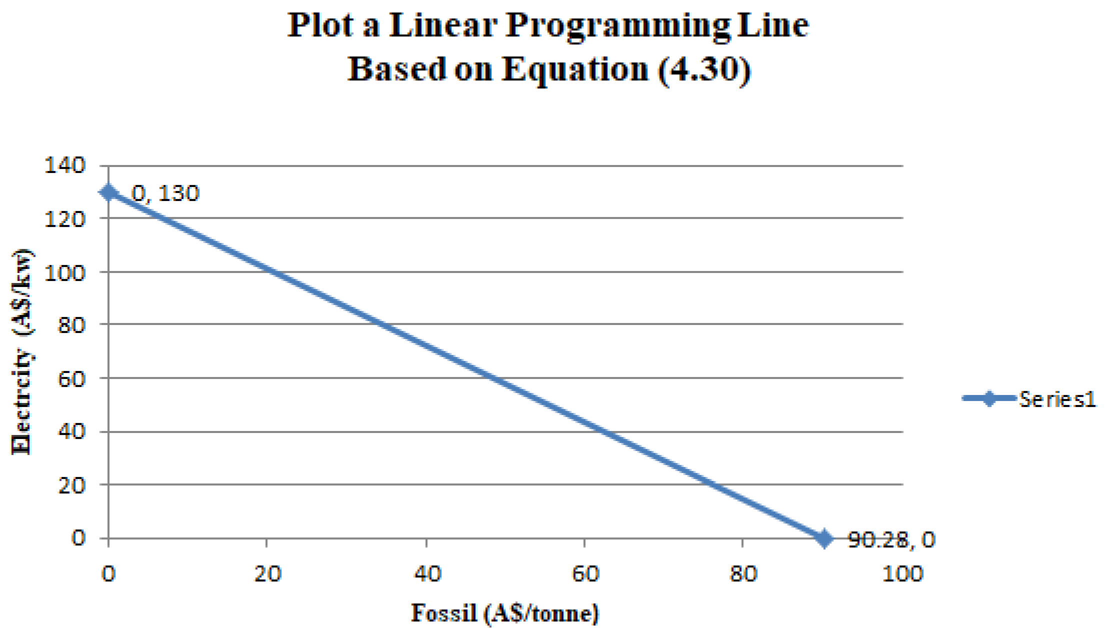


Figure 4.26 Linear Programming Line Based on Equation (4.30) for Scenario 3

Figures (4.26) to (4.27) illustrate the graphical method based on equations (4.30) to (4.31) and Tables (4.43) to (4.44) seeking an optimal solution for Scenario 3. This section solves the optimal use of energy in cement production.

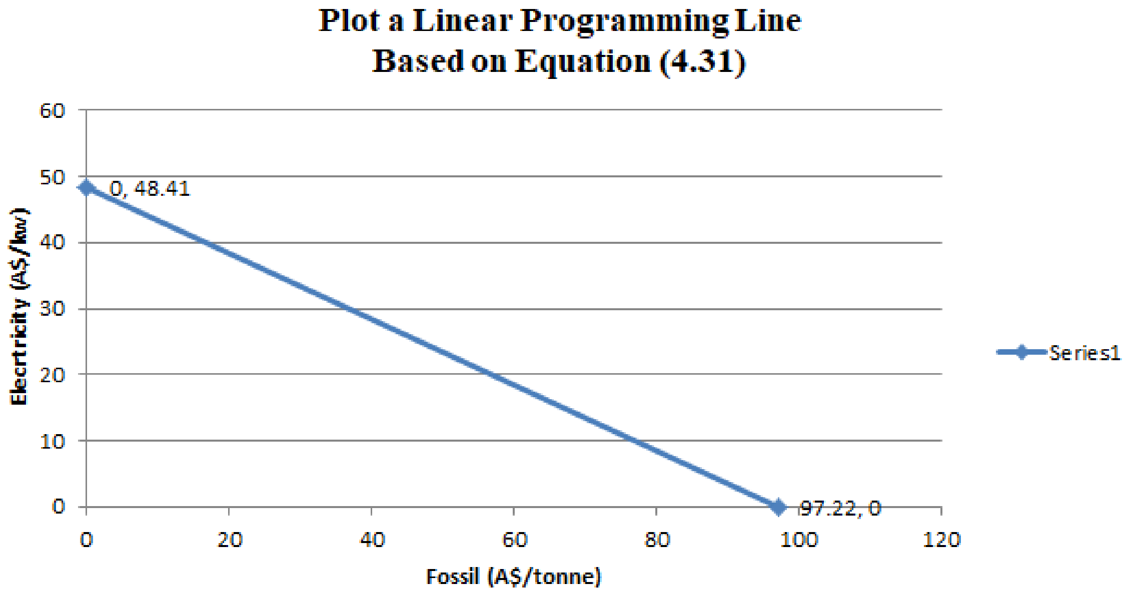


Figure 4.27 Linear Programming Line Based on Equation (4.31) for Scenario 3

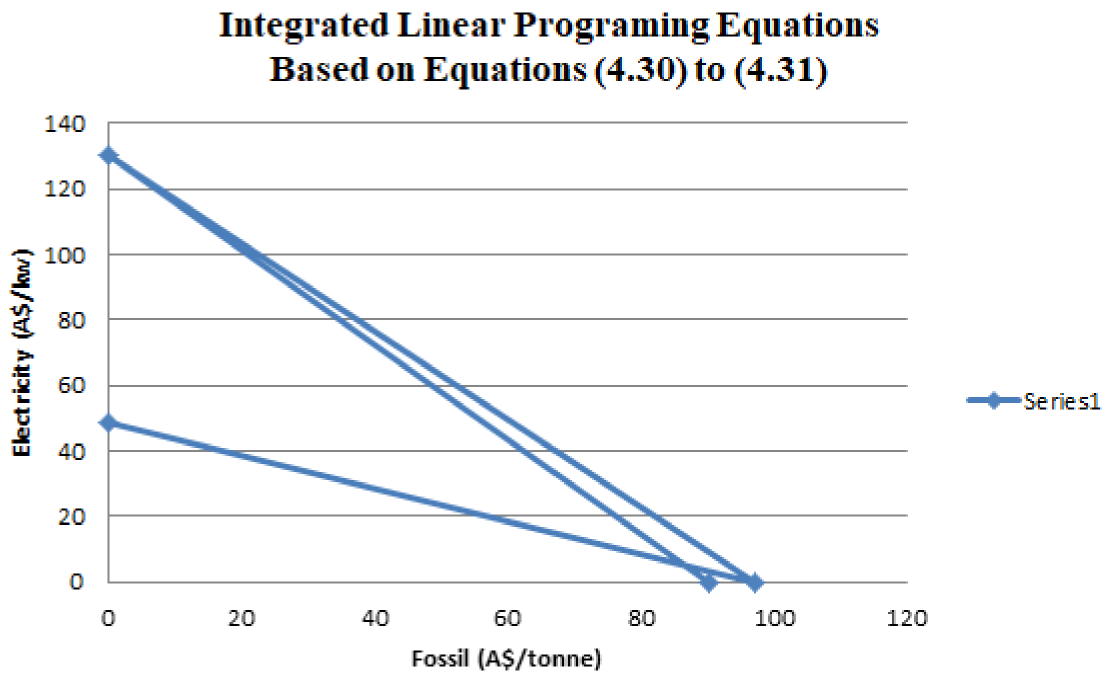


Figure 4.28 Integrated Linear Programming Equations Based on Equations (4.30) to (4.31) Seeking Optimal Solution for Scenario 3

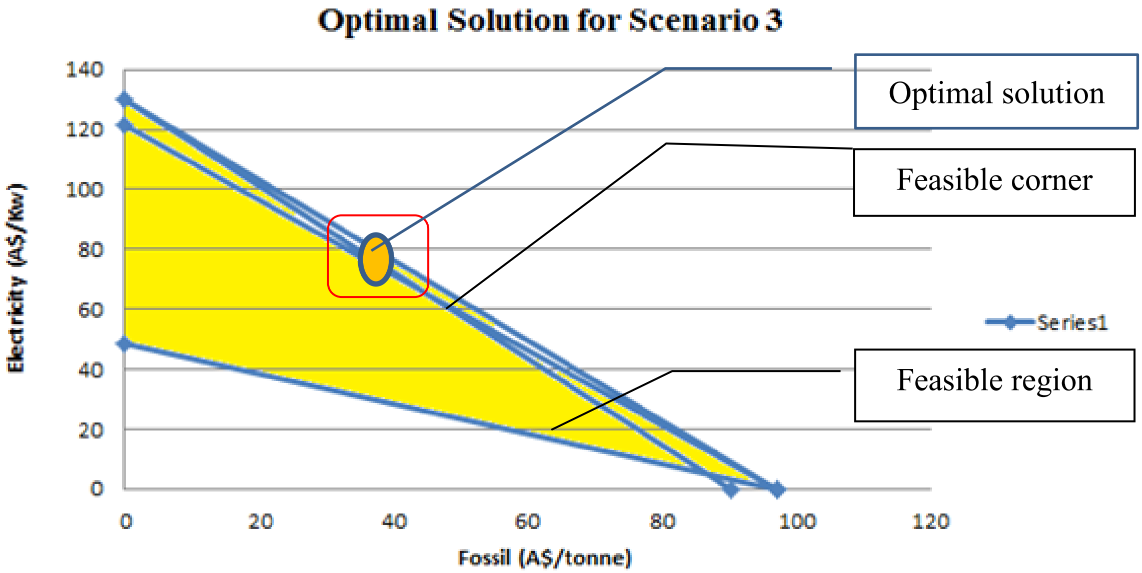


Figure 4.29 Graphical Method to Calculate the Linear Programming Problems Seeking Optimal Solution for Scenario 3

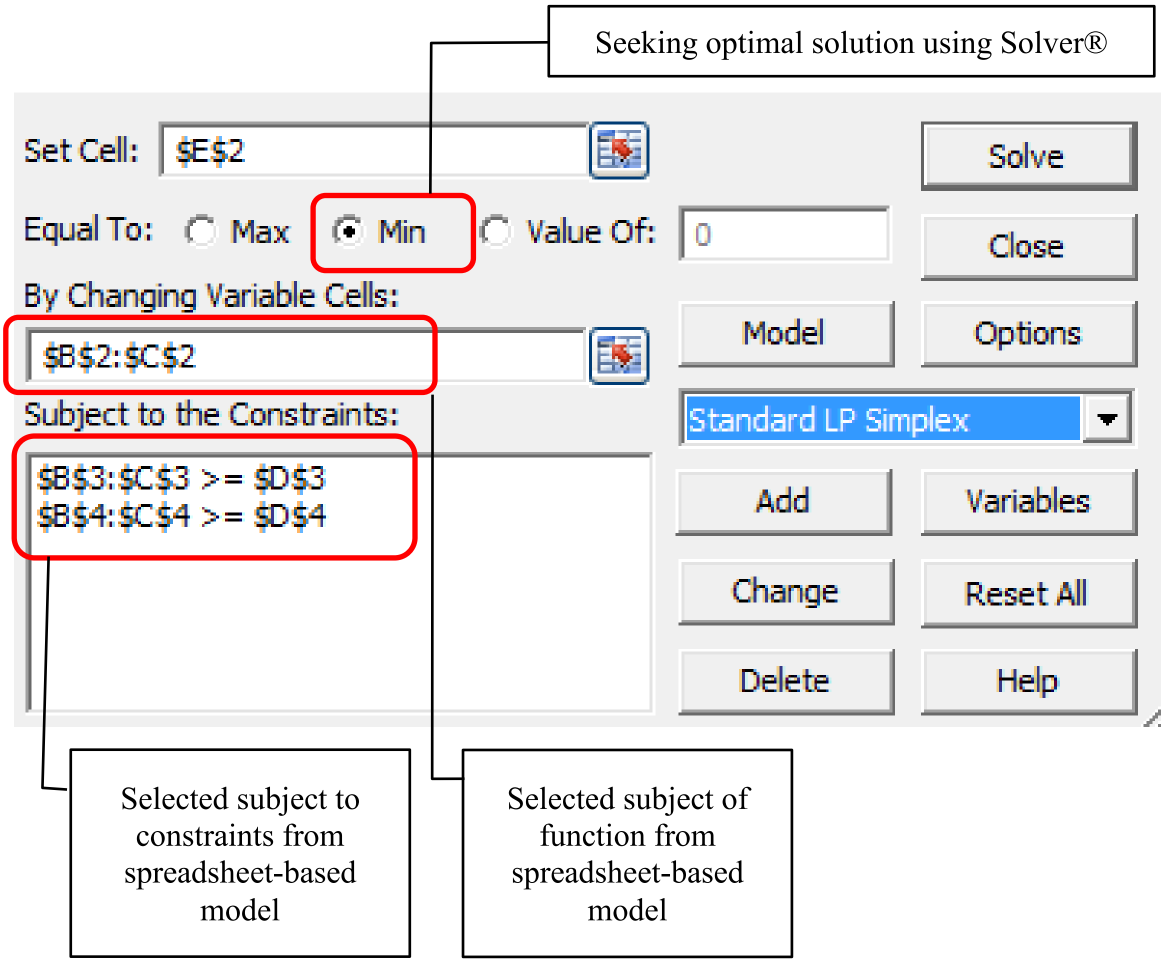
The optimal solution of Scenario 3 is in the red rectangular box, found by moving the bottom line (e.g. Subject to function) upward until it meets other lines, as shown in Figure 4.29. Here the optimal solution is $\{Q_{electricity} \quad Q_{fossil}\} = \{51.21 \quad 56.26\}$.

The Gaussian-Jordan Elimination (Grcar, 2011 and 2012) and graphical methods were used to solve the linear equations problems in respect to different views to probe the solution for Scenario 3. The spreadsheet-based model for Scenario 3 further probed the optimal operation using Solver© as shown in Figure 4.30. The scope of this report is that:

(a) In the ‘adjustable cell’ paragraph, only a small range was allowed of ‘allowable increase and decrease values’; both are ‘1E+30’ and zero values. This means there was not a big change in the defined adjustable cells.

(b) In the ‘subject of constraints’ paragraph, there were some spaces to allow for ‘allowable increase and allowable decrease’. The results were approaches for allowable decrease rather than allowable increase values to have the alternative optimal solution. This saves energy.

4.4.3.4 Spreadsheet -Based Method for Scenario 3



Seeking optimal solution using Solver®

Set Cell: $E$2

Equal To: ○ Max ● Min ○ Value Of: 0

By Changing Variable Cells:

$B$2:$C$2

Subject to the Constraints:

$B$3:$C$3 >= $D$3
$B$4:$C$4 >= $D$4

Standard LP Simplex

Selected subject to constraints from spreadsheet-based model

Selected subject of function from spreadsheet-based model

Figure 4.30 Spreadsheet-based Model from Solver© for Scenario 3

4.4.3.4.1 Answer Report for Scenario 3

Table 4.45 Answer Report from Solver® for Scenario 3

Target Cell (Max)					
Cell	**Name**	**Original Value**	**Final Value**		
$D$2	Max	0	0		
Adjustable Cells					
Cell	**Name**	**Original Value**	**Final Value**		
$B$2	Fossil	7,500	0		
$C$2	Electricity	9,360	0		
Constraints					
Cell	**Name**	**Cell Value**	**Formula**	**Status**	**Slack**
$B$4	Fossil	5,000	$B$4<=$D$4	Not binding	645,000
$C$4	Electricity	7,200	$C$4<=$D$4	Not binding	642,800
$B$5	Fossil	7,200	$B$5<=$D$5	Not binding	342,800
$C$5	Electricity	3,600	$C$5<=$D$5	Not binding	346,400

Not binding means all parameters here would be changed until optimal solution

4.4.3.4.2 Sensitivity Report for Scenario 3

Table 4.46 Outcome of Sensitivity Report for Scenario 3

Target Cell (Max)						
Cell	**Name**	**Final Value**				
$D$2	Max	0				
Adjustable Cells						
Cell	**Name**	**Final Value**	**Reduced Cost**	**Objective Coefficient**	**Allowable Increase**	**Allowable Decrease**
$B$2	Fossil	0	0	0	1E+30	0
$C$2	Electricity	0	0	0	1E+30	0
Constraints						
Cell	**Name**	**Final Value**	**Shadow Price**	**Constraint R.H. Side**	**Allowable Increase**	**Allowable Decrease**
$B$4	Fossil	5,000	0	650,000	1E+30	645,000
$C$4	Electricity	7,200	0	650,000	1E+30	642,800
$B$5	Fossil	7,200	0	350,000	1E+30	342,800
$C$5	Electricity	3,600	0	350,000	1E+30	346,400

4.4.3.4.3 Limit Report for Scenario 3

Table 4.47 Limit Report from Solver® for Scenario 3

Cell	**Target Value**					
$D$2	Max	0				
Cell	**Adjustable Name**	**Value**	**Lower Limit**	**Target Result**	**Upper Limit**	**Target Result**
$B$2	Fossil	0	0	0	0	0
$C$2	Electricity	0	0	0	0	0

The ‘upper and lower limits’ report, as shown in Table 4.47, is marked by the red rectangular box, based on Figure 4.30 spreadsheet-based model and equations (4.29) to (4.31), settings were zero.

4.4.3.4.4 Compendium for Scenario 3

Two methods, traditional and spreadsheet-based, were used to illustrate the optimal solution for Scenario 3. This is promising because the results were towards the ‘allowable decrease’ as shown in Table 4.46. This means that to minimise operational costs in energy in the production process, fossil fuel is better than electricity. However, one of the disadvantages of this type of energy is that it emits large quantities of carbon dioxide.

Scenario 3 measured optimal use of energy types in cement production. Scenarios 4 and 5 will quantitatively measure carbon dioxide emission by using the Carbon Dioxide Emission Equivalent method and Australian National Greenhouse Accounts Factors (2014 to 2016) as the ‘subject of function’ and ‘subject to constraints’ remains at the same values to examine this issue with respect to transport of raw material from site to cement factory, including ordinary Portland cement, ordinary Portland cement with supplementary cement material and geopolymer-based cement, to seek optimal solutions to minimise carbon dioxide emission. The reasons for choosing these two methods are discussed in the literature review and in Chapter 3, where this study identified that these two methods are commonly used in research but are applied in different nations and industries. Therefore, it was a good opportunity to compare which method is best by using fundamental theory (Chapter 3, Methodology)

4.4.4 SCENARIO 4

The aim of this section is to compare the outcomes results of Scenario 4 using Australian Greenhouse National Accounts Factors (2014 to 2016) as the ‘subject to function’ and Carbon Dioxide Emission Equivalent as a ‘subject to function’ in Scenario 5. The rest of the ‘subject to constraints’ are the same in scenarios 4 and 5. These two methods are used to measure carbon dioxide emission when delivering raw materials from upfront factories or site to an ordinary Portland cement factory, seeking minimisation of carbon dioxide emission through the production processes, in transport. The reason why transport was selected for study rather than the clinker processes is because both ordinary Portland cement and fly ash based geopolymer cement production also need transport to deliver raw materials from sites to factories. Additionally, Companies A to C have a guideline to deliver cement using route arrangement. However, it is not clear which route was most efficient with respect to Companies A to C’s cement operations and also what types of fuel use would produce less carbon dioxide emission and save costs.

To construct linear programming equations for the same method of production, all data for scenarios 4 and 5 are from primary and secondary data, Companies A to C are located in Brisbane city, and so on, and their methods of delivering raw materials are the same, but the cement market segments differ. The spreadsheet-based model for linear programming equations problems were developed based on equations (3.5) to (3.7) and (3.15) to (3.20) respectively.

However, there are several limitations of this study, as listed below:

(a) This study only considers the transport within the defined boundary based on Figures 2.6 and Table 2.4. The transport to import raw materials and semi-cement products from overseas (USGS, 2014; Australian Bureau of Statistics, 2014 and 2015; Company C, 2014 to 2015) do not consider because of out of boundaries.

(b) Distances were measured from quarry sites to fly ash based geopolymer cement and ordinary Portland cement factories as the result of the consideration of optimal transportation for raw materials.

(c) The ‘subject to function’ equation is from the Australian National Greenhouse Accounts Factors (2014 to 2016) as discussed in Chapter 3.

(d) An assumption was made that one litre of diesel fuels a 40-tonne truck to travel 11.1 km (Australian Bureau of Statistics, 2014). Therefore, 324.32 litres of diesel fuel was consumed with a full load, per 40-tonne truck per trip per day, as shown in Tables 4.48 and 4.49 which provide an estimation of distances of delivery of cement from Companies A and B.

Table 4.48 Distance Apart from Raw Materials to Fly Ash Based Geopolymer Cement Factory of Companies A and B

Description	Distances	Travelled method
Delivered fly ash to factory	500 km	Truck / ship / railway
Delivered sodium hydroxide (NaOH) to factory	1,100 km	Truck / ship /railway
Delivered to brine factory	2,000 km	Truck / ship / railway
Subtotal	3,600 km	Truck / ship / railway

Table 4.49 Distances Apart from Raw Materials to OPC Factory for Companies A and B

Delivered raw materials to OPC factories	Distances	Travelled method
From quarry sites to limestone factory	2,150 km	Truck / ship / railway
From lime factory to cement factory	2,150 km	Truck /ship /railway
From gravel quarry site to cement factory	3,150 km	Truck / ship / railway
From the sand factory to cement factory	500 km	Truck / ship / railway
From slag factory to cement factory	2,150 km	Truck / ship /railway
From gypsum factory to cement factory	3,000 km	Truck / ship / railway
Subtotal	12,650 km	Truck / ship / railway

(e) It is assumed that diesel oil is the major fuel in transport (Australian Bureau of Statistics, 2014 and Companies B, 2015). Nearly 86% of trucks or production facilities for mining, construction and building industries use diesel, and an average of 1 litre of diesel fuels a truck for 11.1km. Additionally, this study also identifies diesel fuel as the major energy source based on Company A (2016). Therefore, 1139.64 litre of diesel would be used in transport every single trip every day.

(f) An account of carbon dioxide emission was taken based on single trip fuel consumption; this can be extended to multiple trips based on the same route.

The three methods used in this study to solve the linear programming equation seeking optimal transport uses are:

(a) Gaussian-Jordan Elimination (Grcar, 2011 and 2012) method.

(b) Graphical method.

(c) Spreadsheet-based method with the assistance of (Solver®). The answer, sensitivity and limit reports will be generated to seek ways to minimise fuel consumption as a way of driving down the carbon dioxide emission because of long-distance delivery.

4.4.4.1 Identified Cost Drivers as Variable Building Linear Programming Equation for Scenario 4

One of the pre-conditions of optimisation is to evaluate fly ash based geopolymer cement and ordinary Portland cement production, as obtained:

Subject to function equation based on Australian National Greenhouse Factors Accounts (2014 to 2016) for Scenario 4.

$$Min(CO_2) = \frac{Q_{electricity} * EF}{1000} + \frac{Q_{diesel} * EC * EF_{ijoxec}}{1000} \quad \ldots\ldots\ldots\ldots\ldots \quad (4.33)$$

where

EC = the energy contents factor of fuel type

EF = the scope emission factor, for the state. Here Queensland the Emission factor $0.81 kgCO_{2-e} KWh$

EF_{ijoxec} = the emission factor for each gas type

$Q_{electricity}$ = the quantity of electricity purchased (kilowatt hours)

Q_{diesel} = the quantity of diesel fuel measured in gigajoules

Subject to Constraints for Scenario 4

$$6Q_{diesel} + 2Q_{electricity} \geq 1139.64 * 300 + 1000000 \quad \ldots\ldots\ldots\ldots\ldots \quad (4.34)$$

$$6Q_{diesel} + 2Q_{electricity} \geq 1341892 \quad \ldots\ldots\ldots\ldots\ldots \quad (4.35)$$

Reorganised equation (4.33) and (4.34) as obtained:

$$6Q_{diesel} + Q_{electricity} \geq 324.32 * 300 + 500000 \quad \text{……………...} \quad (4.36)$$

$$6Q_{diesel} + Q_{electricity} \geq 597296 \quad \text{……………...} \quad (4.37)$$

Linear equations for calculation of minimising carbon dioxide emission

Non-negativity constraints:

$$Q_{diesel} \geq 0, Q_{electricity} \geq 0, EC \geq 0, EF \geq 0, EF_{ijoexc} \geq 0, GWP \geq 0$$

4.4.4.2 Traditional Mathematical Method for Scenario 4

Based on equations (4.35) to (4.36), the matrix as obtained:

$$\left(\begin{array}{cc|c} 6 & 2 & 1341892 \\ 6 & 1 & 597296 \end{array}\right)$$

Using Gaussian-Jordan Elimination method (Grcar, 2011 and 2012)

$$r_2 \rightarrow r_1 - r_2$$

where

r_1 = row number one

r_2 = row number two

$$\Rightarrow \quad \left(\begin{array}{cc|c} 6 & 2 & 1341892 \\ 0 & 1 & 744596 \end{array}\right)$$

$$Q_{diesel} = 24550$$

$$Q_{electricity} = 744596$$

Substituted back the values of $Q_{diesel} = 24550$ and $Q_{electricity} = 744596$ into equation (4.41), EF and EF_{ijoexe} from Tables 4.3 to 4.6 and as obtained:

$$Min(CO_2) = 0.07 * Q_{diesel} + 0.81 * Q_{electricity} \quad \text{……………...} \quad (4.38)$$

and

$$\Rightarrow Min(CO_2) = (24550 * 0.07) + (0.81 * 744596) \quad \text{…………...} \quad (4.39)$$

4.4.4.3 Graphical Method for Scenario 4

Table 4.50 Cut-Points at X and Y Axis, Seeking Optimal Solution Using Graphical Method for Scenario 4

	Equation of Line	**Cut $Q_{electricity}$-axis when $Q_{diesel} = 0$**	**Cut Q_{diesel}-axis when $Q_{electricity} = 0$**
Fossil	$6\dot{Q}_{diesel} + 2\dot{Q}_{electrcity} = 1341892$	$\dot{Q}_{electricty} = 670947$	$\dot{Q}_{diesel} = 223648.67$
Electricity	$6\dot{Q}_{diesel} + \dot{Q}_{electricity} = 597296$	$\dot{Q}_{electricity} = 597296$	$\dot{Q}_{electricity} = 99549.33$
Minimising	$Min(CO_2) = \frac{Q_{electricity} * EF}{1000} + \frac{Q_{diesel} * EC * EF_{ijoxec}}{1000}$ or $Min\ (CO_2) = 10^{-3}(69.1 * Q_{diesel} + 0.81 * Q_{electricity})$ where EF = 0.81, EC = 1 and $EF_{ijoxec} = 69.1$ (Australian National Greenhouse Accounts Factors, 2014 to 2016)		

The purpose of Table 4.50 is to find out the points of intersection with the axes by:

(a) Treating each inequality as an equation as shown in 'equation of line' column.

(b) Setting either Q_{diesel} to zero and finding out $Q_{electricity}$ values as shown in 'cut $Q_{electrity}$-axis' column.

(c) Setting either $Q_{electricity}$ to zero and finding out Q_{diesel} values as shown in 'cut Q_{diesel}-axis' column.

Table 4.51 Trial-and-Error Method Seeking Optimal Solution for Scenario 4

Trial	**Corner point**	**Diesel**	**Electricity**	**Total Contribution Margin**
1	(670947, 0)	670,947	0	670947*2+0 = 1,341,894
2	(0, 22364867)	0	22,364,867	0 + 6*22364867 = 134,189,202
3	(597296,0)	597,296	0	6*597296 + 0 = 3,583,776
4	(0, 99549.33)	0	99,549.33	0+ 99549.33 = 3,583,776
5	(0,746716.05)	0	746,716.05	0 + 0.81*746716.05 = 604,840.76
6	(8640582.29,0)	8,640,582	0	0.07 * 8640582 = 604,840.76

The results of the cut-points either on X or Y axis are shown in Tables 4.50 to 4.51, which provide data to Figures 4.28 and 4.29 plotted graphs, seeking the optimal solution for Scenario 4.

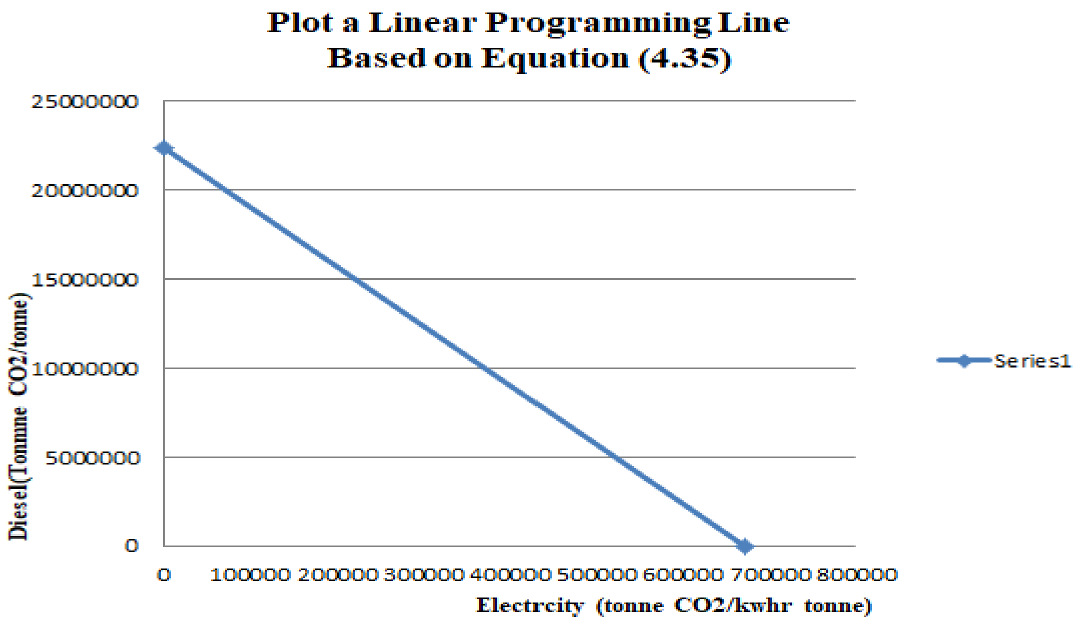


Figure 4.31 Linear Programming Lines Based on Equation (4.35) for Scenario 4

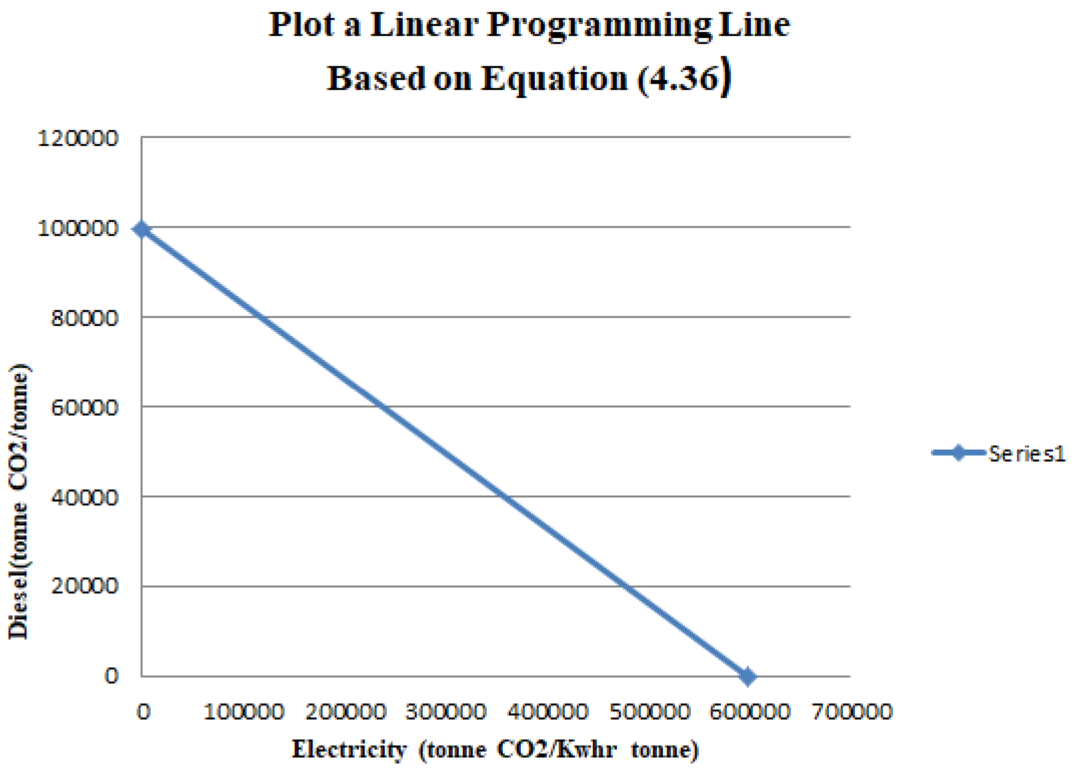


Figure 4.32 Linear Programming Line Based on Equation (4.36) for Scenario 4

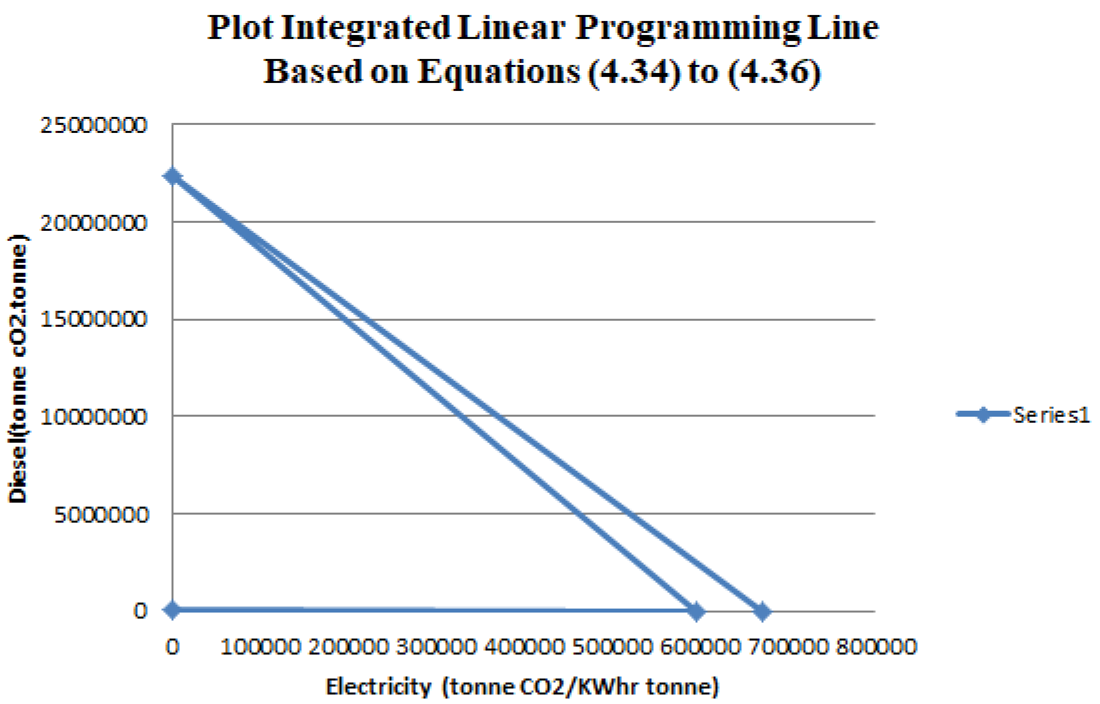


Figure 4.33 Integrated Programming Line Based on Equations (4.34) to (4.36) for Scenario 4

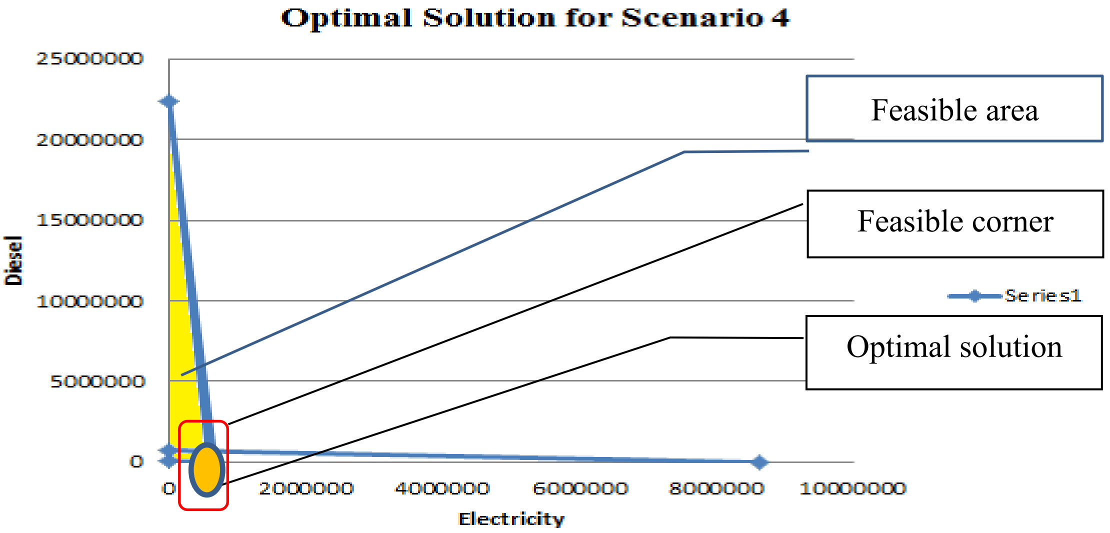


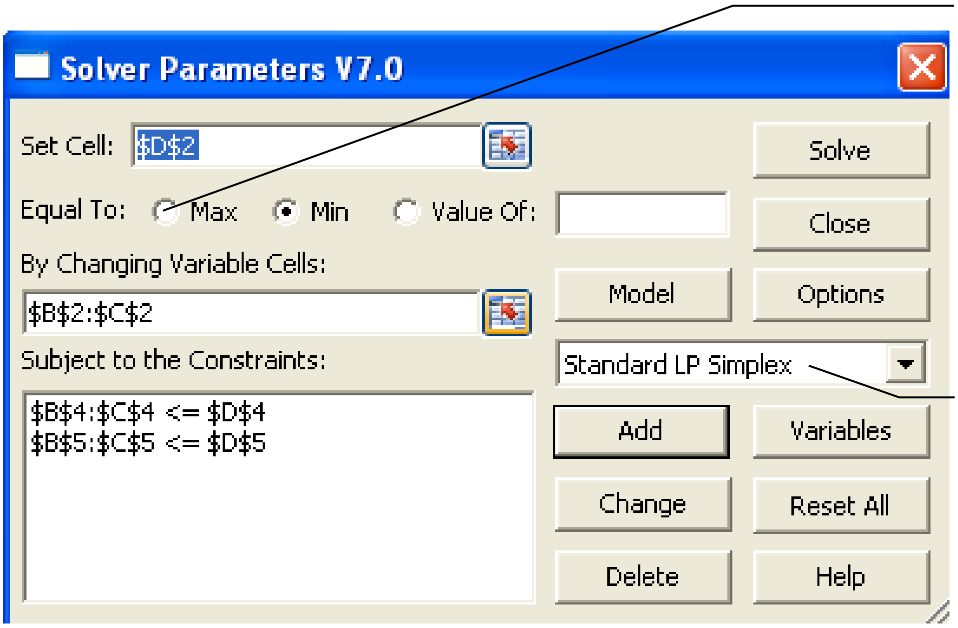
Figure 4.34 Graphical Method Seeking Optimal Solution for Scenario 4

The yellow area, as shown in Figure 4.30, is the feasible area, including the feasible corner. The red sliding line moves upward until it meets the blue line to seek an optimal solution. The optimal solution is shown by the blue circle within the feasible corner. This section was calculated to minimise carbon dioxide emission in transport using Australian National Greenhouse Accounts Factors (2014 to 2016) method. The result was more reasonable than Scenario 4 using Carbon Dioxide Emission Equivalent method.

4.4.4.4 Spreadsheet-Based Method for Scenario 4

The Solver® icon for Scenario 4 as shown in Figure 4.35 includes all ranges of subject to function, subject to constraints and the expected results. Three reports will be included:

(a) The answer report, as shown in Table 4.52.
(b) The sensitivity report, as shown in Table 4.53.
(c) limit report, as shown in Table 4.54.



Solver Parameters V7.0

Set Cell: $D$2

Equal To: ○ Max ● Min ○ Value Of:

By Changing Variable Cells:

$B$2:$C$2

Subject to the Constraints:

$B$4:$C$4 <= $D$4
$B$5:$C$5 <= $D$5

Standard LP Simplex

Seeking minimisation of carbon dioxide emission in delivered raw/semi-materials

Using linear programming equation skills seeking optimisation

Figure 4.35 Spreadsheet-based Model from Solver® for Scenario 4 - Minimising Carbon Dioxide Emission for Transport Using Australian National Greenhouse Accounts Factors (2014 to 2016) Method

4.4.4.4.1 Answer Report for Scenario 4

Table 4.52 Answer Report from Solver® for Scenario 4

Target Cell (Min)					
Cell	**Name**	**Original Value**	**Final Value**		
$D$2	max	0	0		
Adjustable Cells					
Cell	**Name**	**Original Value**	**Final Value**		
$B$2		0	0		
$C$2		0	0		
Constraints					
Cell	**Name**	**Cell Value**	**Formula**	**Status**	**Slack**
$B$4		6	$B$4<=$D$4	Not binding	1,341,886
$C$4		2	$C$4<=$D$4	Not binding	1,341,890
$B$5		6	$B$5<=$D$5	Not binding	597,290
$C$5		1	$C$5<=$D$5	Not binding	597,295

This report was not binding at the ‘subject to constraints’ paragraph and had an opportunity in slack status, although adjustable cells values were in zero values.

4.4.4.4.2 Sensitivity Report for Scenario 4

Table 4.53 Sensitivity Report for Scenario 4

Target Cell (Min)						
Cell	**Name**	**Final Value**				
$D$2	max	0				
Adjustable Cells						
Cell	**Name**	**Final Value**	**Reduced Cost**	**Objective Coefficient**	**Allowable Increase**	**Allowable Decrease**
$B$2		0	0	0	0	1E+30
$C$2		0	0	0	0	1E+30
Constraints						
Cell	**Name**	**Final Value**	**Shadow Price**	**Constraint R.H. Side**	**Allowable Increase**	**Allowable Decrease**
$B$4		6	0	1,341,892	1E+30	1,341,886
$C$4		2	0	1,341,892	1E+30	1,341,890
$B$5		6	0	597,296	1E+30	597,290
$C$5		1	0	597,296	1E+30	597,295

The sensitivity report is shown in Table 5.48. Marked in the red rectangular box is the 'subject to constraints' paragraph; the results were towards 'allowable decrease' values compared with 'constraints right-hand side'. Rather, 'allowable increase' remained '1E+30'. This means carbon dioxide emission can be reduced with respect to transport events based on this calculation. This also shows that if the transport route is reorganised, this could reduce carbon dioxide emission and use less energy, thereby reducing costs.

4.4.4.4.3 Limit Report for Scenario 4

Table 4.54 Limit Report for Scenario 4

Cell	**Target Value**					
$D$2	Max	0				
Cell	**Adjustable Name**	**Value**	**Lower Limit**	**Target Result**	**Upper Limit**	**Target Result**
$B$2		0	0	0	0	0
$C$2		0	0	0	0	0

The 'upper and lower limits' were zero values as marked in Table 5.41 (red rectangular box). The target results were also zero values matching the 'upper and lower limits' values. This means the results are within expectations and working inside the boundary.

4.4.4.4.4 Compendium for Scenario 4

The traditional mathematical and spreadsheet-based modelling methods were discussed in this Scenario. The results of the 'sensitivity report' based on the Solver® calculation are 'allowable decrease' values to seek optimal transport arrangements. In this case, there were only two types of energy under consideration when seeking which type of energy was able to reduce carbon dioxide emission in transport within an Australian cement business environment.

4.4.5 SCENARIO 5

Scenario 5 is an extension of Scenario 4, which used the Carbon Dioxide Emission Equivalent method instead of the Australian National Greenhouse Accounts Factors (2014) as a ‘subject to function’. The rest of the information, such as ‘subject to constraints’ remains the same as for Scenario 4. The reason for this is because this Scenario is designed to use another popular carbon dioxide emission method to evaluate carbon dioxide in transport, seeking the optimal solution. This outcome provides the pre-requisite to compare the two methods’ advantages and disadvantages. The linear programming equations are below:

4.4.5.1 Identified Multiple Drivers and Variables Building Linear Programming Equation

Carbon Dioxide Emission Equivalent method as ‘subject to function’ and as obtained:

Subject to function for Scenario 5

$$Min(CO_{2-e}) = GWP * Q_{diesel} * EC_{diesel} + GWP * Q_{electricity} * EC_{electricity} \qquad (4.40)$$

But in this case, GWP = 1 (Habert et al., 2010) and equation (4.40) became

$$Min(CO_{2-e}) = Q_{diesel} * EC_{diesel} + Q_{electricity} * EC_{electricity} \quad ..………….. \quad (4.41)$$

Subject to Constraints for Scenario 5

Identified six process using diesel power and 2 processes for electric power in Companies A and B (2014), so the linear programming equation as obtained:

$$6Q_{diesel} + 2Q_{electricity} \geq 1341892 \quad ……..…….. \quad (4.42)$$

The power for geopolymer-based production as obtained:

$$6Q_{diesel} + Q_{electricity} \geq 597296 \quad ………… \quad (4.43)$$

Non-negativity constraints:

$$Q_{diesel} \geq 0, Q_{electricity} \geq 0, EC \geq 0, EF \geq 0, EF_{ijoexc} \geq 0, GWP \geq 0$$

4.4.5.2 Traditional Mathematical Method for Scenario 5

Based on equations (4.42) to (4.43), the matrix as obtained:

$$\left(\begin{array}{cc|c} 6 & 2 & 1341892 \\ 6 & 1 & 597296 \end{array}\right)$$

Use Gaussian-Jordan Elimination method (Grcar, 2011 and 2012) and make the pivot in the first column by dividing the first row by 6

$$\begin{bmatrix} 1 & 1/3 & 670946/3 \\ 6 & 1 & 597296 \end{bmatrix}$$

Eliminate the first column

$$\begin{bmatrix} 1 & 1/3 & 670946/3 \\ 0 & -1 & -744596 \end{bmatrix}$$

Find the pivot in the second column in the second row (inversing the sign in the whole row)

$$\begin{bmatrix} 1 & 1/3 & 670946/3 \\ 0 & 1 & 744596 \end{bmatrix}$$

Eliminate the second column

$$\begin{bmatrix} 1 & 0 & -24550 \\ 0 & 1 & 744596 \end{bmatrix}$$

$Q_{diesel} = -24550$ and $Q_{electricity} = 744596$ …………… (4.44)

This result provides evidence of using more electricity and emitting less carbon dioxide. But electricity prices rose 5% in the past year (Australian Bureau of Statistics, 2016; Parliament of Australia, 2017) by using LPG fuel instead of coal.

To seek the minimisation of carbon dioxide emission using the Carbon Dioxide Emission Equivalent method, the values of $Q_{diesel} = -24550$ and $Q_{electricity} = 744596$ from equation (4.44) into equations (3.1) to (3.3) and EC from Table 3.1, whose diesel = 2.68 and $EC_{electricity} = 1.35$ and as obtained:

$$Min(CO_2) = Q_{electriciy} * EC_{electriciy} + Q_{diesel} * EC_{diesel} \quad \ldots\ldots\ldots\ldots\ldots \quad (4.45)$$

$$\Rightarrow \quad Min(CO_2) = 744596 * 1.35 + (-24550 * 2.68)$$

$$\Rightarrow \quad Min(CO_2) = 1005204 - 65794 = 939410 \quad \ldots\ldots\ldots\ldots\ldots \quad (4.46)$$

4.4.5.3 Graphical Method for Scenario 5

Based on the previous outcome, the graphical equation as obtained:

Table 4.55 Cut-Points at X and Y Axis, Seeking Optimal Solution Using Graphical Method for Scenario 5

	Equation of Line	**Cut $Q_{electricity}$-axis when $Q_{diesel} = 0$**	**Cut Q_{diesel}-axis when $Q_{electricity} = 0$**
Fossil based on Equation (4.42)	$6\dot{Q}_{diesel} + 2\dot{Q}_{electrcity} = 1341892$	$\dot{Q}_{electricty} = 670947$	$\dot{Q}_{diesel} = 223648.67$
Electricity based on Equation (4.43)	$6\dot{Q}_{diesel} + \dot{Q}_{electriciy} = 597296$	$\dot{Q}_{electriciy} = 597296$	$\dot{Q}_{electriciy} = 99549.33$
Minimising	$Min(CO_2) = Q_{electriciy} * EC_{electriciy} + Q_{diesel} * EC_{diesel}$		

The trial-and-error method is one of the best methods to seek the optimal solution by substituting back all outcomes into equations (4.41). The outcomes are listed in Table 4.56, which using cut-points skills by setting X (diesel) = 0 or Y (electricity) = 0 at axis to calculate the corresponding values. It provides the pre-requisite to plot the graph and is discussed in coming section.

Table 4.56 Trail-and-Error Method Seeking Optimal Solution for Scenario 5

Trial	**Corner point**	**Diesel**	**Electricity**	**Total Contribution Margin**
1	(670947, 0)	670,947	0	670947*2+0 = 1,341,894
2	(0, 223648.67)	0	223648.67	0 + 6*223648.67 = 1,341,892
3	(597296,0)	597,296	0	6*597296 + 0 = 3,583,776
4	(0, 99549.33)	0	99,549.33	0+ 99549.33 = 99,549.33
5	(-793331.85,0)	-793,331.85	0	0 -1.35 * 793331.85 = -1,070,998
6	(0, 399626.12)	0	399,626.12	2.68 * 399626.12 + 0 = 1,070,998

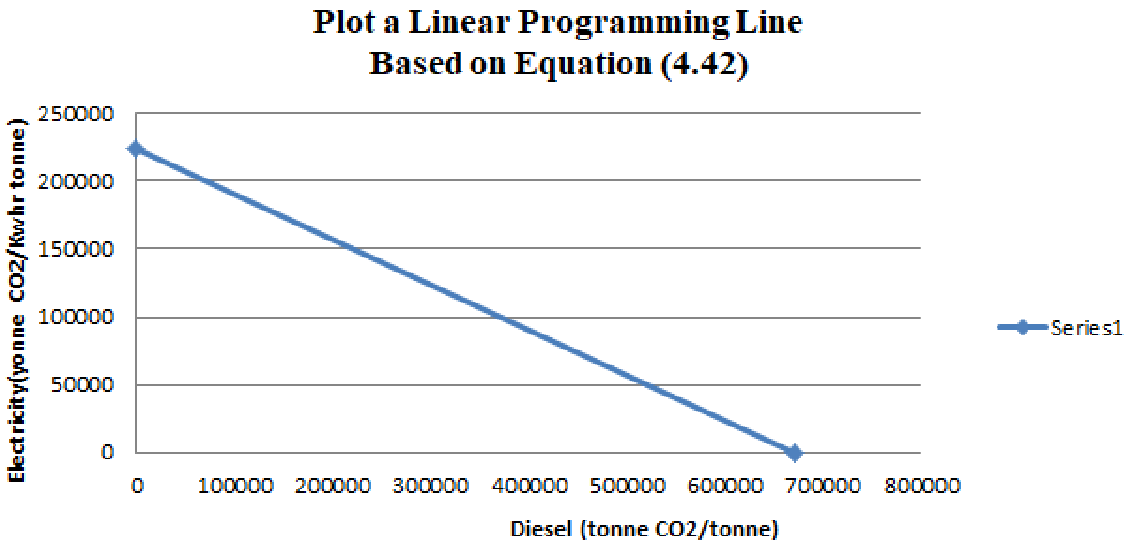


Figure 4.36 Linear Programming Lines Based on Equation (4.42) for Scenario 5

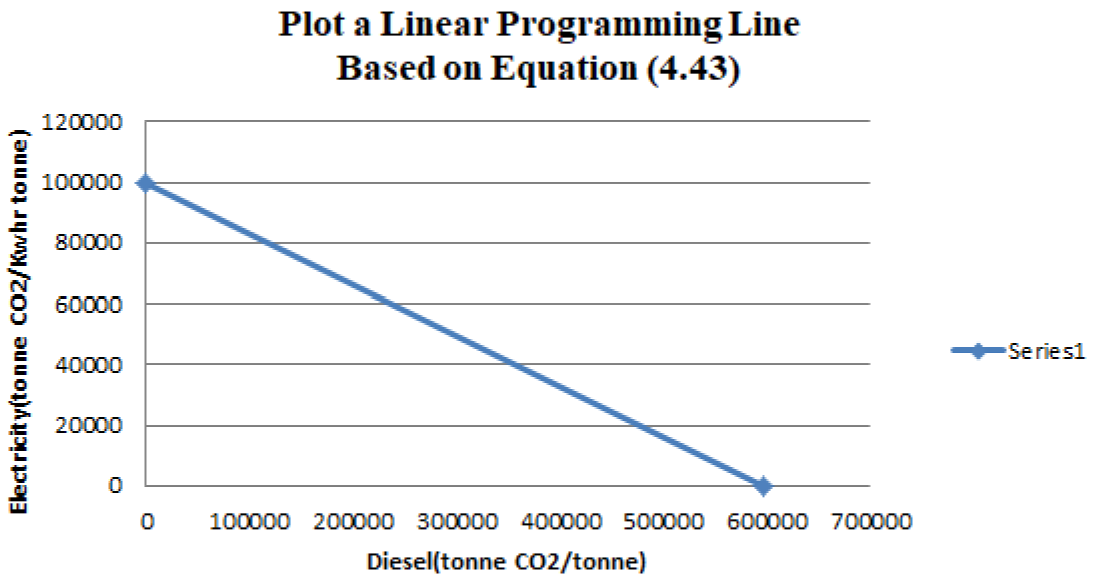


Figure 4.37 Linear Programming Lines Based on Equation (4.43) for Scenario 5

Figures 4.36 to 4.37 plot two separate lines based on the outcomes of Table 4.55 and equations 4.42 and 4.43. This is the first step of constructing a graphical method, seeking the optimal solution.

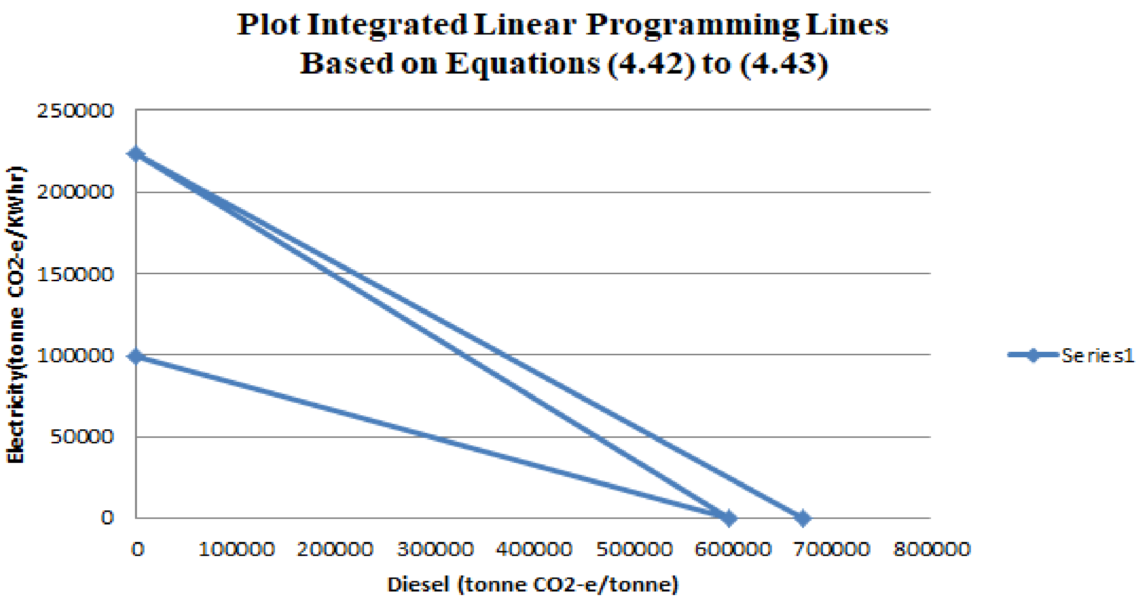


Figure 4.38 Integrated Linear Programming Lines Based on Equations (4.42) and (4.43) for Scenario 5

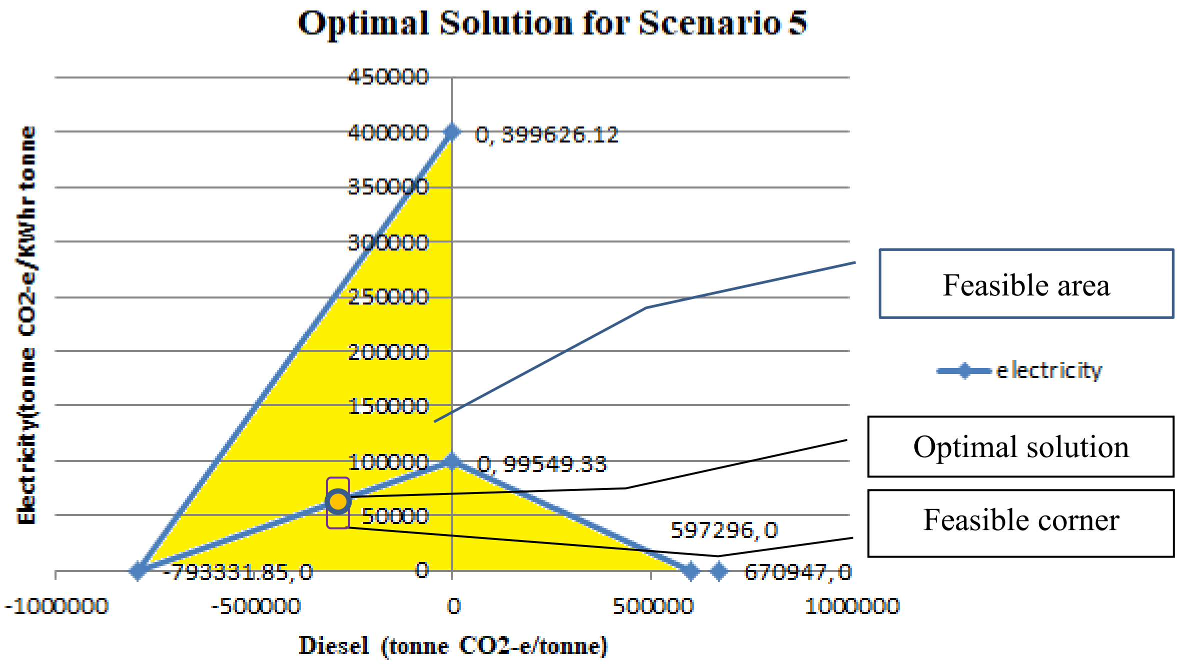
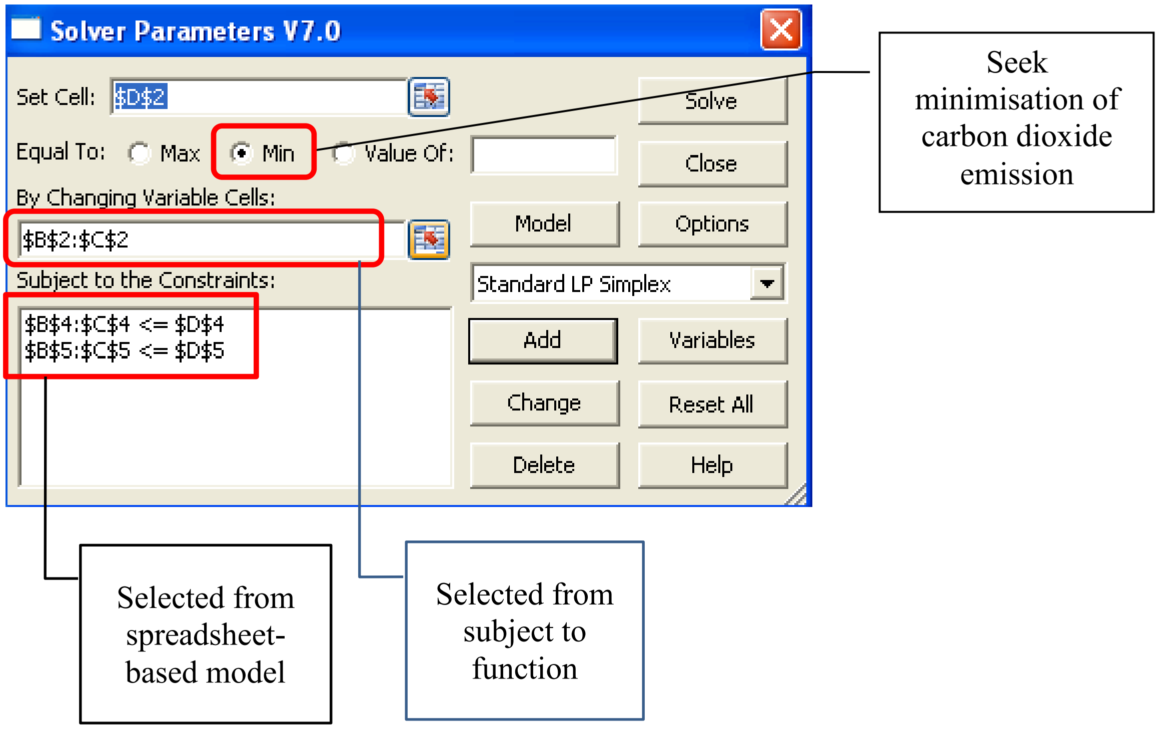


Figure 4.39 Using Carbon Dioxide Emission Equivalent Method as Subject to Function Equation Seeking Optimal Solution for Scenario 5

Figures 4.35 based on Tables 4.55 and 4.56 were plotted within the feasible area. By sliding parallel to the ‘subject to function’ equation downward or upwards and meeting the other two intersecting lines, the optimal solution was found (shown in the orange box of Figure 4.39. The solution recommended does not use diesel oil and as a result there is no carbon dioxide emission in production.

4.4.5.4 Spreadsheet-Based Method for Scenario 5

To seek the answer, sensitivity and limit results, this study used Solver® to assist these events as obtained:


Solver Parameters V7.0

Set Cell: $D$2

Equal To: ○ Max ● Min ○ Value Of:

By Changing Variable Cells:

$B$2:$C$2

Subject to the Constraints:

$B$4:$C$4 <= $D$4
$B$5:$C$5 <= $D$5

Standard LP Simplex

Seek minimisation of carbon dioxide emission

Selected from spreadsheet-based model

Selected from subject to function

Figure 4.40 Spreadsheet-Based Model Using Solver® to Solve Linear Programming Problems and Optimal Solution for Scenario 5

Solver® captured all parameter ranges from the spreadsheet-based model, as shown in Figure 4.40. Three reports were generated, as shown in Tables 4.57 to 4.59.

4.4.5.4.1 Answer Report for Scenario 5

Table 4.57 Answer Report from Solver® for Scenario 5

Target Cell (Min)					
Cell	**Name**	**Original Value**	**Final Value**		
$D$2	Max	0	0		
Adjustable Cells					
Cell	**Name**	**Original Value**	**Final Value**		
$B$2	Electricity	2.68	0		
$C$2	Diesel	1.35	0		
Constraints					
Cell	**Name**	**Cell Value**	**Formula**	**Status**	**Slack**
$B$4	Electricity	6	$B$4<=$D$4	Not binding	1,341,886
$C$4	Diesel	2	$C$4<=$D$4	Not binding	1,341,890
$B$5	Electricity	6	$B$5<=$D$5	Not binding	597,290
$C$5	Diesel	1	$C$5<=$D$5	Not binding	597,295

The ‘not binding’ results were shown in Table 4.57 (red rectangular box). This is because of the slack status. To improve this status, one of the most efficient solutions was to adjust cell parameters such as $B$4, $C$4, $B$5, $C$5, $B$2, $C$2, $D$2 and so on, until the result was in ‘binding’ status.

4.4.5.4.2 Sensitivity Report for Scenario 5

Table 4.58 Sensitivity Report from Solver® for Scenario 5

Target Cell (Min)						
Cell	**Name**	**Final Value**				
$D$2	max	0				
Adjustable Cells						
Cell	**Name**	**Final Value**	**Reduced Cost**	**Objective Coefficient**	**Allowable Increase**	**Allowable Decrease**
$B$2	electricity	0	0	0	0	1E+30
$C$2	diesel	0	0	0	0	1E+30
Constraints						
Cell	**Name**	**Final Value**	**Shadow Price**	**Constraint R.H. Side**	**Allowable Increase**	**Allowable Decrease**
$B$4	electricity	6	0	1,341,892	1E+30	1,341,886
$C$4	diesel	2	0	1,341,892	1E+30	1,341,890
$B$5	electricity	6	0	597,296	1E+30	597,290
$C$5	diesel	1	0	597,296	1E+30	597,295

The sensitivity report results are shown in Table 4.58, as marked in the red rectangular box. The 'subject to constraints' provided the opportunity to 'allowable decrease' data compared with 'subject to constraints' on the right-hand side values. This means this could reduce carbon dioxide emission in transport events. Additionally, the values in Table 4.58, in 'subject to constraints' was different from Table 4.56, because of two different calculation methods. But the 'allowable increase' remained at the same values.

4.4.5.4.3 Limit Report for Scenario 5

Table 4.59 Limit Report from Solver® for Scenario 5

Cell	**Target Value**					
$D$2	Max	0				
Cell	**Adjustable Name**	**Value**	**Lower Limit**	**Target Result**	**Upper Limit**	**Target Result**
$B$2	Electricity	0	0	0	0	0
$C$2	Diesel	0	0	0	0	0

All zero values, as shown Table 4.58, are shown in the red rectangular box. This means all operations were within limits and boundaries. This showed that the two energies' calculations were within target results (e.g. zero values).

4.4.5.4.4 Compendium for Scenario 5

The traditional mathematical and spreadsheet-based model was discussed in Scenario 5. This method had somewhat different results compared with Scenario 4, in the 'sensitivity report'. This means that the Carbon Dioxide Emission Equivalent and Australian National Greenhouse Accounts Factors (2014 to 2016) have their own advantages and disadvantages. Because they collected the data from different sources and submitted these back into assigned equations, the results were quite different from each production method. This is further discussed in Chapter 5 - Results. Additionally, the main advantage of the Carbon Dioxide Emission Equivalent method is that it only uses one equation for every production event, including limestone production and transport events. The Australian National Greenhouse Accounts Factors (2014 to 2016) method involves several equations and needs more data to conduct calculations, as discussed in Chapter 3. The objective of each equation was considered for different cement production methods as the result of the previous outcome. The Australian National Greenhouse Accounts Factors (2014 to 2016) is more accurately to measure carbon footprint than the Carbon Dioxide Emission Equivalent method.

4.4.6 SCENARIO 6

The objective of Scenario 6 is to calculate the minimisation of use of natural resources to produce ordinary Portland cement. It also provides information to the cement and mining industries about their safety stock level using equations (3.13) to (3.14) to maintain sustainable cement production with affordable operating and material costs.

Manufacturing ordinary Portland cement uses a lot of natural raw materials, which are quarried from elsewhere in Australia. These are different material resources from those used to produce fly ash based geopolymer cement and metakaolin-based geopolymer cement. These materials are the by-products from a different industry, and classified as solid waste, such as fly ash from coal-fired power stations, iron slag from refined iron ore being made into steel, metakaolin from calcinations, and so on.

In 2014, Australia produced 9.1 million tonnes, including ordinary Portland cement and fly ash based cement and other types of cement (Australia Bureau of Statistics, 2014; Cement Industry Federation, 2014 to 2016). To construct a linear programming equation to seek the optimal use of abiotic natural resources in Australia, the ‘subject to function’ of the scenario is obtained based on equation (3.8) and ‘subject to constraints’ based on the assigned quarry sites and known reserve stock in Australia.

This scenario was probed further based on equation (3.8) and examined abiotic depletion in the Australian business environment, in contrast to Habert et al., (2010) who only focused on the French business environment.

4.4.6.1 Identified Multiple Drivers & Variable Building Linear Programming Equation

There are several assumptions in Scenario 6 as listed:

(a) The subject to constraints linear equations and subject to function equation was developed seeking optimisation based on equation (4.12) and Operating Mines and Quarries of South Australia (2015).

(b) The raw material consumption for cement production is supplied from known quarry sites within the defined boundaries for Companies A to C.

(c) Fly ash based geopolymer cement ratio and ordinary Portland cement proportion ratio were used based on Habert et al., (2010) and Yang et al., (2014), to evaluate cement consumption in Australian business environment.

Subject to function based on equation (3.8) and the minimisation of abiotic depletion in cement production as obtained:

$$Min(z) = (CF_{CaCO_3} * m_{CaCO_3}) + (CF_{clay} * m_{clay}) + (CF_{sand} * m_{sand}) + (CF_{gypsum} * m_{gypsum}) \quad \ldots\ldots \quad (4.47)$$

where

CF_{CaCO3} = characteristic factor for limestone abiotic depletion of resources
CF_{clay} = characteristic factor for clay abiotic depletion of resources
CF_{sand} = characteristic factor for sand abiotic depletion of resources
CF_{gypsum} = characteristic factor for gypsum abiotic depletion of resources
m_{CaCO3} = mass of limestone ($CaCO_3$) consumed in the process
m_{clay} = mass of clay consumed in the process
m_{sand} = mass of sand consumed in the process
m_{gypsum} = mass of gypsum consumed in the process

Subject to Constraints:

$$89200CF_{CaCO_3} + 120200CF_{clay} + 144000CF_{sand} + 16920CF_{gypsum} \geq 9100000 \quad .. \quad (4.48)$$

$$71200CF_{CaCO_3} + 97600CF_{clay} + 11900CF_{sand} + 137200CF_{gypsum} \geq 9000000 \quad .. \quad (4.49)$$

$$53200CF_{CaCO_3} + 72100CF_{clay} + 37000CF_{sand} + 71000CF_{gypsum} \geq 8800000 \quad .. \quad (4.50)$$

$$35200CF_{CaCO_3} + 48600CF_{clay} + 71000CF_{sand} + 7170CF_{gypsum} \geq 8000000 \quad .. \quad (4.51)$$

$$CF_{CaCO_3}, CF_{clay}, CF_{sand}, CF_{gypsum} \geq 0$$

4.4.6.2 Traditional Mathematical Method for Scenario 6

Based on equation (4.48) to (4.51), the matrix as obtained:

$$\left(\begin{array}{cccc|c} 89200 & 120200 & 144000 & 16920 & 9100000 \\ 71200 & 97600 & 11900 & 137200 & 9000000 \\ 53200 & 72100 & 37000 & 71000 & 8800000 \\ 35200 & 48600 & 71000 & 7170 & 8000000 \end{array}\right)$$

Use Gaussian-Jordan Elimination method (Grcar, 2011 and 2012). Make the pivot in the first column by dividing the first row by 89200:

$$\left(\begin{array}{cccc|c} 1 & 601/446 & 360/223 & 423/2230 & 22750/223 \\ 71200 & 97600 & 11900 & 137200 & 9000000 \\ 53200 & 72100 & 37000 & 71000 & 8800000 \\ 35200 & 48600 & 71000 & 7170 & 8000000 \end{array}\right)$$

Eliminate the first column:

$$\left(\begin{array}{cccc|c} 1 & 1.35 & 1.61 & 1.9 & 102.02 \\ 0 & -91976.39 & -103041.7 & 123694.35 & 1736322.87 \\ 0 & 411.21 & -48883.41 & -2991.3 & 3372645.74 \\ 0 & 1166.82 & -49725.11 & 493.05 & 4408968.61 \end{array}\right)$$

Make the pivot in the second column by dividing the second row by - 20510736/223:

$$\left(\begin{array}{cccc|c} 1 & 1.35 & 1.61 & 1.9 & 102.02 \\ 0 & 1 & 0.01 & -1.34 & -18.88 \\ 0 & 411.21 & -48883.41 & -2991.3 & 3372645.74 \\ 0 & 1166.82 & -49725.11 & 493.05 & 4408968.61 \end{array}\right)$$

Make the pivot in the third column by dividing the third row by - 49.34:

$$\left(\begin{array}{cccc|c} 1 & 0 & 0.1 & 2 & 127.46 \\ 0 & 1 & 1.12 & -1.4 & -18.88 \\ 0 & 0 & 1 & 0.05 & -68.51 \\ 0 & 0 & -51032.3 & 2062.24 & 4430995.67 \end{array}\right)$$

Eliminate the third column:

$$\left(\begin{array}{cccc|c} 1 & 0 & 0 & 2 & 134.63 \\ 0 & 1 & 0 & -1.4 & 57.87 \\ 0 & 0 & 1 & 0.05 & -68.51 \\ 0 & 0 & 0 & 4583.95 & 934932.94 \end{array}\right)$$

Make the pivot in the fourth column by dividing the fourth row by - 4583.95:

$$\left(\begin{array}{cccc|c} 1 & 0 & 0 & 2 & 134.63 \\ 0 & 1 & 0 & -1.4 & 57.87 \\ 0 & 0 & 1 & 0.05 & -68.52 \\ 0 & 0 & 0 & 1 & 203.96 \end{array}\right)$$

Eliminate the second column:

$$\left(\begin{array}{cccc|c} 1 & 0 & 0.1 & 2 & 127.46 \\ 0 & 1 & 1.12 & -1.34 & -18.88 \\ 0 & 0 & -49344.09 & -2438.28 & 3380408.54 \\ 0 & 0 & -51032.3 & 2062.24 & 4430995.67 \end{array}\right)$$

Eliminate the fourth column:

$$\left(\begin{array}{cccc|c} 1 & 0 & 0 & 0 & -272.622 \\ 0 & 1 & 0 & 0 & 343.45 \\ 0 & 0 & 1 & 0 & -0.08 \\ 0 & 0 & 0 & 1 & 203.96 \end{array}\right)$$

The solution was that:

CF_{CaCO3} = -272.622
CF_{clay} = 343.45
CF_{sand} = -0.08
CF_{gypsum} = 203.96

Based on this solution, the variety characteristic factor (CF) values were found. However, these solutions, in particular $CF_{CaCO_3} = -272.622$ and $CF_{sand} = -0.08$ were only worked under the assumption of an ideal case. In reality, the current limestone and sand sites would be soon exhausted. New sites within Australia would be explored by the mining companies based on the current ordinary Portland cement formulation and outcomes because limestone and sand are major elements of making cement, and their availability consequently affects current cement production events. Imported limestone and calcium oxide from overseas are an alternative method of avoiding this potential crisis.

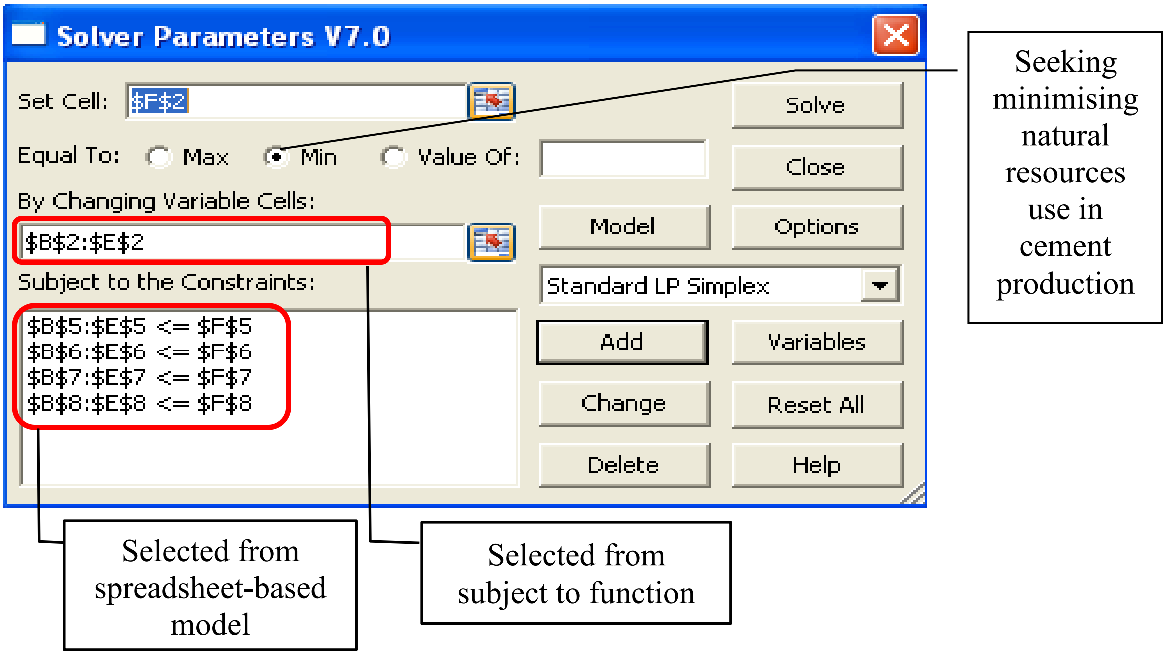
Additionally, this outcome result provides some clues that using less calcium carbonate ($CaCO_3$) would reduce carbon dioxide emission. However, if calcium oxide (CaO) is used instead of $CaCO_3$, the outcome would be different because CaO contains no carbon dioxide. Based on this solution, CaO is one of the best ways to solve the problem. However, the cement industry has been using limestone for a long time because it is cheaper than CaO, and as it requires no extra processing from $CaCO_3$ to CaO (by elevating temperature to 1500°C) it saves energy consumption. Then the equation (4.47) becomes:

$$Min(z) = (CF_{CaO} * m_{CaO}) + (CF_{clay} * m_{clay}) + (CF_{sand} * m_{sand}) + (CF_{gypsum} * m_{gypsum}) \quad \ldots\ldots (4.52)$$

Equation (4.47) is reorganised as function and retains the subject to constraints to re-assess this scenario again in the Results Chapter.

4.4.6.3 Spreadsheet-Based Method for Scenario 6

The spreadsheet-based method was further used to examine the linear programming problems. The Solver icon for Scenario 6 is shown in Figure 4.34.



Solver Parameters V7.0

Set Cell: $F$2

Equal To: ○ Max ● Min ○ Value Of:

By Changing Variable Cells:

$B$2:$E$2

Subject to the Constraints:

$B$5:$E$5 <= $F$5
$B$6:$E$6 <= $F$6
$B$7:$E$7 <= $F$7
$B$8:$E$8 <= $F$8

Standard LP Simplex

Seeking minimising natural resources use in cement production

Selected from spreadsheet-based model

Selected from subject to function

Figure 4.41 Using Solver® to Seek Optimal Solution for Scenario 6-Minimising Abiotic Depletion for Cement Production

4.4.6.3.1 Answer Report for Scenario 6

Table 4.60 Answer Report from Solver® for Scenario 6

Target Cell (Min)					
Cell	**Name**	**Original Value**	**Final Value**		
$F$2		0	0		
Adjustable Cells					
Cell	**Name**	**Original Value**	**Final Value**		
$B$2		18,100	0		
$C$2		27,000	0		
$D$2		25,000	0		
$E$2		30,000	0		
Constraints					
Cell	**Name**	**Cell Value**	**Formula**	**Status**	**Slack**
$B$5	$CaCO_3$	89,200	$B$5<=$F$5	Not binding	9,010,800
$C$5	Clay	120,200	$C$5<=$F$5	Not binding	8,979,800
$D$5	Sand	144,000	$D$5<=$F$5	Not binding	8,956,000
$E$5	Gypsum	16,920	$E$5<=$F$5	Not binding	9,083,080
$B$6	$CaCO_3$	71,200	$B$6<=$F$6	Not binding	8,928,800
$C$6	Clay	97,600	$C$6<=$F$6	Not binding	8,902,400
$D$6	Sand	11,900	$D$6<=$F$6	Not binding	8,988,100
$E$6	Gypsum	137,200	$E$6<=$F$6	Not binding	8862,800
$B$7	$CaCO_3$	53,200	$B$7<=$F$7	Not binding	8,746,800
$C$7	Clay	72,100	$C$7<=$F$7	Not binding	8,727,900
$D$7	Sand	37,000	$D$7<=$F$7	Not binding	8,763,000
$E$7	Gypsum	71,000	$E$7<=$F$7	Not binding	8,729,000
$B$8	$CaCO_3$	15,200	$B$8<=$F$8	Not binding	7,984,800
$C$8	Clay	48,600	$C$8<=$F$8	Not binding	7,951,400
$D$8	Sand	71,000	$D$8<=$F$8	Not binding	7,929,000
$E$8	Gypsum	7,170	$E$8<=$F$8	Not binding	7,992,830

The 'answer report' for Scenario 6 is shown in Table 4.60, which informs us that the system is not binding and in slack status. This provides favourable conditions to justify the data in the adjustable cell with respect to 'subject to constraints' until it reaches optimal heights, driving down the natural resources depletion rate. This report is not an overall assessment of raw materials status, only including calcium carbonate, clay, sand and by-product like fly ash for cement production.

This gives a clear message to mining and construction industries that the natural resources market will be in turbulence in the foreseeable future if production and mining circumstances remain the same. To avoid this potential crisis, new sources such as new overseas natural resources suppliers, new quarrying sites and others, will be assumed in next operation, in limestone sites. This is because the majority of cement factories are built close to major raw material suppliers (Cement Industry Federation, 2013).

4.4.6.3.2 Sensitivity Report for Scenario 6

Table 4.61 Sensitivity Report from Solver® for Scenario 6

Target Cell (Min)						
Cell	**Name**	**Final Value**				
$F$2		0				
Adjustable Cells						
Cell	**Name**	**Final Value**	**Reduced Cost**	**Objective coefficient**	**Allowable Increase**	**Allowable Decrease**
$B$2		0	0	0	0	1E+30
$C$2		0	0	0	0	1E+30
$D$2		0	0	0	0	1E+30
$E$2		0	0	0	0	1E+30
Constraints						
Cell	**Name**	**Final Value**	**Shadow Price**	**Constraint R.H. Side**	**Allowable Increase**	**Allowable Decrease**
$B$5	CacO3	89,200	0	9,100,000	1E+30	9,010,800
$C$5	Clay	120,200	0	9,100,000	1E+30	8,979,800
$D$5	Slag	144,000	0	9,100,000	1E+30	8,956,000
$E$5	Gypsum	16,920	0	9,100,000	1E+30	9,083,080
$B$6	CacO3	71,200	0	9,000,000	1E+30	8,928,800
$C$6	Clay	97,600	0	9,000,000	1E+30	8,902,400
$D$6	Slag	11,900	0	9,000,000	1E+30	8,988,100
$E$6	Gypsum	137,200	0	9,000,000	1E+30	8,862,800
$B$7	CacO3	53,200	0	8,800,000	1E+30	8,746,800
$C$7	Clay	72,100	0	8,800,000	1E+30	8,727,900
$D$7	Slag	37,000	0	8,800,000	1E+30	8,763,000
$E$7	Gypsum	71,000	0	8,800,000	1E+30	8,729,000
$B$8	CacO3	15,200	0	8,000,000	1E+30	7,984,800
$C$8	Clay	48,600	0	8,000,000	1E+30	7,951,400
$D$8	Slag	71,000	0	8,000,000	1E+30	7,929,000
$E$8	Gypsum	7,170	0	8,000,000	1E+30	7,992,830

The ‘sensitivity report’ for Scenario 6 is shown in Table 4.61, which informs us that the values of ‘subject of constraint’ are towards ‘allowable decrease’ but the ‘allowable increase’ remains as ‘1E+30’. The means the system could optimise the minimisation of natural resources (abiotic) depletion using adjustable values through ‘adjustable cells’ on the spreadsheet. Additionally, it also quantitatively measures the fact that the natural resources depletion rate could be slowed under these operational conditions. However, Scenario 6 only considers abiotic materials for manufacturing ordinary Portland cement, and does not directly consider by-products such as fly ash, slag and so on. This was one of the in perfections to evaluate the natural resources’ exhaustible status for fly ash based geopolymer cement production. However, fly ash is a by-product of coal, and slag is a by-product of iron ore processing. To better assess this situation, the consumption of coal or iron ore, based on the portion method (e.g., 10 to 13% of total consumption), is used to calculate how many tonnes of fly ash and slag would be produced by upfront processes. However, the proportion method also refers to the characteristics of coal. One example is that brown coal-fired power station provides 10 to 13% of fly ash per each tonne and 6 to 7% of each tonne of charcoal (Cement Industry Federation, 2014). This provides data to extend and formulate domestic material consumption (Habert et al., 2010) equation to solve natural resources depletion. Further discussion is in Chapter 5.

4.4.6.3.3 Limit Report for Scenario 6

Table 4.62 Limit Report for Scenario 6

Cell	**Target Value**					
$F$2		0				
Cell	**Adjustable Name**	**Value**	**Lower Limit**	**Target Result**	**Upper Limit**	**Target Result**
$B$2		0	0	0	0	0
$C$2		0	0	0	0	0
$D$2		0	0	0	0	0
$E$2		0	0	0	0	0

This report shown in Table 4.62 has zero values, the final value minus target values. Therefore, this was within the ‘upper and lower limits’ and boundary. The means the optimal solution approaches inferior values compared with the original setting values, and provides evidence that natural resources depletion could be reduced gradually under this type of operation for cement production.

4.4.6.3.4 Compendium for Scenario 6

This scenario discussed a traditional mathematical and spreadsheet-based model to solve the linear programming equations problems. The overall result was ‘allowable decrease’ for the values within the adjustable cells or ‘subject to constraints’ for optimisation in Scenario 6. Sand and calcium carbonate values were in negative values in the traditional mathematical method calculation and in slack status including not binding in the spreadsheet-based model outcome under current feedstock in an Australian business environment. This means a single natural resources supplier would be facing a potential crisis under this production status, although it is stable and has price advantages for obtaining the necessary raw materials for ordinary Portland cement and geopolymer-based cement production. Using multiple sources including from overseas would be an alternative to solve this issue. This strategy also avoids further unnecessary abiotic depletion. However, the logistics and supply chains would have to be reorganised to meet the strategy and maintain growth.

4.5 SUMMARY

This chapter was divided into two parts. The first part discussed data collection and analysis methods of the primary and secondary data. The sources of those data are the literature review, the Australian Bureau of Statistics (2013 to 2016), Cement Industry Federation (2013), Australian Quarry Institution (2013), Institute of Engineers (2014), Australian Fly Ash Association (2014), Australian Government - Department of Foreign Affairs and Trade, (2013), Companies A to C (2014), etc. This data includes carbon dioxide emission of the manufacturing processes, abiotic depletion, resources within Australia, quarry production rates, production operational costs, raw materials costs, method of cement production, specification of the production facilities, energy and fuels used and miles being taken by transport to deliver raw materials from quarry to cement factories. These provide an opportunity for data analysis regarding the trend of abiotic depletion potential for ordinary Portland cement production, and also related issues around by-products of refined iron ore and coal-fired power station, the status of natural resources depletion, carbon dioxide emission produced by the three areas, and a financial effect costs measure of the three areas using a linear programming study. The second part discussed six scenarios based on primary and secondary data for probing further to evaluate manufacturing options for cement production with respect to maximising profits and mininising carbon dioxide emission and natural resources depletion, both in the short term and the lifetime of ordinary Portland cement, ordinary Portland cement with supplementary cementitious materials and fly ash based including metakaolin geopolymer cement. This was based on Chapter 3 (Methodology) as a result of validating the proposed framework under a wide range of parameters and scientific measures of their performance. This chapter is also introduced a spreadsheet-based model that effectively studies the linear equations providing the optimal solution of each scenario. The outcomes from scenarios 1 to 6 are based on one-pierce-flow manufacturing production (Chan and Yung, 2008) method instead of built-by-order because of setting the hours of operation at 5 days a week, 8 hours a day and 300 working days per year.

In the data analysis section, the equations from Chapter 3 were fully applied to perform the calculations, such as abiotic depletion potential from Habert et al., (2013) and Yellishetty (2012) and Grcar (2011 and 2012) and others, by using linear programming equations seeking optimisation. However, equations alone did not do enough to examine the evaluation of the three areas, in domestic material consumption calculation. Therefore the data collection process played a vital role in making the equations to provide quantitative measures of the three areas. To make this happen, this study needed to collect domestic material consumption data including fuel and energy used, and export of raw materials in Australia and the Asia-Pacific region. This is because the original data were only suitable for France and America and its domestic material consumption equation is an exponential equation, e^x. In the previous section, the discussion identified the domestic material consumption curve as a polynomial equation, so this was one of the major differences between France and Australia’s domestic material consumption statuses. In developing the scenarios, some data were obtained from Companies A to C (2014) and treated as secondary data. Therefore, each scenario uses data that is a combination of primary and secondary data.

The preliminary results of the scenarios are less efficiency and higher operational costs than faced by competitors from overseas cement producers. Further, some of them only grind cement. The semi-product of cement is imported from overseas and the final stages of production such as mixing gypsum, fine-grinding and packing, are carried out in Australia reducing operational costs and raw materials costs and lowering environmental effects. because of raw materials and semi-products coming from overseas, the carbon dioxide emission of transportation must be considered, as well as less efficient kilns, because 90% of cement factories use pre-calciner kilns instead of long wet kilns (Cement Industry Federation, 2012), using less energy and providing an alternative method to reduce carbon dioxide emission in the production process.

CHAPTER 5

RESULTS

CHAPTER 5 RESULTS

This chapter examines the outcomes from Chapter 4 including scenario-based studies results using a scoreboard method. It also investigates carbon dioxide emission variation in whole-life-cycle costs in cement production by using Australian National Greenhouse Accounts Factors (2014 to 2016) and Carbon Dioxide Emission Equivalent methods, determining which is superior. Abiotic depletion and domestic material depletion of each raw material for cement production were also studied, ensuring their reserves in normal conditions. The data were based on curve identification outcomes in Chapter 4 as the result of the linear line equation solution. This was applied into a reserve equation to conduct the calculation, as discussed in Chapter 3.

5.1 INTRODUCTION

Numerous results were found in Chapter 4, based on statistical, traditional mathematics and spreadsheet-based calculation methods. The roles of each method are explained further below:

(a) Statistical Method. This was used to examine the trends of raw materials consumption and distribution. It provided mean, average, medium and standard deviation values of those raw materials' status. The prediction trend was developed based on the outcomes.

(b) Traditional mathematics method. This was one of the calculation methods solving linear programming problems. It was used to solve multiple unknown problems in linear equations by using the Gaussian-Jordan Elimination method (Grcar, 2011 and 2012). A graphical method was also part of the calculation in solving the linear equation problems with respect to maximising three unknowns with three to four equations. Its advantage was that it can easily test a wide range of parameters and present them in graphical format. In Scenario 6, there were four more unknowns in one single equation, so Gaussian-Jordan Elimination (Grcar, 2011 and 2012) method was one solution.

(c) Spreadsheet-based method using Solver®. This was an overall evaluation of each linear programming equation and provided three reports, namely answer, sensitivity and limit reports. It also measured each single scenario performance within the Australian cement manufacturing environment, and provided the range of values to which 'subject to constraints' values should be justified until optimal.

(d) This spreadsheet-based model method has also a disadvantage in the case of wrongly defined cell locations, as the result would be a series of mistakes in all three reports (Ragsdale, 2007). To avoid this happening, the location of each working cell such as 'subject to function' and 'subject to constraints' and so on it must be carefully designed and correspond to the outcomes cell in each row in the same spreadsheet to seek the optimal solution. Chapter 4 discussed Solver® as below:

(i) Section 4.4.1.4 spreadsheet-based method for scenario 1
(ii) Section 4.4.2.4 spreadsheet-based method for scenario 2
(iii) Section 4.4.3.4 spreadsheet-based method for scenario 3
(iv) Section 4.4.4.4 spreadsheet-based method for scenario 4
(v) Section 4.4.5.4 spreadsheet-based method for scenario 5
(vi) Section 4.4.6.3 spreadsheet-based method for scenario 6

However, the advantage of this method was that it was easy to justify spreadsheet-based data by directly keying in numerical data and employing the *Solver*®. The new solution would appear in a separate spreadsheet.

5.2 METHOD OF EVALUATION THREE AREAS BASED ON SIX SCENARIOS OUTCOMES FROM CHAPTER 4

Chapter 4, Section 4.4 discussed the scenarios and how they were developed for analysing the three areas of performance, ensuring that carbon footprint, financial effect cost and natural resources depletion meet target outcomes. Therefore, a score and scale system is one of the solutions to examine their performances. Score and scale consists of:

(a) The selection criteria.
(b) Evaluation based on selection criteria.

5.2.1 SELECTION CRITERIA

This consisted of three parts in the selection criteria:

(a) Carbon footprint. The carbon footprint throughout the manufacture of ordinary Portland cement, ordinary Portland cement with supplementary cementitious materials and fly ash based geopolymer cement production. The goal is to minimise the carbon dioxide emission.
(b) Financial effect cost. The financial effect cost, including raw materials costs, production costs and operational costs. The goal is to minimise financial effect costs.
(c) Natural resources depletion. This study only considered abiotic depletion from natural resources, including all raw materials for ordinary Portland cement production, and considered the by-products, slag and fly ash, from iron and steel refinery factories and coal-fired power stations, etc.

Each column in Table 5.1 consists of a '1 to 6' ranking scale, which is part of the evaluation of the score and scale system. A figure in each column is circled as an indicator of the performance of each scenario. Each scenario only examines one subject, such as the financial effect cost of ordinary Portland cement production, financial effect of fly ash based geopolymer cement production, operational cost of cement production, carbon dioxide emission of ordinary Portland cement production, natural resources depletion of cement production, modified extended life-cycle cost of cement production, modified extended life-cycle cost of fly ash based geopolymer cement production, and so on. This provides an opportunity to evaluate the three areas using a three-step approach and a linear programming equation.

5.2.2 EVALUATION BASED ON SELECTION CRITERIA

Table 5.1 Scenario Performance

Case studies	Aims	Carbon dioxide emission	Natural resources depletion	Financial effect cost	Average score
Scenario	Seeking optimum	1 2 3 4 5 6	1 2 3 4 5 6	1 2 3 4 5 6	1 2 3 4 5 6

Table 5.1 illustrates the method of evaluating each scenario performance of the three areas with respect to financial effect cost, including maximising operational profit and minimising natural resources depletion and carbon dioxide emission.

The six-point scoring scale was developed based on a '1' to '6' system, where 1 is the lowest score and 6 is the highest score. The meanings of each score are outlined below:

(a) If the scenario outcome is scored '1', this means the performances of the three areas of maximising profit and mininising natural resources depletion and carbon dioxide emission do not meet the requirements.

(b) If the scenario outcome is scored '2', this means the performance is slightly better than score '1'.

(c) If the scenario outcome is scored '3', this means its performance is average.

(d) If the scenario outcome is scored '4', this means its performance is above the average.

(e) If the scenario is scored '5', this means its performance is close to the target mark of maximising profit and mininising carbon dioxide emission and natural resources depletion.

(f) If the scenario is scored ‘6’, this means its performance is excellent and meets the all selection criteria, maximising profit and minimising carbon dioxide emission and natural resources depletion.

The results are shown in Table 5.2. All performances scored ‘6’ value because all equations from Chapter 3 and data from Chapter 4 were fully used to develop each linear programming problem seeking optimal solutions.

5.2.3 SCORE RESULTS OF THE EVALUATION

Table 5.2 Scoreboard of Each Scenario

	Aims	**Carbon Dioxide Emission Score**	**Natural Resource Depletion Score**	**Financial Effect Cost Score**
Scenario 1	Optimal production of ordinary Portland cement and ordinary Portland cement with supplementary cement material production of cement based within defined boundary			6
Scenario 2	Optimal production of fly ash based geopolymer cement including fly ash based geopolymer and metakaolin-based geopolymer cement within defined boundary			6
Scenario 3	Optimal production of fly ash based geopolymer cement and ordinary Portland cement within defined boundaries			6
Scenario 4	Mininising carbon dioxide emission because of transport to deliver materials using Australian National Greenhouse Accounts Factors (2014 to 2016) method	6		
Scenario 5	Mininising carbon dioxide emission because of transport to deliver materials using Carbon Dioxide Emission Equivalent method	6		
Scenario 6	Optimal use mininising abiotic depletion of ordinary Portland cement in production		6	

The score result of each scenario, as shown in Table 5.2, was full marks, based on the assessment method in Table 5.1. This means each linear programming equation for each single scenario was well developed, solving the maximisation and minimisation problems for the three areas based on the defined boundary and the same conditions.

The performance of each scenario was based on the equations of ‘subject to constraints’ and ‘subject to functions’ setting. Their sources are from primary and secondary data. In the case of the outcome of a scenario being outside of expectations, one method of improvement is to justify the data in the spreadsheet-based model, and compute with the Solver® again until the outcomes, such as answer, sensitivity and limit reports, reach an expected optimal solution, by changing the parameters in the ‘subject to constraints’ row in a spreadsheet model.

Every Scenario uses three methods, including traditional mathematics, graphical and spreadsheet-based methods to solve the linear programming equation problems in Chapter 4. Each method has its advantages and disadvantages. The summarised findings are shown in Table 5.3.

5.3 COMPARISON OF ADVANTAGES AND DISADVANTAGES USING THREE METHODS CALCULATED LINEAR PROGRAMMING EQUATION PROBLEM

Table 5.3 Advantages and Disadvantages of Three Methods Using Linear Programming with Simplex Method for Each Scenario

Three Methods	**Advantages**	**Disadvantages**
Matrix using Gaussian-Jordan Elimination (Grcar, 2011 and 2012) method	It is one of the traditional calculation methods derived from ‘First Principles’ and one can easily track back the calculation procedures in case of unexpected results.	It is one of the longer calculation methods, unless performed with the assistance of Matlab® (Appendix G) and Gaussian-Jordan Elimination Calculators.
Graphical method	It is a method commonly used to solve LP problems. It enables trial-and-error with a wide range of parameters of constraints to seek optimal solutions.	This method is only able to effectively solve two to three unknowns.
Spreadsheet-based (Solver®) method	This method uses Solver® symmetrically and effectively solving a series of linear programming equations in a short timeframe.	It is very easy to apply the wrong cell setting and consequently obtain the wrong answers and analysis results. Cross-checking all procedures and outcomes is important when using this method.

5.4 COMPARISON BETWEEN AUSTRALIAN NATIONAL GREENHOUSE ACCOUNTS FACTORS (2014 to 2016) AND CARBON DIOXIDE EMISSION EQUIVALENT METHODS RESULTS

In Chapter 4, the Australian National Greenhouse Accounts Factors (2014 to 2016) method was used in Scenario 4 and the Carbon Dioxide Carbon Dioxide Emission Equivalent method was used in Scenario 5 as ‘subject to function’, and the ‘subject to constraints’ uses the same data, ensuring the same conditions, including boundaries, to seek the optimal solution for carbon dioxide emission in cement production. However, Scenario 4 does not cover the Australian National Greenhouse Accounts Factors (2014 to 2016) method for ‘all types’ (see Table 2.1) of cement production including clinker production, lime production, indirect emission from consumption of purchased electricity, etc., and as a result, the two methods’ advantages and disadvantages cannot be adequately compared. Table 5.4 summarises the outcome results of the two methods at each stage of production, by using:

(a) Equations (3.4) to (3.7) for the Australian National Greenhouse Accounts Factors (2014 to 2016) method.

The different results from the Australian National Greenhouse Accounts Factors (2014 to 2015) and the Carbon Dioxide Equivalent methods are shown in Table 5.4. The second column result is higher than the third column, as marked in the red rectangular box. This is because there is more data required to complete the Australian National Greenhouse Accounts Factors (2014 to 2015) equation calculation, such as dust data, size and so on. It was also necessary to select the correct carbon dioxide emission method, which is discussed in Chapter 3. This is an accurate method.

Table 5.4 Compared Two Calculation Methods for Carbon Dioxide Emission

Process	Australian National Greenhouse Accounts Factors (2014 to 2016)	Carbon Dioxide Emission Equivalent	Unit
Clinker production	0.9310	0.851	kg $CO_{2\text{-}e}$/kg
Lime production	0.981	0.891	kg $CO_{2\text{-}e}$/kg
Slag	0.045	0.035	kg $CO_{2\text{-}e}$/kg
Fly ash	0.021	0.034	kg $CO_{2\text{-}e}$/kg
Sodium hydroxide (NaOH)	0.0391	0.0281	kg $CO_{2\text{-}e}$/kg
OPC production	0.9861	0.861	kg $CO_{2\text{-}e}$/kg
FA-based geopolymer production	0.6631	0.6621	kg $CO_{2\text{-}e}$/kg
Transport	0.923	0.789	kg $CO_{2\text{-}e}$/kg
Indirect purchased electricity	0.895	0.811	kg $CO_{2\text{-}e}$/Kwh
Electricity	0.75	0.745	kg$CO_{2\text{-}e}$/Kwh

The Carbon Dioxide Equivalent Emission method is a general and quick method to achieve calculation. Previous studies did not consider which methods are superior or inferior with respect to calculating carbon dioxide emission, but instead depended on the application area or industry and regions.

To find the whole-life-cycle emission based on the outcome in Table 5.4, one multiplies by 300 working days and raw materials consumption. The results are shown in Table 5.5. There were several assumptions:

(a) A 20-years' service life (Chan et al., 2015) of the cement factory.

(b) The same formulation for ordinary Portland cement, ordinary Portland cement with supplementary cementitious materials and fly ash based geopolymer cement production.

(c) The same Figure 2.6 and Figure 2.9, and also Table 2.4 and Table 2.6 defined boundaries, cradle-to-function and cradle-to-cradle conditions.

(d) All production events were in Australia.

(e) 20 years of production of cement results were based on each year, maintained at 9.1 to 11.1 million tonnes (Cement Industry Federation, 2016) by using an Australian National Greenhouse Accounts Factors (2015 to 2016) and Carbon Dioxide Emission Equivalent method.

Table 5.5 Whole- Life - Cycle Carbon Dioxide Emission in Cement Production Processes

Process	**Whole-of-life**		**Difference**	**Unit**
	Australian National Greenhouse Accounts Factors (2016)	**Carbon Dioxide Emission Equivalent**		
Clinker	372,400,000	372,400,000	0	$kgCO_{2-e}/kg$
Lime	392,400,000	356,400,000	-36,000,000	$kgCO_{2-e}/kg$
Slag	18,000,000	14,000,000	- 4,000,000	$kgCO_{2-e}/kg$
Fy ash	8,400,000	13,600,000	5,200,000	$kgCO_{2-e}/kg$
Sodium hydroxide (NaOH)	15,640,000	11,240,000	- 4,400,000	$kgCO_{2-e}/kg$
OPC production	39,444,000	344,400,000	304,956,000	$kgCO_{2-e}/kg$
FA-based geopolymer cement	248,400,000	264,840,000	16,440,000	$kgCO_{2-e}/kg$
Transport	36,920,000	315,600,000	278,680,000	$kgCO_{2-e}/kg$
Indirect purchased electricity	358,000,000	324,400,000	-33,600,000	$kgCO_{2-}/kwh$
Electricity	30,000,000	264,840,000	16,440,000	$kgCO_{2-}/Kwh$

Table 5.5 shows as whole-life-cycle of carbon dioxide emission results by using Australian National Greenhouse Accounts Factors (2014 to 2016) and the Carbon Dioxide Emission Equivalent method. It is very significant to find that the two methods do not yield the same values. Probing further their difference in terms of value, the values of each corresponding process minus each other must be examined. For example, the value from clinker can be found by using the Carbon Dioxide Emission Equivalent method minus the corresponding value from clinker using Australian National Greenhouse Accounts Factors (2014 to 2016). The results are given in the 'difference' column as shown in the red rectangular box. One finding is 'lime', 'slag', 'sodium hydroxide (NaOH)' and 'indirect purchased electricity' are scored negative values. This means the outcome results from Australian National Greenhouse Accounts Factors (2014 to 2016) were higher than those from the Carbon Dioxide Emission Equivalent method for the same process. In contrast, the rest of the values are positive values.

However, the equation from Australian National Greenhouse Accounts Factors (2014 to 2016) is more complex than the Carbon Dioxide Emission Equivalent method. This causes a certain degree of difficulty in data collection whether primary or secondary, particularly regarding the origins of the materials (purchased in Australia or imported from overseas), and what types of production facilities or methods the cement company used in cement manufacture. For example, Company C is only a grinding factory as some upfront processes are carried out overseas, and its dust level is apparently lower than that of ordinary Portland cement manufacturers like Company B.

In addition to the two major carbon dioxide emission calculation methods that have been discussed, abiotic depletion potential was also one of the major causes in cement production happened because the process is raw material intensive. There were several assumptions:

(a) Assumptions of the same production yield each year and the same types of production facilities.
(b) Assumption of the defined boundaries over 20 years of production events.

Table 5.6 Abiotic Depletion Calculation Outcomes Between Production of Ordinary Portland Cement and Fly Ash Based Geopolymer Cement from 2013 to 2015

Raw Materials	**Results**	
	Ordinary Portland Cement Production (10^{-6})	**Fly Ash Based Geopolymer Cement Production** (10^{-6})
Limestone	0.02	
Clay	0.45	
Sand	0.5	
Slag	0.5	
Gypsum	0.05	
Sand	0.5	0.5
Gravel	0.5	0.5
Fly ash		0.62
Sodium hydroxide		0.45

The outcome result of abiotic depletion potential is shown in Table 5.6, based on Chapter 4, Section 4.3.2.1.3. The overall limestone and fly ash were 0.02. This means there is at least 50 years' worth of stock, based on a prediction of 9.1 million tonnes of cement production per year of consumption of feedstock. However, fly ash is a by-product from coal-fired power stations and not a raw material. If power stations started to use liquefied petroleum gas instead of coal, feedstock of fly ash would face shortages and the price also would also be expected to rise as well. A metakaolin-based cement or GBBS-based cement production would be one of the solutions.

The individual results, including limestone, clay slag, gypsum, sand, gravel, sodium hydroxide, etc., of abiotic depletion of ordinary Portland cement and fly ash based geopolymer cement are shown in Table 5.7. This outcome did not considered feedstock for the cement industry. Raw materials assessment for cement production was based on 9.1 to 11.1 million tonnes per year (Cement Industry Federation, 2013); this will continuously supply raw materials for 40 years for the production of ordinary Portland cement.

Table 5.7 Result for Whole-Life-Cycle for Abiotic Depletion Calculation Between of Production Ordinary Portland Cement and Fly Ash Based Geopolymer Cement

Raw Materials	**Abiotic Depletion Potential Results** (10^{-6})			
	OPC	**FA-based Geopolymer Cement**	**Individual Whole-Life-Cycle**	
			Year	**Subtotal**
Limestone	0.02		20	0.4
Clay	0.45		20	9
Sand	0.5		20	10
Slag	0.5		20	10
Gypsum	0.05		20	1
Sand	0.5	0.5	20	10
Gravel	0.5	0.5	20	10
Fly ash		0.62	20	13
Sodium hydroxide		0.45	20	9
Subtotal	2.52	2.1		
Whole-Life-Cycle of Integration Raw Material for Abiotic Depletion Potential				
Year	20	20		
Total	50.4	42		
Year	40	40		
Total	100.8	84		

There are two red rectangular boxes in Table 5.7. This study was trial-and-error, seeking the maximisation of exhaustible raw materials under the same production conditions of cement formulation and briefing. The results are listed below:

(a) At 20 years: the total raw materials of ordinary Portland cement were 50.4% of the current feedstock and fly ash based geopolymer cement was 42% in stock.

(b) At 40 years: the current feedstock raw materials for ordinary Portland cement were exhausted and new quarrying was assumed. Raw and semi-raw materials for fly ash based geopolymer were 80% of total.

Table 5.8 The Financial Effect of the Cost for Ordinary Portland Cement and Fly Ash Based Geopolymer Cement Production

Cost Distribution	**Raw/Semi Materials Including Energy Cost**		
	Ordinary Portland Cement	**Fly Ash Based Geopolymer Cement**	**Unit**
Raw material costs			
Limestone	0.02		A$/kg
Lime	0.055		A$/kg
Clay	0.045		A$/kg
Gypsum	0.05		A$/kg
Slag	0.139		A$/kg
Sand	0.5		A$/kg
Gravel	0.5		A$/kg
Subtotal	1.308		A$/kg
Fly ash		0.05	A$/kg
Sodium hydroxide		0.45	A$/kg
Sand		0.5	A$/kg
Gravel		0.5	A$/kg
Subtotal		1.5	A$/kg
Energy cost			
Fuel cost	1.1	1.1	A$/ L
Electricity cost	1.1	1.1	A$/ Kw
Total	3.508	3.7	

The calculation of the 'whole-life-cycle' cost of the raw materials for ordinary Portland cement and geopolymer-based cement is shown in Table 5.9, based on Tables 5.5, Tables 4.6 to 4.8 and Companies A to C (2013 to 2015).

Table 5.9 The Whole-Life-Cycle Financial Effect of the Cost for Ordinary Portland Cement and Fly Ash Based Geopolymer Cement Production

Cost Distribution		**Cost**		
		Ordinary Portland Cement	**Fly Ash Based Geopolymer Cement**	**Unit**
Ordinary Portland cement based subtotal		1.308		A$/kg
Fly ash based geopolymer cement subtotal			1.5	A$/kg
Subtotal		2.2	2.2	A$/ L
Total material cost		3.508	3.7	A$/ kw
Whole-life -cycle cost	year	20		
	qty	10,000,000		kg
Total		70,160,000,000	74,000,000,000	A$

Table 5.9 shows the ‘whole-life-cycle’ material cost to produce ordinary Portland cement and fly ash based geopolymer cement. The cost difference was A$384,000,000 after 20 years under the same production conditions and defined boundaries. This means the reason the ordinary Portland cement production has been declining is the cheaper costs of fly ash based geopolymer cement manufacture.

Table 5.9 evaluates the cost of production of ordinary Portland cement and fly ash based geopolymer cement. Geopolymer-based production is still small-scale and over the past three years has had higher operational production costs than ordinary Portland cement and ordinary Portland cement with supplementary cementitious material production, because of material costs and operational costs being very expensive. The main advantages of fly ash based geopolymer cement are that it uses less energy and emits no carbon dioxide in the production process.

5.5 TRADITIONAL MATHEMATICAL METHODS

In Chapter 2, domestic material consumption (Equation 3.10, from Habert et al., (2010)), was only expressed in text format and not in equation format with numerical values. Habert et al., (2010) also states that domestic material consumption is normally expressed in an exponential equation. However, in Chapter 4, Section 4.3.3.1.2 and 4.3.3.13, this study also uses traditional mathematical methods, with the assistance of statistical methods, resulting in domestic material consumption as a linear equation instead of an exponential equation in the Australian business cement environment. It uses Section 3.2.2.2 Resources Calculation. The equation is:

$$\text{DMC (t)} \quad = \quad \text{mx + c or } \frac{y_2 - y_1}{x_2 - x_1} = \frac{y_1 - y_0}{x_1 - x_0} \quad \ldots\ldots\ldots\ldots\ldots \quad (5.1)$$

where m is the slope

x = is the raw materials including limestone, clay, sand, gravel, silica, sodium hydroxide (NaOH), gypsum etc.
c = is the arbitrary constant
t = is the timeframe

To find out the values of m or c by substitution of the consumption of domestic raw values into the linear curve equation, it is a common factor of two unknowns multiplied by one unknown (e.g., m) into the equation; consequently, they are eliminated by subtraction and the value of ‘c’ is found. Regarding solving ‘c’ values, by substitution of the unknown values of ‘m’ into the equation, the value of ‘c’ is found.

Tables 4.4 to 4.17 include domestic materials consumption, distances, the production yield of each quarrying company in South Australia, factory costs, etc.

The reserve to meet sustainable cement production based on equation (3.10) as obtained:

$$R = \int_{total}^{exhaust} DMC(t) * (1 - \frac{I}{DMC}(t)) \quad \ldots\ldots\ldots\ldots\ldots \quad (3.10)$$

where

I = imported or current stock material
t = time including total and exhaust period of times
R = reserve stock

$$R = \int_{total}^{exhaust} (mx + c)(t) * (1 - \frac{I}{(mx + c)}(t)) \quad \ldots\ldots\ldots\ldots\ldots \quad (5.2)$$

Also, the outcome of the ratio $\frac{I}{DMC} = \frac{I}{mx + c}$ provides a yardstick to measure decreased or increased rough values of domestic material consumption.

Additionally, the traditional mathematical method with Integration in Calculus skills (Habert et al., 2010 and 2011; Yellishetty et al., 2011 and 2012; Van Oers et al., 2002; Tunstall, 1992) played an active role in calculating the reserves of various raw materials for ordinary Portland cement and fly ash based geopolymer production in Australia, based on a 20-year (e.g. 2035) projection and Table 4.5. The theoretical raw materials reserves include lime, clay, sand, gypsum, gravel, silica, fly ash and sodium hydroxide (NaOH) lasting for 20-years for ordinary Portland cement, ordinary Portland cement with supplementary cementitious materials, and fly ash based geopolymer cement and are taken in account based on Table 4.7. (Company A, Cement Industry Federation, 2014 and 2015) and discussed in the next section, as below:

(a) Calculate lime reserve.
(b) Calculate clay reserve.
(c) Calculate sand reserve.
(d) Calculate gypsum reserve.
(e) Calculate gravel reserve.
(f) Calculate silica reserve.
(g) Calculate fly ash reserve.
(h) Calculate sodium hydroxide and brine reserve.

a) Calculate lime reserve

To calculate lime reserve based on Tables 4.5 to 4.7 and equation (5.2) using slope equation of traditional mathematical method as obtained:

$$\frac{y_2 - 18100}{x_2 - 2015} = \frac{18100 - 18050}{2015 - 2014}$$

$$\Rightarrow \frac{y_2 - 18100}{x_2 - 2015} = \frac{50}{1}$$

$$\Rightarrow y_2 - 18100 = 50(x_2 - 2015)$$

$$\Rightarrow y_2 = 50(x_2 - 2015) + 18100$$

$$\Rightarrow y_2 = 50x_2 - 82650$$

$$\Rightarrow \frac{I}{50x_2 - 82650}$$

where

I = 1 (Habert et al., 2010 and 2011)

x_2 = 2035

$$R_{\mathrm{lim}estone} = \int_{total}^{exhaust} (m_{\mathrm{lim}etone} x_{\mathrm{lim}estone} + c_{\mathrm{lim}estone})(t) * (1 - \frac{I}{(m_{\mathrm{lim}estone} x_{\mathrm{lim}estone} + c_{\mathrm{lim}estone})}(t))$$

…………………………………………………………………………… (5.3)

$$\Rightarrow R = \int_0^{20} (50x_2 - 82650)(t) * [1 - \frac{1}{50x_2 - 82650}(t)]dt$$

$$\Rightarrow R = \int_0^{20} [(101750 - 82650)(t) * (1 - \frac{1}{(101750 - 82650)}(t)]dt$$

$$\Rightarrow R = \int_0^{20} [19100(t) * (1 - \frac{1}{(19100)}(t)]dt$$

$$\Rightarrow R = \int_0^{20} [19100(t)^2]dt$$

$$\Rightarrow R = 19100\int_0^{20} (t)^2 dt \Rightarrow \frac{19100}{3}\left[t^3\right]_0^{20}$$

$\Rightarrow R = 50{,}933{,}333.33$ thousand matrix tonnes

(b) Calculate clay reserve

The same principle, using equation (5.2) based on Tables 4.5 to 4.7 and 20 years (e.g., 2035) production to calculate clay reserve as obtained:

$$\frac{y_2 - 27000}{x_2 - 2015} = \frac{27000 - 25500}{2015 - 2014}$$

$$\Rightarrow \frac{y_2 - 27000}{x_2 - 2015} = \frac{1500}{1}$$

$$\Rightarrow y_2 - 27000 = 1500(x_2 - 2015)$$

$$\Rightarrow y_2 = 1500(x_2 - 2015) + 27000$$

$$\Rightarrow y_2 = 1500x_2 - 2995500$$

$$\Rightarrow \frac{I}{1500x_2 - 2995500}$$

where

I = 1 (Habert et al., 2010 and 2011)
x_2 = 2035

$$R_{clay} = \int_0^{20} [(1500x - 2995500)(t) * (1 - \frac{I}{(1500x - 2995500)}(t)]dx \qquad \cdots\cdots\cdots \qquad (5.4)$$

$$\Rightarrow R = \int_0^{20} [(57000)(t) * (1 - \frac{1}{(57000)}(t)]dt$$

$$\Rightarrow R = \int_0^{20} [57000(t)^2]dt$$

$$\Rightarrow R = 57000\int_0^{20} [t]^2 dt \Rightarrow 19000\left[t^3\right]_0^{20}$$

$\Rightarrow R = 152{,}000{,}000$ thousand metric tonnes

(c) Calculate sand reserve

The same principle, using equation (5.2) based on Tables 4.5 to 4.7 and 20 years (e.g., 2035) production to calculate san reserve as obtained:

$$\frac{y_2 - 25000}{x_2 - 2015} = \frac{25000 - 24500}{2015 - 2014}$$

$$\Rightarrow \frac{y_2 - 25000}{x_2 - 2015} = \frac{500}{1}$$

$$\Rightarrow y_2 - 25000 = 500(x_2 - 2015)$$

$$\Rightarrow y_2 = 500(x_2 - 2015) + 25000$$

$$\Rightarrow y_2 = 500x_2 - 982500$$

$$\Rightarrow y_2 = 500x_2 - 982500$$

$$\Rightarrow \frac{I}{500x_2 - 982500}$$

where

I = 1 (Habert et al., 2010 and 2011)
x_2 = 2035 ; take into accout from 2015 , so 2035 - 2015 = 20; x_1 = 0 and x_2 =20

$$R_{sand} = \int_0^{20} [(500x_{clay} - 982500)(t) * (1 - \frac{I}{(500x - 982500)}(t)]dt \qquad \ldots\ldots\ldots \quad (5.5)$$

$$\Rightarrow R = \int_0^{20} [(35000)(t) * (1 - \frac{1}{(35000)}(t)]dt$$

$$\Rightarrow R = \int_0^{20} [35000(t)^2]dt$$

$$\Rightarrow R = 35000\int_0^{20} [t]^2 dt \Rightarrow 11666.67\left[t^3\right]_0^{20}$$

$\Rightarrow R = 93{,}333{,}333.33$ thousand metric tonnes

(d) Calculate gypsum reserve

The same principle, using equation (5.2) based on Tables 4.5 to 4.7 and 20 years (e.g., 2035) production to calculate clay reserve as obtained:

$$\frac{y_2 - 3200}{x_2 - 2015} = \frac{3200 - 3100}{2015 - 2014}$$

$$\Rightarrow \frac{y_2 - 3200}{x_2 - 2015} = \frac{100}{1}$$

$$\Rightarrow y_2 - 3200 = 100(x_2 - 2015)$$

$$\Rightarrow y_2 = 100(x_2 - 2015) + 3200$$

$$\Rightarrow y_2 = 100x_2 - 198300$$

$$\Rightarrow \frac{I}{100x_2 - 198300}$$

where

I = 1 (Habert et al., 2010 and 2011)

x_2 = 2035

$$R_{gypsum} = \int_0^{20} [(100x \ \ -198300)(t) * (1 - \frac{I}{(100x - 198300)}(t)]dt \qquad \ldots\ldots\ldots \qquad (5.6)$$

where

I = 1 (Habert et al., 2010 and 2011)

x_2 = 2035 ; take into accout from 2015 , so 2035 - 2015 = 20; $x_1 = 0$ and $x_2 = 20$

$$\Rightarrow R = \int_0^{20} [(203500)(t) * (1 - \frac{1}{(203500)}(t)]dt$$

$$\Rightarrow R = \int_0^{20} [203500(t)^2]dt$$

$$\Rightarrow R = 203500 \int_0^{20} [t]^2 dt \Rightarrow 67833.33 \left[t^3\right]_0^{20}$$

$$\Rightarrow R = 542,666,666.7$$ thousand metric tonnes

(e) Calculate gravel reserve

The same principle, using equation (5.2) based on Tables 4.5 to 4.7 and 20 years (e.g., 2035) production to calculate gravel reserve as obtained:

$$\frac{y_2 - 8300}{x_2 - 2015} = \frac{8300 - 8100}{2015 - 2014}$$

$$\Rightarrow \frac{y_2 - 8300}{x_2 - 2015} = \frac{200}{1}$$

$$\Rightarrow y_2 - 8300 = 200(x_2 - 2015)$$

$$\Rightarrow y_2 = 200(x_2 - 2015) - 394700$$

$$\Rightarrow y_2 = 200x_2 - 394700$$

$$\Rightarrow \frac{I}{200x_2 - 394700}$$

where

I = 1 (Habert et al., 2010 and 2011)
x2 = 2035

$$R_{gravel} = \int_0^{20} [(200x_{gravel} - 394700)(t) * (1 - \frac{I}{(200x_{gravel} - 394700)}(t)]dt \qquad ….. \quad (5.7)$$

where

I = 1 (Habert et al., 2010 and 2011)
x2 = 2035 ; take into accout from 2015 , so 2035 - 2015 = 20; $x_1 = 0$ and $x_2 = 20$

$$\Rightarrow R = \int_0^{20} [(8300)(t) * (1 - \frac{1}{(8300)}(t)]dt$$

$$\Rightarrow R = 8300\int_0^{20} [t]^2 dt \Rightarrow 2766.33\left[t^3\right]_0^{20}$$

$\Rightarrow R = 22{,}133{,}333.33$ thousand metric tonnes

(f) Calculate silica reserve

The same principle, using equation (5.2) based on Tables 4.5 to 4.7 and 20 years (e.g., 2035) production to calculate silica reserve as obtained:

$$\frac{y_2 - 3300}{x_2 - 2015} = \frac{3300 - 3200}{2015 - 2014}$$

$$\Rightarrow \frac{y_2 - 3300}{x_2 - 2015} = \frac{100}{1}$$

$$\Rightarrow y_2 - 3300 = 100(x_2 - 2015)$$

$$\Rightarrow y_2 = 100(x_2 - 2015) - 3300$$

$$\Rightarrow y_2 = 100x_2 - 198200$$

$$\Rightarrow \frac{I}{100x_2 - 198200}$$

$$R_{gravel} = \int_0^{20} [(100x_{gravel} - 198200)(t) * (1 - \frac{I}{(100x_{gravel} - 198200)}(t)]dt \qquad \ldots.. \quad (5.8)$$

where

I = 1 (Habert et al., 2010 and 2011)

x_2 = 2035 ; take into account from 2015 , so 2035 - 2015 = 20; $x_1 = 0$ and $x_2 = 20$

$$\Rightarrow R = \int_0^{20} [(3300)(t) * (1 - \frac{1}{(3300)}(t)]dt$$

$$\Rightarrow R = \int_0^{20} [3300(t)^2]dt$$

$$\Rightarrow R = 3300\int_0^{20} [t]^2 dt \Rightarrow 1100\left[t^3\right]_0^{20}$$

$\Rightarrow R = 8{,}800{,}000$ thousand metric tonnes

(g) Calculate fly ash reserve

The same principle, using equation (5.2) based on Tables 4.5 to 4.7 and 20 years (e.g., 2035) production to calculate silica reserve as obtained:

$$\frac{y_2 - 18100}{x_2 - 2015} = \frac{18100 - 18050}{2015 - 2014}$$

$$\Rightarrow \frac{y_2 - 18100}{x_2 - 2015} = \frac{50}{1}$$

$$\Rightarrow y_2 - 18100 = 50(x_2 - 2015)$$

$$\Rightarrow y_2 = 50(x_2 - 2015) - 18100$$

$$\Rightarrow y_2 = 50x_2 - 82650$$

$$\Rightarrow \frac{I}{50x_2 - 82650}$$

$$R_{flyash} = \int_0^{20} [(50x_{flyashl} - 82650)(t) * (1 - \frac{I}{(50x_{flyash} - 82650}(t)]dt \qquad ..... \qquad (5.9)$$

where

I = 1 (Habert et al., 2010 and 2011)
x_2 = 2035 ; take into account from 2015 , so 2035 - 2015 = 20; $x_1 = 0$ and $x_2 = 20$

$$\Rightarrow R = \int_0^{20} [18100(t)^2]dt$$

$$\Rightarrow R = 18100 \int_0^{20} [t]^2 dt \Rightarrow 6033 \left[t^3\right]_0^{20}$$

$\Rightarrow R = 48{,}266{,}666.67$ thousand metric tonnes

(h) Calculate sodium hydroxide (NaOH) reserve

The same principle, using equation (5.2) based on Tables 4.5 to 4.7 and 20 years (e.g. 2035) production to calculate clay reserve as obtained:

$$\frac{y_2 - 27000}{x_2 - 2015} = \frac{27000 - 25500}{2015 - 2014}$$

$$\Rightarrow \frac{y_2 - 27000}{x_2 - 2015} = \frac{1500}{1}$$

$$\Rightarrow y_2 - 27000 = 1500(x_2 - 2015)$$

$$\Rightarrow y_2 = 1500(x_2 - 2015) + 27000$$

$$\Rightarrow y_2 = 1500x_2 - 2995500$$

$$\Rightarrow \frac{I}{1500x_2 - 2995500}$$

$$R_{NaOH} = \int_0^{20} [(1500x_{NaOH} - 2995500)(t) * (1 - \frac{I}{(1500x_{NaOH} - 2995500)}(t)]dt \quad .. \text{ (5.10)}$$

where

I = 1 (Habert et al., 2010 and 2011)

x_2 = 2035 ; take into account from 2015 , so 2035 - 2015 = 20; $x_1 = 0$ and $x_2 = 20$

$$\Rightarrow R = \int_0^{20} [(57000)(t) * (1 - \frac{1}{(57000)}(t)]dt$$

$$\Rightarrow R = \int_0^{20} [57000(t)^2]dt$$

$$\Rightarrow R = 57000\int_0^{20} [t]^2 dt \Rightarrow 19000\left[t^3\right]_0^{20}$$

$\Rightarrow R = 152{,}000{,}000$ thousand metric tonnes

5.6 SUMMARY

Chapter 5 discussed evaluation methods for the three areas based on scenario outcomes from Chapter 4. Also discussed in detail were other calculation methods, such as carbon dioxide emission from Australian National Greenhouse Accounts Factors (2014 to 2016), including lime production, clinker production, purchased electricity, greenhouse gas emission from different fuel types, the Carbon Dioxide Emission Equivalent method, World Business Council for Sustainable Development, and so on, financial effect cost, including raw material cost, energy cost and operational cost, and abiotic depletion, developed in Chapter 3 (Methodology). All these methods and outcomes were used to fully evaluate the three areas and provide information as to which type of cement manufacture is optimal in minimising carbon dioxide emission and natural resources depletion and maximising profit.

Additionally, the aim of this chapter was also to validate the proposed methodology with a wide range of parameters and the proposed equations. It also provided information as to which methods of calculation, such as the Carbon Dioxide Emission Equivalent, are the most suitable to which production areas or regions.

Further, this chapter also discussed the reserve (R) of each raw material for ordinary Portland cement and fly ash based geopolymer cement production over 20 years, and production methods using the defined equation from the methodology chapter. This reserve calculation was not part of the scenario study because in Chapter 5 we were only concerned with minimising the use of raw materials.

This chapter also proved domestic material consumption based on linear equation characteristics instead of an exponential equation (Habert et al., 2010) to solve the reserve issue in the Australian cement business environment.

It further examined 20 years of raw material consumption and provided an indication as to what kind of raw materials will be facing shortages, aiding the development of a strategies to develop new quarry sites and a production strategy in order to meet the demands of the market.

CHAPTER 6

CONCLUSIONS

CHAPTER 6 CONCLUSIONS

The purpose of this chapter is to discuss the achievements of this research based on Chapter 1 Objectives, Chapter 2 Research Questions, and the overall findings relating to an evaluation of the options for cement manufacture for sustainable infrastructure. Future research has also been discussed in this Chapter, including shortening delivery distance times for fly ash from coal-fired power station, leading to lower carbon dioxide emissions in transport, maximising use of another by-product, sodium hydroxide solution from chlorine solution generation, This is because sodium hydroxide solution is the by-product from coal-fired power stations, which use sea water to cool super dry steam to condensate water; and also maximising the use of power station waste heat from high pressure heater-170 Megapascal (MPa) with 1450°C; low pressure heater at 1200°C with 80 Megapascal (MPa) and condenser at 1200°C with 80 MPa which is sufficient to raise kiln temperatures to one MPa with 1400°C for the chemical reaction to take place inside the kiln and results in driving down costs. This also minimises the use of the natural resource of coal.

6.1 ACHIEVEMENT OF OBJECTIVES

Chapter 1, Section 1.2 (objectives), clearly addresses the research direction and the research questions. Achievement of the objectives is listed below:

(a) *Identify carbon dioxide emissions production process, including calcium carbonate ($CaCO_3$) in the kiln and energy consumption in milling, calcination, transport. And more.*

  (i) Chapter 2 Literature Review, Sections 2.1.1 to 2.1.3, identified cement production processes including kiln, grinding, carbon dioxide emission and energy consumption. Table 2.5 compared work that current researchers have done in these areas and the gaps in the research.

(b) *Investigate the calculation methods of natural resources depletion and reserves in different regions, particular in Australian for cement production.*

  (i) Chapter 2 Literature Review, Sections 2.2.3, intensively investigated calculation methods for natural resources depletion. Table 2.7 also compared work that current researchers have done in these areas and the gaps in the research.

(c) *Examine the life cycle cost of the three areas based on defined boundaries.*

  (i) Chapter 2 Literature Review, Sections 2.2.3 to 2.2.5, intensively investigated and evaluated a variety of methods of calculating carbon dioxide and the life-cycle cost for cement production. Tables 2.7 and 2.8 also compared work that current researchers have done in these areas and the gaps in the research. Additionally, the production boundary in this research is identified in Figure 2.6 and Table 2.4 (ordinary Portland cement) and Figure 2.9 and Table 2.6 (fly ash based geopolymer cement), which provide fair conditions to evaluate the three areas.

(d) *Examine the optimal methods of the three areas with respect to carbon dioxide emission, natural resources depletion and financial effects.*

  (i) Chapter 2 Literature Review, Section 2.2.2, intensively investigated common methods of calculating carbon dioxide emission, such as the Carbon Dioxide Emission Equivalent, Australian National Greenhouse Accounts Factors (2014 to 2016) and World Sustainable Trade and Development Council methods, etc. To satisfy the requirements of these equations it was necessary to collect more data, from both primary and secondary sources, to screen which parameters are suitable for the proposed equations, and which conditions, including the regions, apply.

  (ii) Chapter 2 Literature Review, Section 2.2.3 to 2.2.5, discussed natural resources depletion and financial effects as well as Chapter 3 Methodology.

(e) *Investigate and evaluate a variety of methods of calculating CO_2.*

  (i) The Carbon Dioxide Emission Equivalent method is a general method of calculating carbon dioxide emission, applicable to every industry. It provides a simple and direct method of solving the calculation issue. It collects several parameters, such as quantities of fuel being used, greenhouse effect parameters and fuel factors etc., to calculate the carbon footprint.

  (ii) Australian National Greenhouse Accounts Factors (2014 to 2016) method is specifically used in the Australian region and is suitable for every industry operating in Australia.

  (iii) Chapter 2, Section 2.2.2 and Section 2.3, discussed the issue of how to calculate carbon dioxide emission for cement production.

(f) *Develop a framework to effectively assess abiotic depletion, energy cost, fuel type used, raw materials including by-products such as fly ash, slag, etc., consumption, life-cycle cost and cost assessment, including whole-cycle for the three areas.*

  (i) The proposed advanced framework was developed and illustrated in Chapter 3 based on outcomes from Chapter 2.

6.2 ACHIEVEMENT OF RESEARCH QUESTIONS

The achievement of the research objectives is discussed in Section 6.1. The achievements in regard to research questions are listed as below:

A. Boundary for Environmental Effect Measure

(a) This is discussed in Section 6.1. Several researchers formulated assessments of concrete production (Habert et al., 2010; Collins and Turner, 2013) based on ISO 14000:2000 series within defined boundaries with the assistance of well-known environmental software to assess environmental effect, in terms of carbon dioxide emission in production processes. This study adapted and extended work those researchers have done and applied it in an Australian cement production environment (meaning that all raw materials and by-products are produced in Australia and not imported). These boundaries are based on Australian Cement Industry Federation (2014 to 2016) data, providing the same production conditions for fair evaluation of cement manufacture options under the defined boundaries. Chapter 4, Section 4.4.1, was based on these conditions and they were used to develop six scenario studies.

(b) Calculation Carbon Dioxide Emission Method

(i) Several methods were identified in Chapter 2, including Australian National Greenhouse Accounts Factors (2014 to 2016), the Carbon Dioxide Emission Equivalent methods and the World Sustainable Trade and Development Council method. Each method has its own characteristics and needed different data to complete calculations; it takes time to collect these different types of data, such as amount of dust, size of production device, limestone production, clinker production, transport, purchased electricity and so on. One of the solutions was to use both primary and secondary sources to achieve the goal of measuring the carbon footprint throughout the production process. The World Sustainable Trade for Development Council method (Chapter 2) is an official methodology. However, this method can be linked to other methods and share a database to enrich its assessment capability. Because of the complexity and flexibility of this method, Chapter 3, Section 3.2.1 discussed it in detail. No matter which method is used, a lot of data are needed to satisfy the requirements of the calculation. This is one of the most time consuming phases of the research.

(ii) To probe further to calculate optimal carbon dioxide emission in production, Chapter 4 used scenario studies using the Australian National Greenhouse Accounts Factors (2014 to 2015) equation as ‘subject to function’ in Scenario 4 and also used the Carbon Dioxide Emission Equivalent equation as ‘subject to function’ in Scenario 5. The rest of the data and ‘subject to constraints’ are the same, in order to develop a full set of linear programming equations seeking optimal carbon dioxide emission. Based on their outcomes results were able to be compared for superiority and limitations.

(c) Abiotic Depletion Potential

(i) Chapter 2 in Section 2.2.3 discusses current researchers work and limitation in abiotic depletion potentials as the result to identify Habert et al., (2010) calculation method is suitable for this research. But domestic material consumption is in text form and also only used in French region. So, this research solved domestic materials consumption equation to suit this equation for Australia. Chapter 3 in Sections 3.2.2.1 to 3.2.2.1 for Section 3.2.2 is further discussion.

(ii) Chapter 4 in Section 4.3 discusses data collection and analyses domestic materials consumption trend in cement industry as a result of linear programming equation is suitable in Australia region. Chapter 5 in Section 5.5 based on Section 4.3 outcomes calculates reserves raw materials.

(d) Financial Effect Measure

(i) Chapter 2 in Sections 2.1 to 2.2 identifies various calculation methods for financial effect measure. Chapter 3 in Sections 3.2.3.2 and 3.2.3.3 based on Sections 2.1 to 2.2 findings develops a tool for financial effect measure.

(ii) Chapter 4 in Sections 4.1 to 4.2 and Section 4.4 is data collection and analysis for developing linear programming equations for six scenarios studies, which were used to financial effect measure.

(e) Optimisation

(i) Research questions (a) to (c) were discussed in Chapter 2. Literature review and detailed methodology were discussed in Chapter 3.

(ii) Chapter 4 also discusses research questions (d) to (f).

6.3 FINDINGS AND SUMMARY OF FINDINGS FROM ITEMS ‘A’ to’ G’

Sections 6.1 and 6.2 discussed the achievement of objectives and research questions. Several finding as listed below:

6.3.1 FINDINGS:

A. The first finding is that the Australian National Greenhouse Accounts Factors (2014 to 2016) with the assistance of the Carbon Dioxide Emission Equivalent method is the most suitable in this research to calculate carbon dioxide in cement production. This is because the cement product is seldom shipped to Europe as the result of the ex-factory cost being higher than worldwide cement competitors’ costs based on scenario analysis results.

B. The second finding is that the production of ordinary Portland cement uses a large quantity of raw materials and is energy intensive, which is commonly used as constitute materials worldwide (Company A, 2015; Turner and Collins, 2013). Australian-owned cement factories produced 9.1 million tonnes (Cement Industry Federation, 2104) in 2014, meaning corresponding natural resources including limestone (lime), clay, sand, gypsum, slag, gravel, etc. were also consumed in proportion based on Figure 4.15 results. To measure natural resources depletion, Habert et al., (2010) directly applied abiotic depletion and abiotic depletion potential methods to French and American construction and concrete industries, successfully developing a series of indicators. Here, this research adapts and extends their theories to be used in an Australian environment. The finding is that the domestic material consumption equation is totally different from that suggested by Habert et al., (2010), based on Chapter 4 (Section 4.14) outcomes as the result of a polynomial equation including linear equation, instead of an exponential equation in the Australian cement business environment. Most raw materials used, including fly ash, sodium hydroxide (aqueous alkali hydroxide), sodium silicate (silica solution), slag, etc., for geopolymer-based cement production are by-products. The equation of calculating abiotic depletion potential from Habert et al., (2010) is not suitable for this purpose because they do not all deplete abiotic resources.

The set of data collected concerned coal-fired power stations' coal consumption every year, how much iron ore is refined each year, etc. This directly measures the total quantity of fly ash produced from coal-fired power stations and iron slag produced each year from this directly measures the total quantity of fly ash produced from coal-fired power stations and iron slag produced each year from steel refinery factories until these kinds of factories are replaced in the future by ones using liquefied natural gas.

C. The third finding is that the cement and concrete industries are essential elements for civil and construction work. However, the profit margin of this kind of industry is very sensitive and related to the cost of raw materials and operational costs. Therefore, in the Literature Review with Evaluation Alternative Chapter, this study identified that cost estimation and linear programming methods are suitable in this research. This work has been discussed in the Data Collection and Analysis and Results Chapter. The outcomes are promising. To maintain sustainable factory infrastructure, numerous researchers have used life-cycle cost, which evaluates environmental effects and costs for every industry. However, these methods have limitations because of the difficulty of defining the different boundaries and lifelong evaluation. Some data will be uncertain or hard to predict. One of the solutions was to adapt and extended Chan et al., (2015) and 'whole-life-cycle' methods to estimate the life-cycle cost calculation, discussed in Chapter 5, Section 5.4.

D. The fourth finding is that integrated abiotic depletion potential and seasonality indices are seldom used to give insight into natural resources depletion (NRD) status for the cement industry. Habert et al., (2010) used this method, but only to study France and America. Therefore, one of the methods in the advanced integrated proposed framework being developed for bridging this gap is using a time-series for regression model to solve this issue. Additionally, the indices and forecasts were also developed based on this time-series. This research also extended Habert et al.,'s (2010) approach and studied abiotic depletion and resources in the Australia region.

The outcome is designed to give cement manufacturers and users information to prevent natural resources depletion or seek new feedstock and resources, and improve ‘greenness’ without extra environmental costs. A combination of primary and secondary data collection was the key to formulating the equations, as discussion in Chapter 4, Section 4.3.2.1.3.

The primary data are from a survey. Secondary data are from literature, the Australian Bureau of Statistics, the Australian Cement Industry and Ash Development Association of Australia, etc. Secondary data are from literature, the Australian Bureau of Statistics, the Australian Cement Industry and Ash Development Association of Australia, etc.

E. The fifth finding is that cement companies use a variety of strategies to formulate cement production with respect to maximising profit, and minimising carbon dioxide emissions and depletion of natural resources, as discussed in Chapter 4.

F. The sixth finding is that there is a mix design and mix proportion for reducing carbon dioxide emission for supplementary cementitious material with ordinary Portland cement and also fly ash based geopolymer cement production, but the chemical contents and sources for supplementary cementitious materials are seldom analysed. In Chapter 4, Section 4.2.2.7 of this study, a time-series and regression model has been used to develop the indices to solve this issue. This research also used a simulation experimental model as explained in Appendix G, to collect another set of theoretical data for validating the proposed framework’s functionality.

G. The seventh finding is that the major sources of carbon dioxide emission were the kiln process and delivery of the raw materials from quarry sites to ordinary Portland cement factories. Therefore, the location selection of ordinary Portland cement and fly ash based geopolymer factories is a major issue, meaning the upfront waste and downstream factories like cement factories may be one of the raw materials. This would reduce the rates of natural resources depletion and maximise the use of waste heat (energy) from the coal-fired power stations, saving the factory operational costs.

6.3.2 SUMMARY OF FINDINGS FROM ITEMS ‘A’ TO ‘G’

Table 6.1 Summary of Findings and Analysis from Items ‘A’ to ‘G’

Items	Summary	Methods
A	Method of Measure CO_2 emission in cement production. Cement production cost is more expensive than worldwide competitors.	Used Australian National Greenhouse Factors with assistance of CO_2 equivalent methods to calculate CO_2 emision.Cost control of production processes is one of the solutions for better profit and less environmental effect.
B	Domestic material consumption (DMC) equation for abiotic depletion potential (ADP) calculation.	Used Habert et al’s., (2010) ADP method to calculate ADP status. But DMC equation is part of ADP equation. So, data collection and analysis (Chapter 4) is one of the main roles to seek a suitable DMC equation using times-series model method.
C	Whole-Life-Cost calculation.	Adapted and extended Chan et al’s., (2015) “whole-of-life” method to calculate the life cycle costs related to cement production.
D	Seasonaility indices for natural resource (abiotic depletion potential) calculation.	Used times- series with regressive model to analyse previous raw material consumption in Australia as the result of identifying both seasonality indices and DMC are linear equations characteristics.
E	Cement production strategies	Used variety cement production strategies for three Austrlian-owned cement factories as the result of better profit, less envirnemntal effect, etc.
F	Mix design and mix proportion	Used supplementary cementitious material (SCM) is one of alternative methods for mix design and mixed proportion for cement production to reduce carbon dioxide emission.
G	Factory location	Closed to feedstock of cement factory as the result better profit and less environment effect.

6.4 LIMITATION AND FUTURE RESEARCH

6.4.1 LIMITATION

There is a limitation in this research related to three types of cement production. Fly ash based geopolymer cement was intensively studied and other types of geopolymer-based cement were not intensively examined, such as metakaolin-based geopolymer cement, ground-granulate blast slag-based geopolymer cement, etc. The raw materials are commonly imported from New Zealand (Australian Bureau of Statistics, 2014), but this has not yet been studied as the result of a pre-defined boundary; this provides an opportunity for future research.

Further, as liquefied natural gas-based power stations become the main type of power generation in Australia, fly ash will be imported from overseas to maintain the fly ash based geopolymer cement product. The overall cost of cement will therefore rise sharply. Therefore, metakaolin-based geopolymer or ground-granulate blast based cement production might replace them soon. This is an opportunity for future research. The Parliament of Australia (2017) conducted an enquiry into the retirement of coal-fired power stations; the Liddell coal-fired power station will be closed in 2022, although the Parliament of Australia is still pursuing AGL Company to remain operational because of potential uncertainty about fly ash supplies.

This all means that there will probably be shortages of fly ash soon. Regarding cement, this research only concerned production and evaluation of ordinary Portland cement and ordinary Portland cement with supplementary cementitious materials and geopolymer-based cement. There are other types of cement (Table 2.1) such as high Portland cement, high-early-strength Portland cement, low-head Portland cement, sulfate-resisting Portland cement, Portland, air-entraining Portland cement, Portland blast-furnace slag cement, white Portland cement, Portland Pozzolan cement, magnesium-based cement and so on, which have not yet been studied, and this also provides an opportunity for future research.

6.4.2 FUTURE RESEARCH

However, no matter what types of Portland cement production occur in Australia, minimising energy used, producing less carbon dioxide emission in production and maximising profit are the main issues. To solve these, a future plant likes the one shown in Figure 6.1 is one of the solutions, despite the geographical location. The essential facilities of this factory will consist of:

(a) Coal-fired and heavy oil fired power stations (Yahya et al., 2014).
(b) Chlorine plant (Torres and Bevia, 2012).
(c) Surface condenser (Torres and Bevia, 2012).
(d) Wind and solar energies (Gabel and Tillman, 2005; Chan et al., 2011).
(e) Silos.
(f) Quarry sites.
(g) Transport.

(a) Coal-fired and heavy oil fired power stations (Yahya et al., 2014)

Each year, power stations, including coal and heavy oil based, produce 1.2 million tonnes of fly ash in Australia (Cement Industry Federation, 2014). All fly ash is collected by a series of cyclones (Figures 6.1 to 6.2) to make fly ash based geopolymer cement and also supplementary cementitious materials. This feedstock is very convenient, avoiding extra carbon dioxide emission in transport. However, the Liddell coal-fired power station is scheduled to close in 2022, and Hazelwood brown coal-fired power station will be de-commissioned in Victoria. This is one of the issues to affect fly ash supplies, and as a result, the selling prices will increase in the coming year until a green coal is used (Parliament of Australia, 2017) instead of brown coal. Careful organisation of transport can reduce carbon dioxide (Company A, 2015; Chan et al., 2015).

(b) Chlorine plant (Torres and Bevia, 2012)

A chlorine gas or liquid is produced using an electrolysis process with sea water, as shown in Figure 6.2. The calculation method is in Appendix C. One of the by-products is a sodium hydroxide solution, but power stations are only interested in chlorine liquid, which they use to stop marine species damaging the facilities. However, sodium hydroxide (NaOH) liquid is one of the major raw materials needed for making fly ash based geopolymer cement, and much of it is purchased from overseas (USGS, 2012). Waste therefore becomes a useful material; it saves a money and time. The issue is how to properly collect NaOH liquid in production. One of the solutions is to pump NaOH liquid into day tanks, ensuring its concentration is suitable to make fly ash based geopolymer cement. The correct ratio of NaOH solution and sodium silicates solution to fly ash are just enough to complete the chemical reaction. Figure 4.15 is an earlier solution using the proportion method.

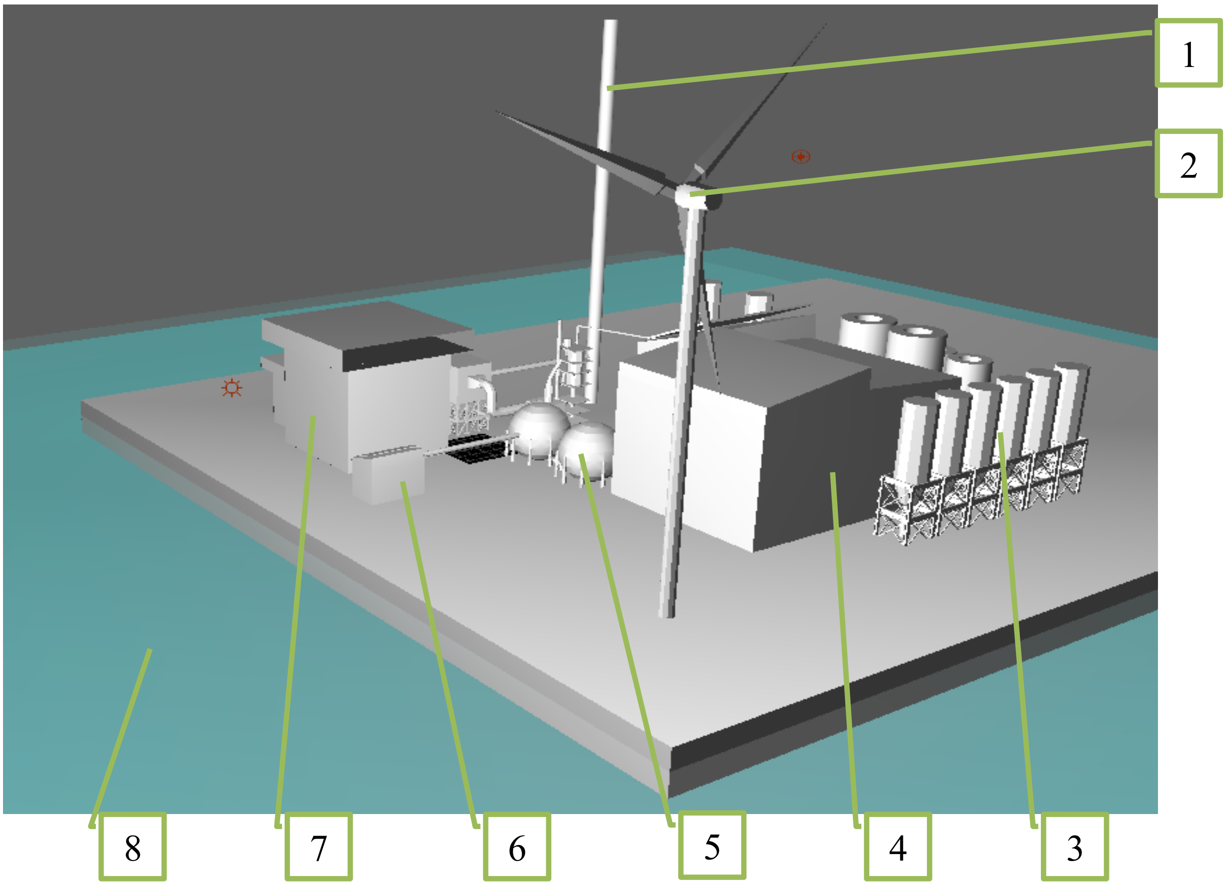


Figure 6.1 Future Advanced Integration Cement Plant (Front View)

Legend	
1	Waste heat from boiler
2	Wind-power
3	Raw material silos
4	Fly ash based geopolymer cement factory
5	Chlorine solution silos
6	Chlorine plant
7	Coal-fired power station
8	Sea

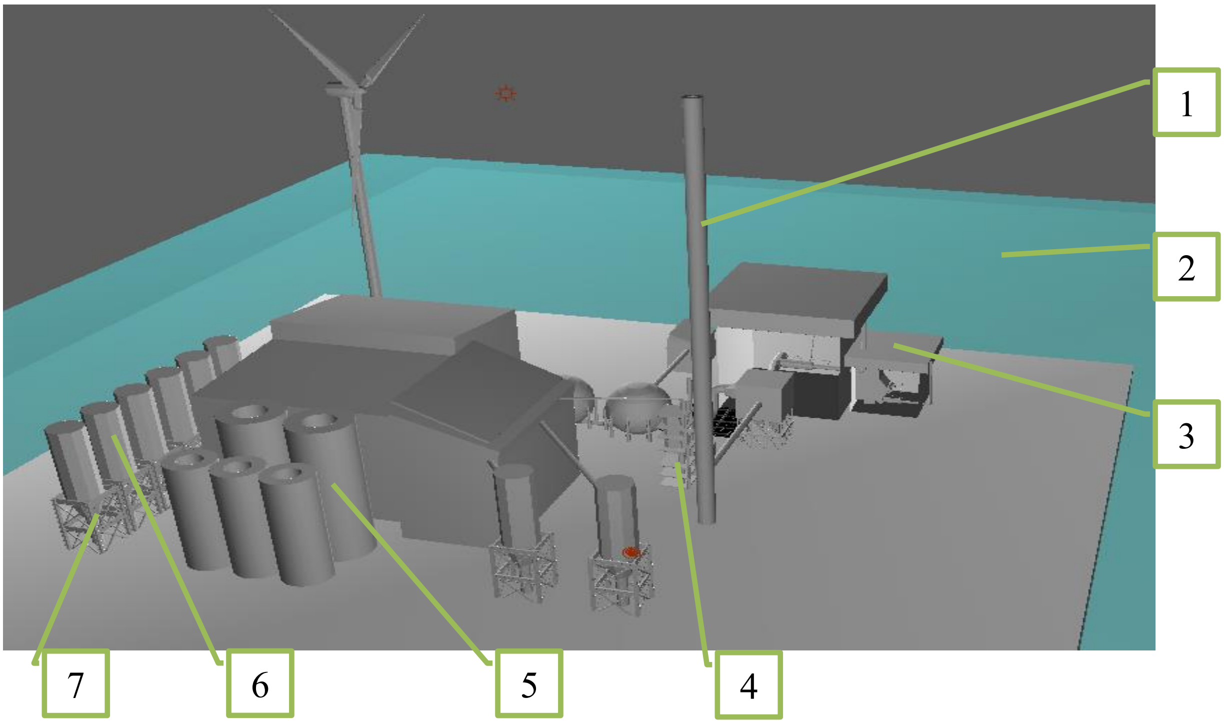


Figure 6.2 Future Advanced Integration Cement Plant (Rear View)

Legend	
1	Chimney
2	Sea
3	Auxiliary power
4	Fly ash silo
5	Cement product silo
6	Raw material silo
7	Silo

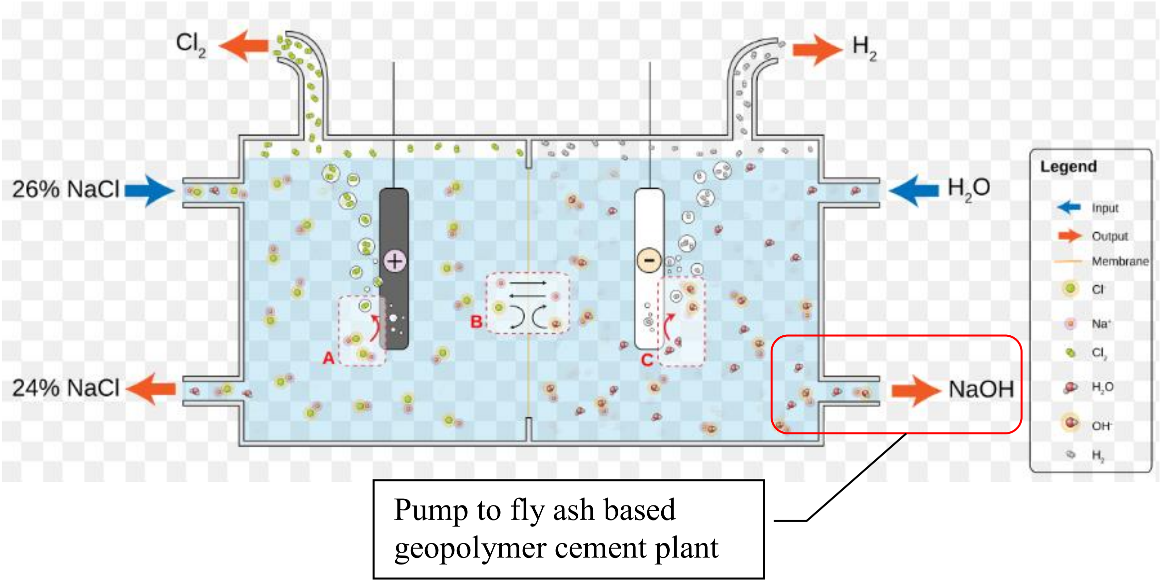


Figure 6.3 Chlorine Including Sodium Hydroxide Solution Generation through Electrolysis Process (Chlorine Production Image Courtesy of Wikipedia, 2017)

To protect the cooling system from small crabs, mussels and so on, a certain amount of chlorine liquid is injected into the sea water inlet to kill them. Therefore, in the future plant, the chlorine gas or liquid will be generated using an electrolysis process and it will have special tubes to transfer it into a silo for temporary storage and later re-distribution to each inlet of the high-speed sea water pump. This is one of the solutions to control the concentration and chlorine solution flow rate into the sea bed, ensuring protection against small sea species coming into surface condenser and causing damage. One of the by-products of this process is a sodium hydroxide solution, which is one of the most important raw materials to make fly ash based geopolymer cement, as shown in Figure 6.3. To meet yearly demand for 1.2 million tonnes of fly ash produced from coal-fired power stations in Australia, the expansion of chlorine plants in coal-fired stations is one of the solutions for maximising the use of fly ash.

A special tube or device will deliver sodium hydroxide solution to a specially designed silo for storage, as shown in Figures 6.1 and 6.2, to make fly ash based geopolymer cement. This feedstock is very convenient and reliable, and it avoids extra carbon dioxide emission in transport. It converts a waste solution to useful raw materials, saving money and time. To achieve this goal, a considerable investment will be made in the facilities.

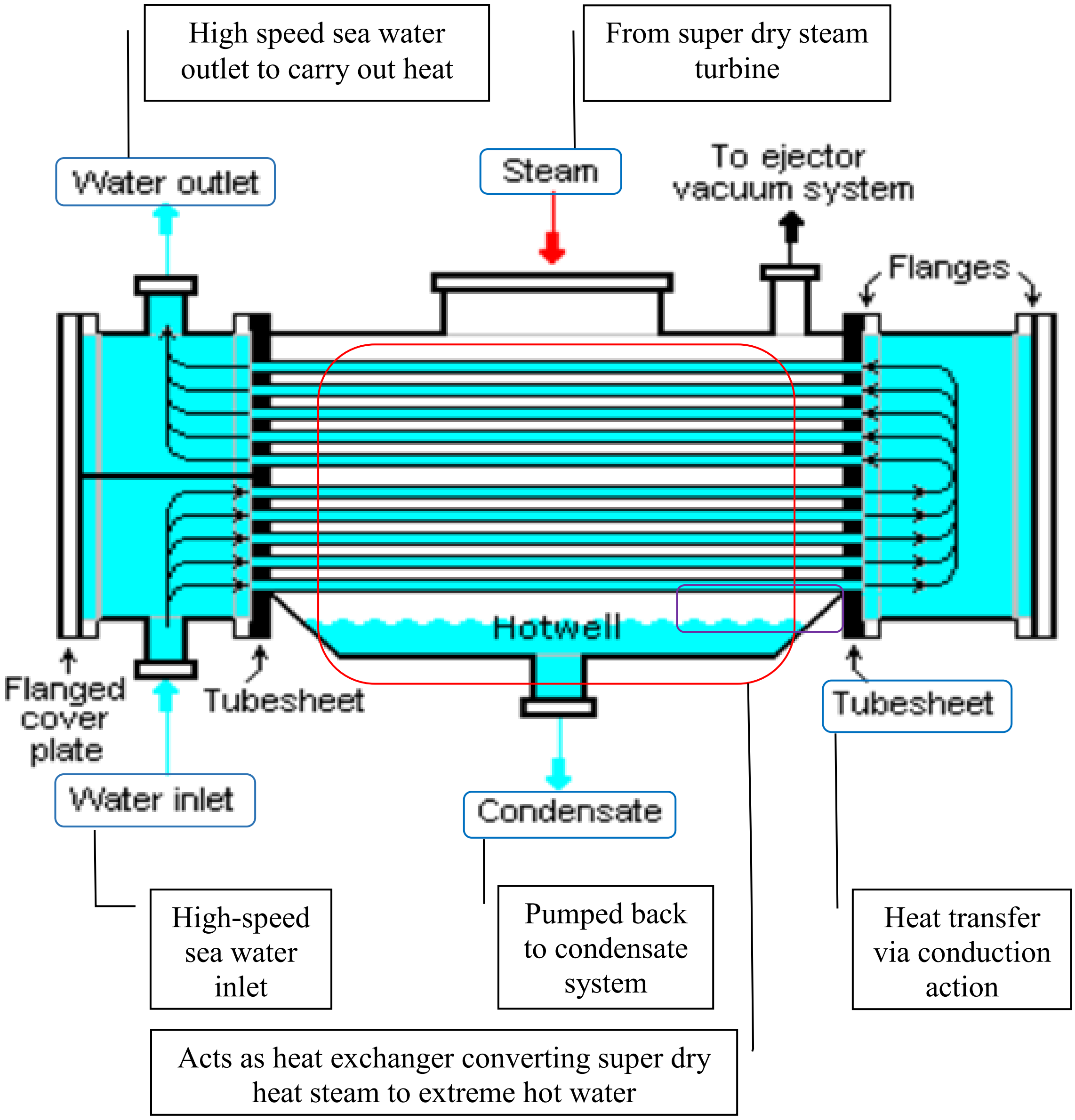


Figure 6.4 Heat Exchanger of Power Station Condenser. (Surface Condenser Image Courtesy of Wikipedia, 2017)

(c) Surface condenser (Torres and Bevia, 2012)

Figure 6.4 is a typical surface condenser (Wikipedia, 2017). High-speed sea water, as marked by the green box, passes through a series of long specially designed tubes, as marked by the purple box. This reduces heat and converts steam from a gaseous to a liquid state at a pressure below atmospheric pressure, as marked in the brown box. This action causes significant heat loss, as marked by the red box. This heat is either from a super heat dry stream from a boiler or extreme hot water at the bottom of the condenser (shown in the red box of Figure 6.4); this is sufficient to raise the kiln temperature for the chemical reaction of making cement. Careful design of heat transfer and heat conduction with superheated steam or superheated water for the chemical reaction in the kiln is next generation cement production. A new production process will be expected in cement production and there will be a re-design of boiler heat loss and gain systems when new coal-fired power stations are built.

(d) Wind and solar energy (Gabel and Tillman, 2005; Chan et al., 2011)

These are renewable energies and have a smaller carbon footprint for power generation (Australian Bureau of Statistics 2014). The future cement plant, as shown in Figure 6.1, will be one of the alternatives for providing electricity for the electrolysis process, lighting, security systems, radio system, and pumping system and so on. This plant is considered to use green energy because it acts as an auxiliary power to provide main or backup power to the chlorine plant.

(e) Silos

Temporary storage of limestone, sand, clay, slag, fly ash, sodium hydroxide solution, sodium silicate solution and so on, is as shown in Figures 6.1 and 6.2. The size of the silos depends on the cement factory’s capability.

(f) Quarry sites

The major quarry sites are North Queensland. This is because the area has a rich brown coal reserve. The distance from quarry sites to cement plants is less than 200km for Company A (Google Maps, 2016). Therefore, this saves times and money in transport and reduces carbon dioxides emission. Additionally, coal-fired power stations and steel refinery factories are in the same part of Queensland, and their by-products, such as fly ash, slag, and so on, are the major elements to make fly ash geopolymer cement. This is one of the solutions to reduce transport and administration costs, as well as supplementary cementitious materials costs.

(g) Transport

This factory uses mass transport such as trains, ships and so on, to deliver bulk cement or quarry products. Such transport will reduce the carbon dioxide footprint (Australian Bureau of Statistics, 2015) as well.

Although this future plant is designed for a location in the northern part of Queensland, this concept plant is also suitable for Western Australia because of its rich coal and mineral areas (USGS, 2012).

The conclusion of evaluating ordinary Portland cement, ordinary Portland cement with supplementary material and fly ash based geopolymer cement production issues, based on Chapters 4 and 5, is that production costs of fly ash geopolymer cement are relatively higher than for ordinary Portland cement in materials costs. It also emits less carbon dioxide in production, slows down abiotic depletion and uses less energy. One of the solutions is to shift fly ash based geopolymer cement production as close as possible to coal-fired power stations. Because coal-fired power stations produce solid waste such as fly ash, bottom fly ash, sodium hydroxide and so on, they have the raw materials on hand to make fly ash based geopolymer. This is a very reliable feedstock and, importantly, the two industries can benefit each other. Upstream coal-fired power stations generate electricity and consequently produce a lot of waste products such as fly ash, sodium hydroxide, waste heat and so on, but these kinds of waste products are useful materials for downstream ordinary Portland cement and supplementary cementitious (slag and fly ash) materials factories and for fly ash based geopolymer cement factories. This would save raw material costs, in fly ash costs and delivery costs. The most efficient way to deliver these raw materials from quarry sites to cement plant and fly ash based geopolymer plant, is if they are located within one kilometre (Chan and Yung, 2008) because longer raw materials handling systems are very expensive and easily break down. This can affect cement production.

CHAPTER 6 CONCLUSIONS

Driving down energy costs, abiotic depletion consumption (coal) and supplementary cementitious materials consumption (slag), one of the solutions is to provide waste heat to ordinary Portland cement factories and fly ash based geopolymer factories, located close to a coal-fired power station or iron ore (slag) refinery plant. This system can use waste heat instead of the energy intensive kiln process, saving energy costs. Because the sources of energy for the kiln are coal, diesel oil and so on, to elevate temperatures from room temperature to 1400°C for the chemical reaction to produce cement, this process emits a lot of carbon dioxide, as discussed in Figure 6.4. However, facing this challenge, a re-design of auxiliary power systems, including high pressure heaters, lower pressure heaters and a condenser is an important issue to provide sufficient waste heat to the advanced integrated cement plant. The total investment cost of re-designing the auxiliary system will depend on the future capability of the ordinary Portland cement and fly ash based cement plants, such as one million tonnes of fly ash based geopolymer cement plant for each year for each plant and five million tonnes of ordinary Portland cement plant per year, etc.

Additionally, this waste heat could be used to turn limestone to lime. Lime is not limited to use in the cement industry but is also used by the building and medical industries, depending the purity of lime.

A future advanced integrated ordinary Portland cement and fly ash based geopolymer plant, as shown in Figure 6.1 to 6.2, can produce cheaper cement because costs, including raw material costs and energy costs, are significantly lower than with traditional feedstock. This could be expected to improve overseas cement market share as well. Maximising the profit of cement products, minimising abiotic depletion and producing less carbon dioxide emission, using a just-in-time (Chan and Yung, 2008) manufacturing method and time-to-market (Chan and Yung, 2008), are not just theoretical methods in an optimal sustainable production.

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APPENDICES

APPENDIX A DATA COLLECTION QUESTIONAIRE

Your participation will involve completion of a questionnaire that will take approximately one hour. The questionnaire related to the following topics:

- How many together of cement that you produce annually?
- The amount of electricity and fuel would be used in the cement manufacture?
- The average operations cost for cement manufacture?
- The amount of carbon dioxide would be expected to emit in production cement processes?
- The percentage of raw materials that you are imported?
- What types of fuel would be using for producing Portland and geopolymer cement?
- What kinds of vessels would be delivering from quarry-to-factory and factory-to-subsidiary factory site?
- Cement facilities specifications and operational data including machine cost and labour cost of producing ordinary Portland cement and fly ash based geopolymer cement.

Your participation in this project is voluntary. If you do not wish to take part, you are not obliged to. If you decide to take part and later change your mind, you are free to withdraw from the project at any stage. Please note, that if you wish to withdraw from the project after you have submitted your responses, the Research Team are unable to remove your data from the project (unless identifiable information has been collected). If you do wish to withdraw from this project, please contact the Research Team (contact details at the top of this form).

Your decision whether you take part, do not take part, or to take part and then withdraw, will in no way impact your current or future relationship with the University of Southern Queensland.

Thank you for your anticipation

Yours Sincerely,

Chi-Shing **CHAN**
PhD Candidate

APPENDIX B MATERIAL COST DATA COLLECTION E-SURVEY

COVER LETTER FOR e-SURVEY

TO WHOM IT MAY CONCERN

Dear Sir,

Thank you for taking some time to participate in this survey. The aim of this survey is data collection for Doctor of Philosophy research study ‘an Evaluation of Cement Manufacture Options for Sustainable Infrastructure.’ The data collection for survey is divided into three parts.

- Part A - raw materials consumption and cost for cement manufacture per year for your companies.
- Part B - energy and fuel types’ consumption cost per year for your company.
- Part C - plant operation including labour cost and machines cost etc.

Please complete the appropriate box of each question. Based on you gave me the data and information that I will be able to analyse, calculate and validate my proposed framework. Further, the information you provide will be kept in completely confidential and used for academic purposes. Individual information will not be identified. This survey has been approved by Human Ethics Research committee of The University of Southern Queensland.

Thank you for your anticipation

Yours Sincerely,

Chi-Shing **CHAN**
PhD Candidate

APPENDIX B

SURVEY QUESTIONS - PART A

1. **What quantity of ordinary Portland cement do you produce each year?**

   ☐ less than 1 million tonnes
   ☐ between 1 and 2 million tonnes
   ☐ above 3 but less than 9 million tonnes
   ☐ other

2. **What quantity of geopolymer cement do you produce each year?**

   ☐ less than 5 million tonnes
   ☐ between 5 and 10 million tonnes
   ☐ greater than 10 million, but less than 20 million tonnes
   ☐ other

3. **What quantity of fly ash do you use each year?**

   ☐ less than 2 million tonnes
   ☐ between 2 and 5 million tonnes
   ☐ above 5 million but less than 8 million tonnes
   ☐ other

4. **What quantity of limestone do you use each year?**

   ☐ less than 2 million tonnes
   ☐ between and 4 million tonnes
   ☐ above 4 million but less than 6 million tonnes
   ☐ other

5. **What quantity of lime do you use each year?**

   ☐ less than 2 million tonnes
   ☐ between 2 and 3 million tonnes
   ☐ above 3 million but less than 4 million tonnes
   ☐ other

6. What quantity of clay do you use each year?

☐ less than 2 million tonnes
☐ between 2 and 4 million tonnes
☐ above 4 million but less than 6 million tonnes
☐ other

7. What quantity of gypsum do you use each year?

☐ 1 million tonnes
☐ above 1 but less than 2 million tonnes
☐ above 2 but less than 3 million tonnes
☐ other

8. What quantity of Sodium hydroxide (NaOH) do you use each year?

☐ 1 million tonnes
☐ above 1 but less than 2 million tonnes
☐ above 2 but less than 3 million tonnes
☐ other

9. What quantity of slag do you use each year?

☐ 2 million tonnes
☐ above 2 but less than 3 million tonnes
☐ above 3 but less than 4 million tonnes
☐ other

10. What quantity of fly ash do you use each year?

☐ 1 million tonnes
☐ above 1 but less than 2 million tonnes
☐ above 2 but less than 3 million tonnes
☐ other

11. What quantity of potassium hydroxide do you use each year?

☐ less than 1 million tonnes

☐ above 1 but less than 2 million tonnes

☐ above 2 but less than 3 million tonnes

☐ other

12. What quantity of Metakaolin do you use each year?

☐ 2 million tonnes

☐ above 2 but less than 3 million tonnes

☐ above 3 but less than 5 million tonnes

☐ other

13. What quantity of supplementary cementitious material do you use each year?

☐ 2 million tonnes

☐ above 2 but less than 3 million tonnes

☐ above 3 but less than 5 million tonnes

☐ other

14. What is the price of fly ash?

☐ below A$50 per tonnes

☐ above A$50 but less than A$80 per tonnes

☐ above A$80 but less than A$100 per tonnes

☐ other

15. What is the price of gypsum?

☐ below A$40 per tonne

☐ above A$40 but less than A$60 per tonnes

☐ above A$60 but less than A$80 per tonnes

☐ other

16. What is the price of Sodium hydroxide (NaOH)?

- ☐ below A$30 per tonne
- ☐ above A$30 but less than A$50 per tonne
- ☐ above A$50 but less than A$80 per tonne
- ☐ other

17. What is the price of sand?

- ☐ below A$10 per tonne
- ☐ above A$10 but less than A$20
- ☐ above A$20 but less than A$30 per tonne
- ☐ other

18. What is the price of clay?

- ☐ below A$20 per tonne
- ☐ above A$20 but less than A$30 per tonne
- ☐ above A$30 but less than A$40 per tonne
- ☐ other

19. What is the price of slag?

- ☐ below A$100 per tonne
- ☐ above A$100 but less than A$120
- ☐ above A$120 but less than A$140 per tonne
- ☐ other

20. What is the price of KOH?

- ☐ below A$50 per tonne
- ☐ above A$50 but less than A$60 per tonne
- ☐ above A$60 but less than A$70 per tonne
- ☐ other

21. What is the price of metakaolin?

☐ below A$ 80 per tonne

☐ above A$80 but less than A$100 per tonne

☐ above A$100 but less than A$120 per tonne

☐ other

---

22. What is the price of supplementary cementitious materials?

☐ below A$ 80 per tonne

☐ above A$80 but less than A$100 per tonne

☐ above A$100 but less than A$120 per tonne

☐ other

---

23. What kind of transport your company commonly use to deliver raw materials to client?

☐ by ship

☐ by air

☐ by dump vessels

☐ other

---

24. What is the average distance of total delivery raw materials?

☐ by ship ____ Km

☐ by air ____ Km

☐ by heavy truck ______________________________________ Km

☐ by railway ____ Km

☐ other ____ Km

---

25. What is the average price of transport per kilometre?

☐ below A$2 per tonne

☐ above A$3 but less than A$5 per tonne

☐ above A$5 but less than A$10 per tonne

☐ above A$15 per tonne

☐ other

26. What types of fuel they use?

☐ petrol

☐ diesel

☐ electricity

☐ other

27. What is the average fuel price?

☐ petrol A$______________________________

☐ diesel A$______________________________

☐ electricity A$______________________________

☐ others A$______________________________

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SURVEY QUESTIONS - PART B

28. How many together of energy do you use each year?

☐ 1 to 2 gigawatts

☐ above 2 but less than 3 gigawatts

☐ above 3 but less than 4 gigawatts

☐ other

---

29. How many together of fuel do you use each year?

☐ petrol ____ tonnes

☐ diesel ____ tonnes

☐ LPG ____ tonnes

☐ coal ____ tonnes

☐ other ____ tonnes

SURVEY QUESTIONS - PART C

30. How many together of direct labour cost of cement manufacture each year?

☐ 10 to 20 labours
☐ above 20 to less than 30
☐ above 30 but less than 50
☐ other

---

31. How many together of indirect labour hour of cement manufacture each year?

☐ 10 to 20 labours
☐ above 20 to less than 30
☐ less than 30 but less than 50
☐ other

---

32. How many wet type kiln machines do you used for cement manufacture used and their capability each year?

☐ none but only grinding process its capability____

☐ 1 to 2 and their capability____

☐ other

33. How many together of dry type kiln machines do you use for cement manufacture used and their capability each year?

☐ none but only grinding process and its capability________________________

☐ 1 to 2 and their capability____

☐ other

____

34. How many together of pre-heater machines do you use for cement manufacture used and their capability each year?

☐ none but only grinding process and its capability________________________

☐ 1 to 2 and their capability____

☐ other

____

35. How many together of milling machines do you use for cement manufacture used and what is their capability each year?

☐ none but only grinding process its capability__________________________

☐ 1 to 2 and their capability____

☐ other

____

36. How much of carbon dioxide emission?

____ **tonne/CO_2**

APPENDIX C THEORETICAL CALCULATION

C.1 CALCULATED ENERGY CONSUMPTION OF PRODUCING 1 KILOGRAM SODIUM HYDROXIDE AND CHLORINE

Sodium hydroxide (NaOH) is the by-product of produced chlorine gases and hydrogen through an electrolysis cell process of aqueous brine. The operation process is an electrolysis cell that produces chlorine from brine operating at 4.5V with a current of 3.0 *105. It is necessary to calculate the number of kilowatt hours of energy required to produce one kilogram of chlorine gas and sodium hydroxide (NaOH). This is because sodium hydroxide (NaOH) is one the parts of constitution of fly ash based geopolymer cement.

Since 1 joule = 1 watt * second = 1 volt * coulombs …………… (C1)

A kilowatt hour is the expenditure of 1000W for 1 hour.

$$(1000w)(1h)\left(\frac{3000s}{h}\right)\left(\frac{1J/s}{W}\right) = 3.60*10^6\, J/Kwh \qquad \text{……………} \quad \text{(C2)}$$

The reaction providing chlorine gas is

$$2Cl^-(aq) \rightarrow Cl_2(g) + 2e^-$$

- To produce 1 kilogram of Cl_2

$$1.00*10^3 g*\left(\frac{1mol.Cl_2}{79.1g}\right)\left(\frac{2mol.}{1mol.Cl_2}\right)\left(\frac{9.65*10^4}{1mole}C\right) = 2.72*10^6 C \qquad \text{……} \quad \text{(C3)}$$

Substitution into equation (C1) into energy formula and as obtained:

$$Energy(J) = (4.6V)(2.72*10^6 C) = 1.3*10^7 J \qquad \text{……………} \quad \text{(C4)}$$

Substitution equations (C4) into equation (C2) as obtained:

$$\text{The power required} = 1.3*10^7 * \left(\frac{1kwh}{3.6*10^6 J}\right) = 3.5kwh \qquad \text{……………} \quad \text{(C5)}$$

- *To produce 1 kilogram of sodium hydroxide (NaOH)*

$$1*10^3 g*\left(\frac{1mol.NaOH.}{39.979g}\right)\left(\frac{1}{1mol.NaOH}\right)\left(\frac{9.65*10^4}{1mol.C}\right) = 2.41*10^6 C \qquad \text{……} \quad \text{(C6)}$$

Substitution equation (C2) into energy formula and as obtained:

$$Energy(J) = (4.6V)(2.41*10^6) = 11.086*10^6 J \quad \text{..............} \quad (C7)$$

$$\text{Total power required} = 11.086*10^6 J*\left(\frac{1kwh}{3.6*10^6 J}\right) = 3.479kwh \quad \text{......} \quad (C8)$$

Based on Equation (C8) outcome, 3.5KWh can produce 1 kilogram of sodium hydroxide (NaOH) liquid and chlorine gas in the electrolysis process.

C.2 CALCULATED HEAT DECOMPOSITE CALCIUM CARBONATE INTO CALCIUM OXIDE AND CARBON DIOXIDE

Based on Hess's Law given, enthalpy change for reaction = ΔH^o_{rxn}

$$\sum[\Delta H^0_f(products)] - \sum[\Delta H^0_j(reactants)] \quad \text{..............} \quad (C9)$$

Substitution values from Table 3.2 into equations (C9) and is obtained:

$$\Delta H^0_{rxn} = \Delta H^0_f[CaO(s)] + \Delta H^0_f[CO_2(g)] - \Delta H^0_f[CaCO_3(s)]$$

$$= 1mol(-635.1KJ/mol) + 1mol(-393.5KJ/mol) - 1mol(1206.9KJ/mol)$$

$$= 178.3\text{kJ} \quad \text{..............} \quad (C10)$$

Based on the above outcome, the decomposition of limestone to lime and CO_2 is endothermic; energy is required to carry out the process.

C.3 CALCULATED CO_2 EMISSION IN PREPARING SODIUM HYDROXIDE AND LIMESTONE

This study has identified that preparing lime from limestone and sodium hydroxide from an electrolysis process emits large quantities of carbon dioxide, based on the Carbon Dioxide Emission Equivalent (CO_2-e) method as below:

- Calculation of CO_2-e in preparing 0.141 kilogram of calcium oxide (CaO) from calcium carbonate ($CaCO_3$) based on equations (2) and (3) and setting the cost is 1 of producing 1 kilogram of OPC.

$$CO_2 - e = (0.141*[(1.35*1) + (1.54*1)] = 0.4075 \text{ kg } CO_2\text{-e/kg} \quad \text{......} \quad (C11)$$

- Calculation of $CO_{2\text{-}e}$ in preparing 0.11 kilogram of sodium hydroxide (NaOH) and setting all costs are equal to 1.

$$CO_2 - e = 0.11 * 1.35 * 1 = 0.14985 \text{ kg } CO_2\text{-e/kg} \qquad \ldots\ldots \quad (C12)$$

Based on the equation (C12), the CO_2-e for calcium oxide (CaO), is one of the raw materials for ordinary Portland cement production and emits 0.40775 kg CO_2-e/kg and 0.14985 kg CO_2-e/kg for preparing sodium hydroxide (NaOH), which is a major raw material for fly ash based geopolymer manufacturing. In a comparison of ordinary Portland cement and fly ash based geopolymer processes, ordinary Portland cement production emits more carbon dioxide than fly ash based geopolymer manufacturing.

C.4 ENERGY CONSUMPTION IN MILLING AND GRINDING PROCESSES FOR CEMENT PRODUCTION

Atmaca and Kanoglu (2012) identified milling specifications, as shown in Table C4.1. To grind 1 kilogram of raw material requires 3250KW, because it is base-load and takes one hour of milling. This type of grinding machine (Company A, 2015) was used in one the cement companies. The other two cement manufacturers used any type of production facility.

Table C4.1 General Specification of Raw Milling (Atmaca and Kanoglu, 2012)

Model	**Inside diameter (mm)**	**Length (mm)**	**Rotate speed (rev/min)**	**Ball charge capability (tonnes)**	**Processing capability (Tonnes/hours)**	**Power (KW)**
Humboldt	4230	10.95	15.9	125	160	3250

APPENDIX D: CLASSICAL VERTICAL MILL

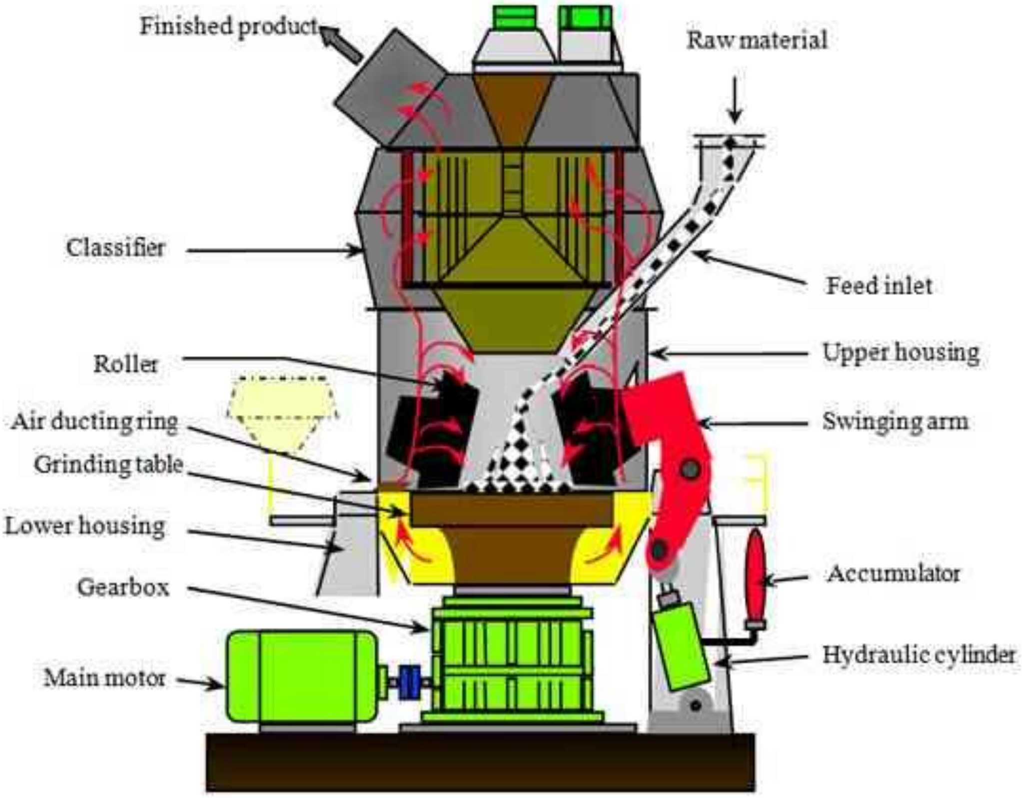


Figure D.1 The Classical Vertical Roller Mill Diagram for Coarse or Fine Grinding of Raw and Semi-Raw Materials in Typical Cement Plant (Image Courtesy of Ciros Mining Equipment, 2016)

This mill (Figure D.1) is composed of a separator, roll grinder, grinder, pressure device, reducer, motor, shell and other components. The separator is an important component for ensuring product fineness; it consists of the drive system, rotor, guide vanes, a shell, a coarse powder blanking cone outlet, etc. The grinding roller is the main component that compacts and crushes the material, and is composed of the roller sleeve and roll heart, axle and bearing, and roller bracket, etc. Each friction has 2-4 grinding rollers. A grinding disc is fixed on the reducer shaft, driven by the speed reducer-rotating disc (Source: Great Wall, 2016).

APPENDIX E: TYPICAL BURNER SYSTEM FOR KILN

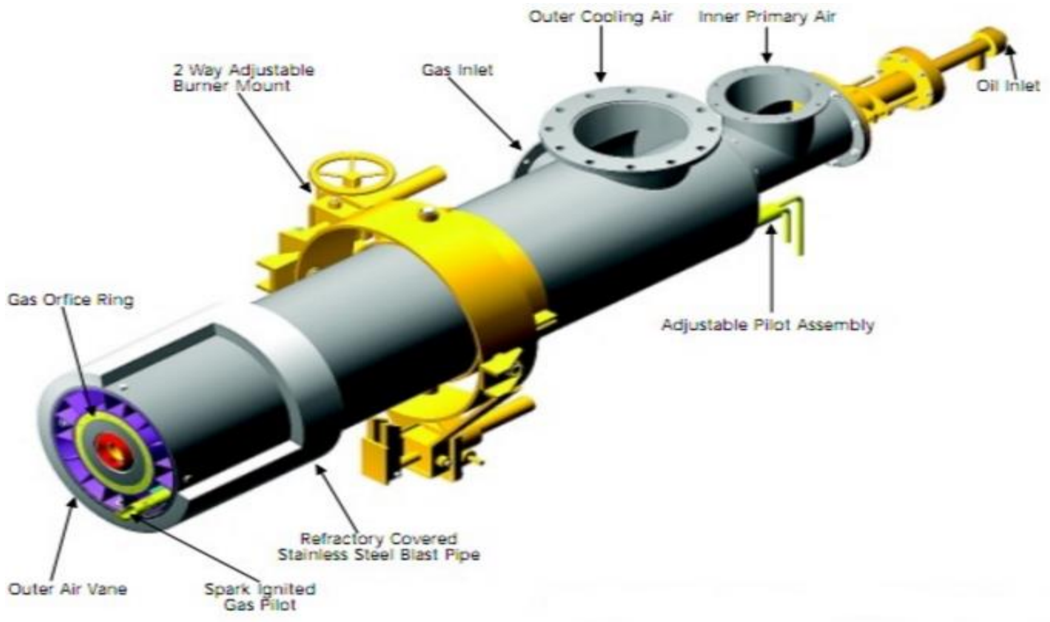


Figure E.1 Typical Burner System for Kiln (Image Courtesy of Gold Mining Equipment, 2016)

Figure E.1 is the combustion system, which is a key element in the efficient thermal processing of ores, minerals, and similar bulk solids in a rotary kiln. The process requirements are stringent in a variety of thermal processing systems such as in cement-making, limestone calcining, recovery of lime in pulp mills, and the combustion of waste, to name a few. The burner system is an important and integral component of a rotary kiln system to optimise the combustion of fuels to release heat in the kiln.

APPENDIX F: TYPICAL BURNER FLAME PROPAGATION SYSTEM FOR KILN

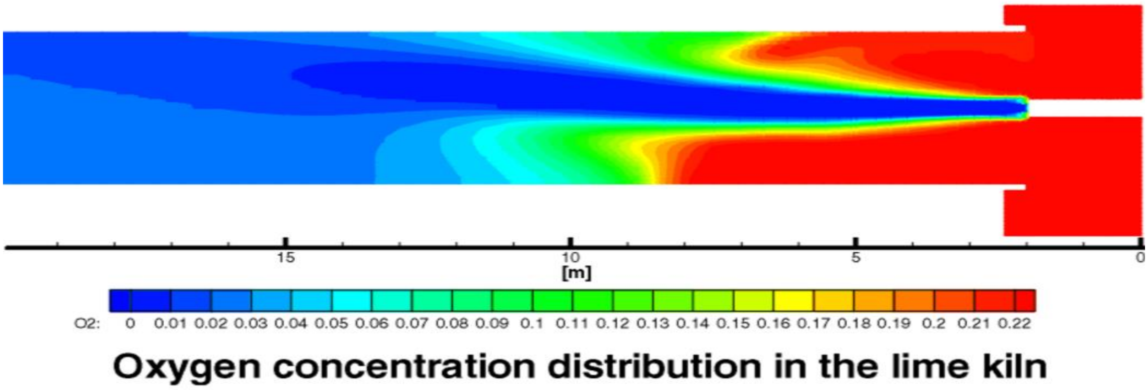


Figure F.1 Flame Propagation within Kiln (Image Courtesy of Cement Kiln, 2016)

Figure F.1 shows the flame propagation performance of oxygen concentration distribution in the lime kiln manufacturing process. The red colour in the diagram represents a high concentration of oxygen and blue represents less oxygen distribution. This means that the time and heat control of preparing lime is a key factor of the chemical reaction speed performances in kiln processes. Additionally, nearly all processes use automatic control ensuring computerisation of cement production in the modern cement plant. This can also guarantee the cement quality, fuel consumption, including diesel oil and coal, and finish time. It also provides as primary data the amount of carbon dioxide that it theoretically emits in each batch of production, based on the Australian National Greenhouse Accounts Factors (2014 to 2016) method. Refer also to Figure E.1. and Figure 2.3.

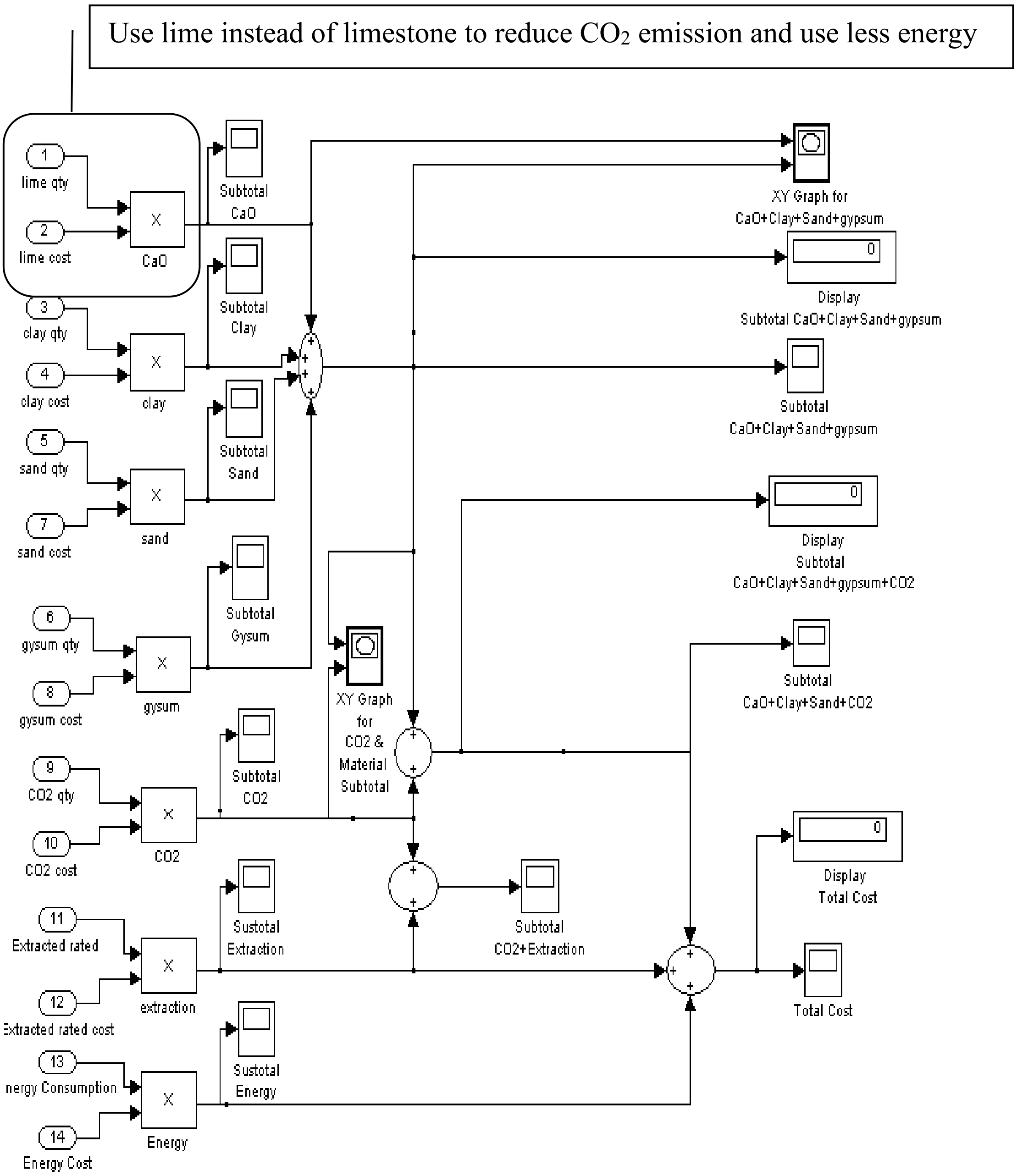
APPENDIX G SIMULATION MODEL USING MATLAB®

G.1 SIMULATION MODEL FOR ORDINARY PORTLAND CEMENT WITH LIME

This study provides three sets of tests for the simulation model and validates the proposed framework as listed below:

- Provides one of tonne of ordinary Portland cement with limestone, clay, sand and gypsum with respect to their financial effect and natural resources depletion. All data are from literature and Australian Bureau of Statistics.
- Provides sustainable ordinary Portland cement limestone, clay, sand and gypsum with respect to the financial effect and natural resources depletion. All data are from literature and Australian Bureau of Statistics websites and well-known procurement websites.
- Provides sustainable ordinary Portland cement lime, clay, sand and gypsum with respect to the financial effect and natural resources depletion. All data are from literature and Australian Bureau of Statistics websites and well-known procurement websites.
- Provides sustainable ordinary Portland cement limestone, clay, sand and gypsum with respect to the financial effect and natural resources depletion. All data are from case studies.
- Provides sustainable ordinary Portland cement including lime, clay, sand and gypsum with respect to the financial effect and natural resources depletion. All data are from case studies.
- Provides sustainable ordinary Portland cement including limestone, clay, sand and gypsum with respect to the financial effect and natural resources depletion. All data are from case studies.
- Provides sustainable ordinary Portland cement including lime, clay, sand and gypsum with respect to the financial effect and natural resources depletion. All data are from case studies.

Based on the above outcomes, this study can compare which areas have an opportunity for improvement.



Use lime instead of limestone to reduce CO_2 emission and use less energy

Figure G.1 Using Matlab® to Develop Lime and Limestone in Cement Production Simulation

APPENDIX G

G.1.1 RESULTS

All data are from literature, the Australian Bureau of Statistics (2014 to 2016) and well-known procurement websites.

- To provide one tonne of ordinary Portland cement, it needs 1.41kg limestone, 1.41kg clay, 0.5kg sand and 0.05kg gypsum raw materials for a series of cement production.
- The results of each entity are illustrated in Figures D.7 to D.11. The linear analysis of total costs is shown in Figure D.12, ensuring all entities and analysis methods inside the simulation model are workable. Using various data further validated the proposed simulation and framework. The sensitivity analysis is based on the outcome.

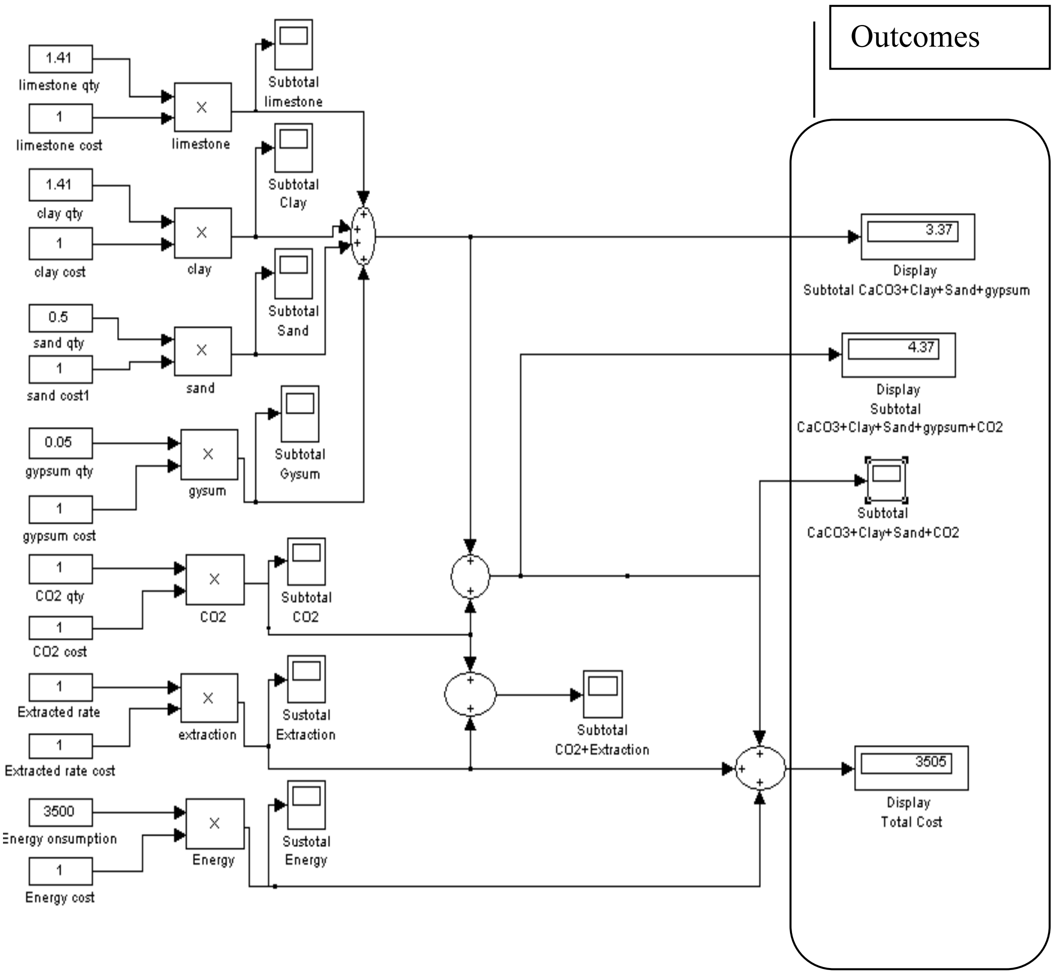


Figure G.2 Using Matlab® to Develop Cost Simulation of Cement Production

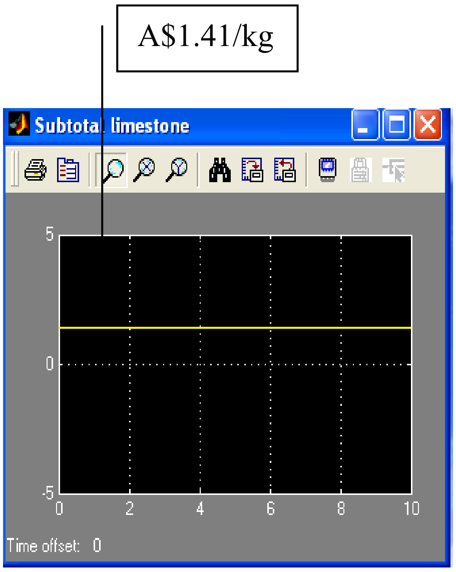


Figure G.3 Result of the $CaCO_3$ Subtotal Cost

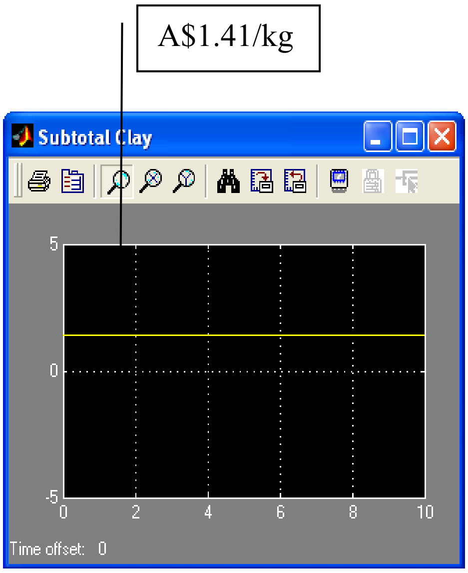


Figure G.4 Result of the Clay Cost Subtotal Cost

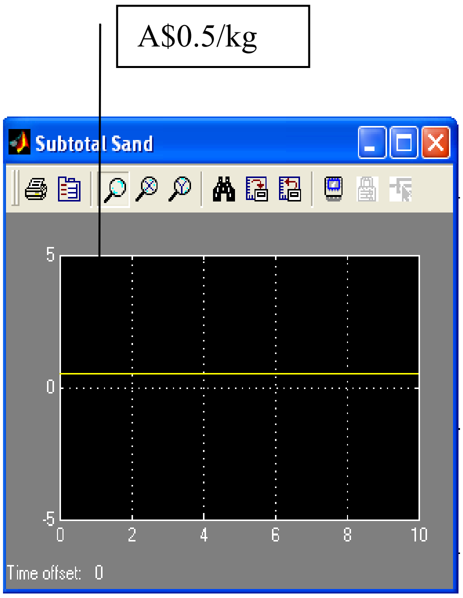


Figure G.5 Result of the Sand Subtotal Cost

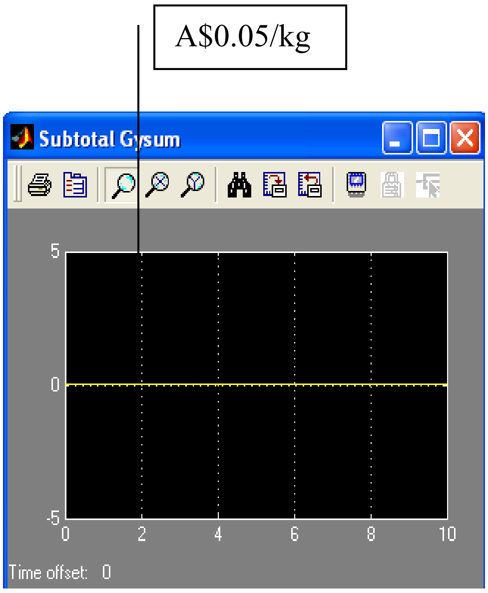


Figure G.6 Result of the Gypsum Subtotal Cost

APPENDIX G

The individual materials processing subtotal costs are shown in Figures 4.3 to 4.6. Those costs were calculated from quantities of individual material multiplied by unit cost. All data are from well-known and reliable procurement websites. This study collects data for 4 quarters per year. These sets of data were from the first quarter of 2015.

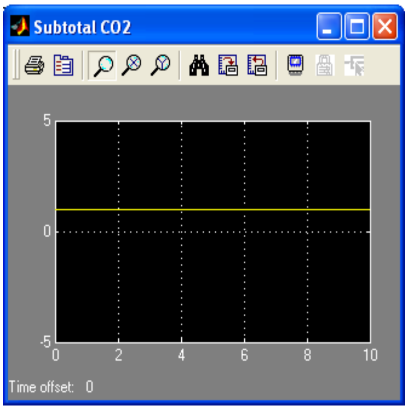


Figure G.7 Subtotal Cost for CO_2 Emission in Extraction Process

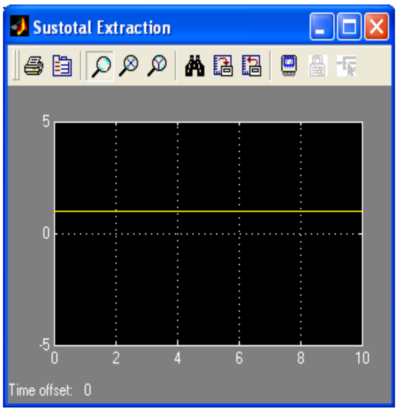


Figure G.8 Subtotal Cost for $CaCO_3$ and Clay Processes

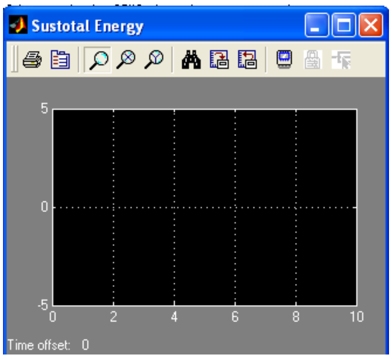


Figure G.9 Subtotal Cost for Energy and Extraction Processes

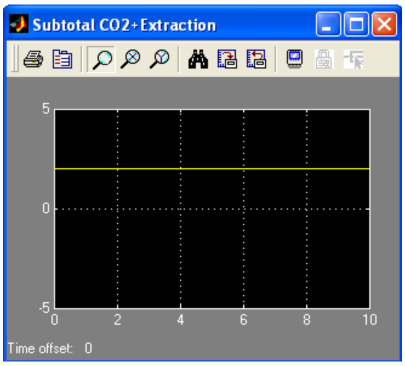


Figure G.10 Subtotal Cost for CO_2 in Cement Production

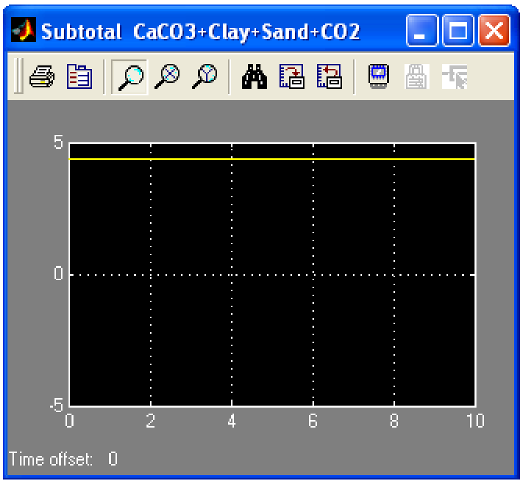
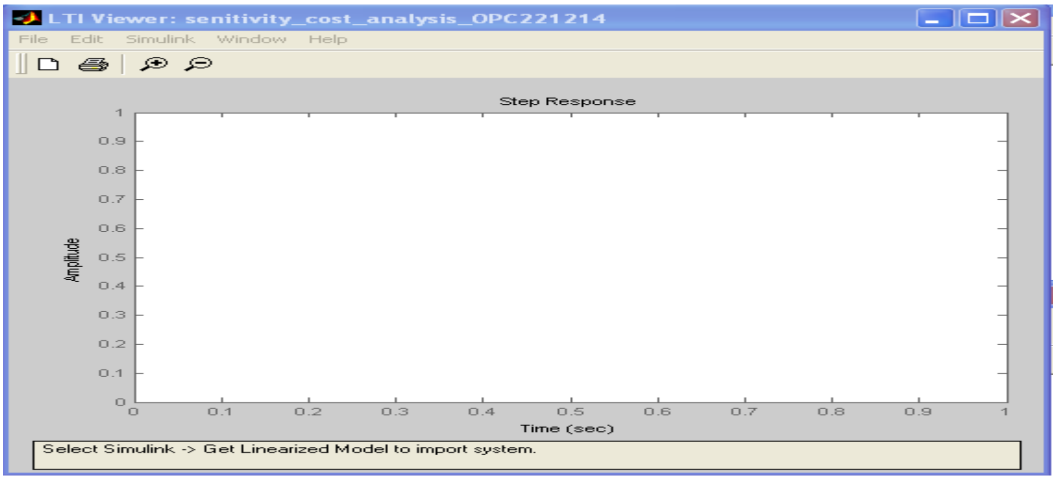


Figure G.11 Subtotal Cost for CaCO3,
Clay and CO_2 in Cement Production



Select Simulink -> Get Linearized Model to import system.

Figure G.12 Simulation of Total Cost in Cement Production Using Matlab®

Figure G.12 also investigates the cost relationship of calcium carbonate ($CaCO_3$), CO_2 and clay to provide the spaces for the sensitivity study in the next section. For example, linear programming could be shifted upward or downward in case of any data parameter changes. Optimal solutions with sustainable measures of infrastructure that met green development issues were found early on.

This study identified function and 11 constraints in the above sections. This research uses spreadsheet-based methods and Matlab-based methods to find the optimal solution for the product mix of geopolymer-based cement, and compares their advantages and disadvantages.

(a) Matlab-based model solving linear programming solver: In the Matlab, there is an Optimisation Toolbox which provides functions for finding parameters that minimise or maximise objectives while satisfying constraints.
(b) Spreadsheet-based (Excel®) model using Solver Parameter V7. All inequality equations are grouped into Excel formats.

G.2 MATLAB® BASED METHOD AND RESULTS

The Matlab-based method is an alternative method to solve the linear programming equation by using the Problems Handle by Optimisation Toolbox Functions. This study illustrates how to solve 3 to 6 matrices with several unknowns at the same time as below:

Let C = A * B or B = A/C …………… (G.1)

Calculate the optimal solution Using Matlab® and rewritten as below:

A = [10 10 10; 50 50 50; 200 0 0; 0 180 0; 0 0 250; 30 30 30]
C = [380 350 359]
C = A*B
B = A/C

Using Matlab® to computing the solution as obtained:

B = [0 0 1.900 1.9444 1.436 0] …………… (G.2)

This calculation method provides an alternative approach to solve linear programming equation multiple unknowns in multiple equations.

APPENDIX H HESS'S LAW

H.1 ENERGY CALCULATION IN CEMENT PRODUCTION

- Hess's Law is a method to calculate energy consumed using changing entropy and enthalpy approaches. Hess's Law (the changes of enthalpy, which is the sum of the internal energy plus the product of the pressure of the gas and its volume in the system of enthalpy change for reaction is obtained:

Enthalpy change for reaction = ΔH^{o}_{rxn}

$$= \sum[\Delta H^{0}_{f}(products)] - \sum[\Delta H^{0}_{j}(reactants)] \qquad \text{..............} \quad (H.1)$$

Change of entropy, ΔS of the system is expressed:

$$\Delta S = \frac{Q}{T} \qquad \text{..............} \quad (H.2)$$

where

ΔS is changed of entropy and H is the enthalpy

Hess's Law an ideal theory which states that if a reaction is the sum of two or more other reactions, the ΔH for the overall process must be the sum of the ΔH values of the constituent reactions. Hess's Law works because enthalpy is the state function, a quantity whose value is determined only by the state of the system. The enthalpy change for a chemical or physical change does not depend on the path someone else chooses from the initial conditions to the final conditions.

APPENDIX I: THERMODYAMICS TABLE RELATED TO $CaCO_3$, CaO and CO_2 AND VARIETY KILN PERFORMANCES

Table I.1 shows extracted part thermodynamic values of known molar enthalpies for calculating energy consumption. Equation (H.1), based on Figure 2.3, is for ordinary Portland cement processes calculation of heat loss and gain, energy consumption in cement production, and the kiln process.

Table I.1 Selected Standard Molar Enthalpies of Formation at 298K (Selected Thermodynamic Values, 2014)

Substance	Standard Molar Enthalpy of Formation (Unit)
$CaCO_3$(s)	-1206.9 (KJ/mol)
CaO(s)	-635.1 (KJ/mol)
CO_2(g)	-393.5 (KJ/mol)

Table I.2 Specific Consumption According to Types of Kiln Process (Hernandez et al., 2014)

Type of Process	Specific Consumption (Kcal/kg of Clinker)
Wet	1250-1400
Semi-wet	1100
Semi-dry	920
Dry	800

APPENDIX J: DAVIDOVITS' PATENT IN MAKING GEOPOLYMER MANUFACTURING PROCEDURES (DAVIDOVIT, 1991)

In one form of this invention, there is provided a solid component activator for use in geopolymer cement comprising a silico-aluminate material which is a mixture of sodium silicate and sodium carbonate for activating the geopolymer cement by increasing reactivity of the silico-aluminate material in the geopolymer cement when forming geopolymer concrete.

The solid component activator of the present invention is stable in the atmosphere, unlike activators such as hygroscopic sodium hydroxide that readily absorb moisture from the atmosphere. Accordingly, the solid component activator can be pre-mixed with silico-aluminate material to create cement and the cement can be stored stably before being transported and/or sold in a ready-for-use dry powder form.

Additionally, the solid component activator does not possess a Dangerous Goods classification. The solid component activator may also yield a product with a similar level of alkalinity to OPC. This provides a safer manufacturing process as well as a safer work environment when the geopolymer cement is used in the preparation or manufacture of concrete.

The sodium silicate of the solid component activator may have a modulus ranging from 1.5-3.3. The modulus in this range improves reactivity of the geopolymer cement.

The sodium carbonate of the solid component activator may have a median particle size ranging from 80 to 500 microns. In one form of the invention, the median particle size ranges from 80 to 200 microns. In another form of the invention, the median particle size ranges from 200 to 300 microns. In a further form of the invention, the median particle size ranges from 300 to 500 microns.

The solid component activator provides a high pH solution when mixed with water or an aqueous solution to activate the silico-aluminate material in the geopolymer cement, thereby increasing the reactivity of the silico-aluminate material (e.g. activating the geopolymer cement) and enabling it to form concrete with desirable or required properties or characteristics.

In another form of the invention, there is provided a geopolymer cement comprising at least one silico-aluminate material, a solid component activator, comprising sodium carbonate and sodium silicate for activating at least one silico-aluminate material for forming a geopolymer concrete.

The silico-aluminate material may comprise any one or a combination of fly ash, pitchstone, blast furnace slag, ground glass or zeolite. Preferably, the silico-aluminate material comprises fly ash and granulated blast-furnace slag.

The geopolymer cement may include mineral additives, such as, for example, limestone to adjust the properties of the cement.

The silico-aluminate material may have a median particle size ranging from 3 to 25 microns. Preferably, the fly ash has a median particle size ranging from 3 to 20 microns. More preferably, the slag has a median particle size ranging from 5 to 20 microns. It was found that using silico-aluminate material with a median particle size range from 3 to 10 microns increases the reactivity of the silico-aluminate material by increasing the surface area to volume ratio of the particles. A fly ash with a median particle size range from 3 to 10 microns also increases the reactivity of the fly ash. It was also found that slag with a median particle size range from 5 to 10 microns increases the early age reactivity of the geopolymer cement and the compressive strength of the geopolymer concrete formed using the geopolymer cement. Preferably, the slag is granulated with a median particle size range from 5 to 10 microns.

The geopolymer cement may further include a retarder comprising either boric acid or salts of boric acid for increasing concrete setting time. Alternatively, the geopolymer cement may further include an accelerator comprising soluble calcium-based material such as hydrated lime, quicklime or Portland cement for reducing concrete setting time.

The solid component activator in the geopolymer cement allows the use of separate retarders or accelerators to control the setting time of the geopolymer cement. The retarders or accelerators may also control the setting time of the concrete made using the geopolymer cement.

In another form of the invention, there is provided a method for preparing a geopolymer cement including the steps of: mixing at least one silico-aluminate material with sodium carbonate; grinding at least one silico-aluminate material and sodium carbonate to a mean particle size ranging from 3 to 15 microns to form a powdered mixture and mixing sodium silicate with the powdered mixture to form the geopolymer cement.

The grinding and mixing processes increase the fineness and homogeneity of the powdered mixture to improve properties including solubility and reactivity when water is added to the powdered mixture. Although sodium silicate can be ground and mixed with other components when preparing the geopolymer cement, it is preferable that the sodium silicate is not ground to avoid exposing the sodium silicate to heat degradation. In this respect, mixing the sodium silicate with the powdered mixture reduces heat degradation of sodium silicate by not exposing the sodium silicate to heat generated during the grinding process. The geopolymer cement may be prepared at a temperature ranging from 10°C to 40°C.

The geopolymer cement may be prepared at ambient temperature without heating. In particularl, the activator comprising sodium silicate and sodium carbonate can be combined at ambient temperature without heating. The method may include a step of adding a retarder to the powdered mixture for increasing concrete setting time. Alternatively, the retarder may be added to the geopolymer cement after mixing sodium silicate with the powdered mixture. The retarder may comprise either boric acid or salts of boric acid.

The method may include a step of adding an accelerator to the powdered mixture for reducing concrete setting time. Alternatively, the accelerator may be added to the geopolymer cement after mixing sodium silicate with the powdered mixture. The accelerator may comprise soluble calcium-based material such as, for example, hydrated lime, quicklime or Portland cement.

In another form of the invention, there is provided a geopolymer concrete comprising at least one silico-aluminate material, a solid component activator comprising sodium carbonate and sodium silicate, an aggregate and water, wherein the water solubilises the solid component activator to form an alkaline environment for activating the silico-aluminate material to bind the silico-aluminate material with the aggregate to form the geopolymer concrete. The alkaline environment requires a pH ranging from 12 to 14 to provide an adequate rate of activation.

The geopolymer concrete may flow at up to 650 mm spread without segregating components of the geopolymer concrete. In another form of the invention, there is provided a method for preparing a geopolymer concrete including the steps of: mixing at least one silico-aluminate material with sodium carbonate; grinding the at least one silico-aluminate material and sodium carbonate to a mean particle size ranging from 3 to 15 microns to form a powdered mixture; mixing sodium silicate with the powdered mixture; and adding water to the sodium silicate and the powdered mixture to form the geopolymer concrete.

The geopolymer concrete produced may have comparable strength properties such as, for example, compressive and tensile strengths, to Portland cement concrete. The geopolymer concrete produced may also have comparable strength properties to geopolymer concrete made using liquid alkali activators.

The method may include a step of adding an aggregate such as gravel and sand to form the geopolymer concrete. Preferably, the aggregate is inert and does not react with water or cement.

The method may include a step of adding a retarder for increasing concrete setting time to the geopolymer concrete, the retarder comprising either boric acid or salts of boric acid. The method may include a step of adding an accelerator for reducing concrete setting time to the geopolymer concrete, the accelerator comprising soluble calcium-based material such as, for example, hydrated lime, quicklime or Portland cement. The step of adding water may provide a flowing geopolymer concrete at up to 650 mm spread without segregating components of the geopolymer concrete.

The method may be carried out at a temperature ranging from 10°C to 40°C to achieve strength growth rates like Portland cement concrete.

The geopolymer concrete may be heated at a temperature ranging from 40°C to 70°C to accelerate strength growth rates. For example, geopolymer concrete heated at 70°C for 4 hours can achieve about 40% maximum compressive strength. In another example, geopolymer concrete heated at 70°C for 12 hours can achieve about 80% maximum compressive strength (Davidovits, 2015).

APPENDIX K: PUBLICATIONS ARISING FROM THIS RESEARCH

Published

1. Chan, C.C.S. and Thorpe, D. (2015). *An Evaluation of Green Contractors Using Fuzzy with Superiority and Inferiority Multiple Criteria Rank Method.* Proceedings of International Conference of Asian Institution of Intelligent Buildings. Hong Kong Chapter.

2. Chan, C.C.S., Thorpe, D. and Islam, M. (2015). *An Evaluation of Life Long Fly Ash Based Geopolymer and Ordinary Portland Cements Costs Using Extended Life Cycle Cost Method in Australia.* Proceedings of International Conference of Industrial Engineering and Engineering Management. Proceedings of International Conference of Industrial Engineering and Engineering Management. IEEE / IEEM. Singapore Chapter.

3. Chan, C.C.S., Thorpe, D. and Islam, M. (2015). *An Evaluation Carbon Footprint in Fly Ash Based Geopolymer and Ordinary Portland Cements Manufacture.* Proceedings of International Conference of Industrial Engineering and Engineering Management. IEEE / IEEM. Singapore Chapter.

In progress

1 Chan, C.C.S. Thorpe, D. and Islam, M. (2017). *Development Geopolymer-based Innovative Product Using Integration Life Cycle Assessment and Simulation Modelling Methods.* Proceedings of International Conference of Industrial Engineering and Engineering Management. IEEM. Singapore Chapter. (Paper No. IEEM 17-P-0419). (Unpublished)