ENERGY INTENSIVE AND TRADE EXPOSED (EITE) PORTLAND CEMENT MANUFACTURING SECTOR: DEVELOPING POLICY AND SUPPORTING MECHANISMS TO MINIMIZE EMISSIONS LEAKAGE

by

Darren Brown

B.Sc., Simon Fraser University, 1999
M.Sc., Royal Roads University, 2009

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

THE COLLEGE OF GRADUATE STUDIES

(Civil Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

(Okanagan)

June 2017

The College of Graduate Studies

The undersigned certify that they have read, and recommend to the College of Graduate Studies for acceptance, a thesis entitled:

ENERGY INTENSIVE AND TRADE EXPOSED (EITE) PORTLAND CEMENT MANUFACTURING SECTOR: DEVELOPING POLICY AND SUPPORTING MECHANISMS TO MINIMIZE EMISSIONS LEAKAGE

submitted by Darren Brown in partial fulfillment of the requirements of the degree of Doctor of Philosophy in Civil Engineering.

Dr. Rehan Sadiq, Faculty of Applied Science, School of Engineering, UBC (Okanagan)

Supervisor, Professor

Dr. Kasun Hewage, Faculty of Applied Science, School of Engineering, UBC (Okanagan)

Supervisory Committee Member, Professor

Dr. Shahria Alam, Faculty of Applied Science, School of Engineering, UBC (Okanagan)

Supervisory Committee Member, Professor

Dr. Eric Li, Faculty of Management, UBC (Okanagan)

University Examiner, Professor

Dr. Leonard Lye, Faculty of Engineering and Applied Science, Memorial University

External Examiner, Professor

June 28, 2017

Date Submitted to Graduate Studies

Abstract

Government intervention to limit and reduce nocuous air emissions from industrial applications focuses on protecting human health and the environment. Unfortunately, energy intensive and trade exposed (EITE) industries in developed countries are susceptible to competitive pressures with their counterparts in jurisdictions that have relaxed compliance requirements, such as emerging markets. Along with the loss of production to the emerging market, the associated air emissions are also displaced. The goal of this research is to develop policy and supporting mechanisms to minimize the leakage of air emissions from trade. The main objectives carried out to support this goal included: identifying a surrogate EITE industry and establishing a baseline air emissions inventory; comparing the environmental performance of the surrogate in the developed and emerging market; and, evaluating policy options and supporting mechanisms.

As an EITE industry the Portland cement manufacturing sector was identified as the industrial surrogate. Life Cycle Impact Assessment (LCIA) methodology was applied to the cement manufacturing sectors in China and Canada for comparative purposes. Nocuous air emissions of oxides of nitrogen (NOx), sulphur dioxide (SO_2), particulate matter (PM) and carbon monoxide (CO) were evaluated in terms of intensity per tonne of Portland cement, and, in respect of their contribution to winter smog. In terms of impact to human respiratory health, using Disability Adjusted Life Years (DALYs), Portland cement produced in China had more than twice the impact of cement produced in Canada.

Using the example of cement exported from China, policy options were devised to manage emissions leakage from Canada. These policy options investigated combinations of open, restricted and closed borders with direct, partial, and no support for domestic manufacturers. Analytic Hierarchy Process (AHP) in conjunction with the three actionable solidarities of Cultural Theory was applied. Results indicated a restricted border with partial support was most strongly favored, and, of the policy mechanisms reviewed, a verification process was supported. Under the *Canadian Environmental Protection Act, 1999* (CEPA) an air quality agreement can be established to include this policy framework between China and Canada. The proposed approach for EITE cement industry can be extended to other industries and international trade.

Lay Summary

The goal of this research is to bring awareness to the unintended impact of domestic legislation that does not consider the global community. Maintaining good air quality is of the utmost importance for the protection of human health and environment. However, when air quality standards are applied to industrial applications to reduce emissions, there is an inherent compliance cost (e.g., purchasing scrubbing technology, using alternate materials, new procedures). This in turn affects the cost of production.

Industries outside of that jurisdiction that are not subject to air quality standards and compliance costs have a competitive advantage. Due to lower pricing, consumers may switch to the non-regulated industry outside of their jurisdiction. On the surface level local air quality may improve, however, emissions are not genuinely reduced, they are simply transferred elsewhere. As such, policy and legislation need to account for this potential in order to genuinely reduce industrial air emissions.

Preface

The information in this thesis was collated and prepared by Darren Brown. Dr. Rehan Sadiq and Dr. Kasun Hewage provided supervision, guidance and feedback in the formation of the research proposal, scientific journal papers, and, this thesis. The majority of content in this thesis originates from submitted or published scientific journal papers.

A version of Chapter 3 has been *published*. Darren Brown was responsible for completing the research, analyzing the data, and preparing the submission. Brown, D., Sadiq, R., Hewage, K. (2014). An overview of air emissions intensities and environmental performance of grey cement manufacturing in Canada. *Clean Technologies and Environmental Policy*, 16(6), 1119-1131.

A version of Chapter 4 has been *accepted*. Darren Brown was responsible for completing the research, analyzing the data, and preparing the submission. Brown, D., Sadiq, R., Hewage, K. (2017). A health-based life cycle impact assessment (LCIA) for cement manufacturing: a comparative study of China and Canada. *Clean Technologies and Environmental Policy*.

A version of Chapter 5 is *under review*. Darren Brown was responsible for completing the research, analyzing the data, and preparing the submission. Brown, D., Sadiq, R., Hewage, K. (2017). Investigating the impacts of plausible Canadian policies and their supporting mechanisms on export-based regional air pollution in China: A case of cement manufacturing. *Environmental Management*.

Chapter 6 is based on conclusions formed during the development and completion of the aforementioned scientific journal papers.

Table of Contents

List of Tables

List of Figures

List of Acronyms

AHP	Analytic Hierarchy Process
APHEA	Agency for Public Health and Education Accreditation
CAA	Clean Air Act
CAC	Cement Association of Canada
CAAQS	Canadian Ambient Air Quality Standards
CEPA	Canadian Environmental Protection Act, 1999
CNAAQS	Chinese National Ambient Air Quality Standards
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_{2e}	Carbon Dioxide Equivalent
CSI	Cement Sustainability Initiative
DALYS	Disability Adjusted Life Years
ECCC	Environment and Climate Change Canada
EEC	European Economic Commission
EITE	Energy Intensive and Trade Exposed
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
EUETS	European Union Emissions Trading Scheme
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
LEED	Leadership in Energy and Environmental Design
MCDA	Multi-criteria Decision Analysis
NAAQS	National Ambient Air Quality Standards
NOx	Oxides of Nitrogen

NPRI	National Pollutant Release Inventory
PAH	Polycyclic Aromatic Hydrocarbon
PCA	Portland Cement Association
PCR	Product Category Rules
PLC	Portland Limestone Cement
PM	Particulate Matter
RGGI	Regional Greenhouse Gas Initiative
SCR	Selective Catalytic Reduction
SNCR	Selective Non-catalytic Reduction
SO_2	Sulphur Dioxide
WBCSD	World Business Council for Sustainable Development
WCI	Western Climate Initiative
WHO	World Health Organization
WTO	World Trade Organization

List of Symbols

A	Air emission
ΔAx^{ext}	Change in air emission externally
ΔAx^{int}	Change in air emission internally
D_{EXP}	Damage from the exporting country product (in DALYs)
D_{IMP}	Damage from the importing country product (in DALYs)
ΔD	Change in damage (in DALYs)
en	Environmental criteria
ec	Economic criteria
g	Group
i	Index of summation
L	Leakage
Lf	Leakage factor
n	Number of groups
P_L	Production leakage
s	Social criteria
S_A	Standard for air emission

Glossary

Air emissions	Polluting gases or particulates released into the atmosphere.
Carbon leakage	Transfer of CO_{2e} emissions to external jurisdictions as a result of domestic climate legislation that increases compliance costs for industry and decreases competitiveness with their counterparts in non-regulated jurisdictions.
EITE industry	Energy intensive (EI) refers to an industry having a high energy input to product output ratio. Trade exposed (TE) indicates the industry does not hold market dominance and is subject to extra-jurisdictional competition.
Emerging market	Refers to the transitional phase of a country becoming developed. This phase is characterized by lower than average per capita income, rapid growth and high volatility.
Emissions leakage	Transfer of emissions to external jurisdictions as a result of domestic air quality legislation that increases compliance costs for industry and decreases competitiveness with their counterparts in non-regulated jurisdictions.
Grey cement	Refers to the most common type of cement manufacturing facility (between grey and white cement).
Portland cement	The most widely produced cement type in the world.
Production leakage	Transfer of production from domestic manufacturers to external manufacturers due to competitive effects.

Acknowledgements

Although this work was completed remotely from the UBC campus, I can personally attest to the validity of John Donne's poem; No Man Is an Island. The faculty and staff at UBC have made the entire process a seamless endeavor.

To my patient supervisor, Dr. Rehan Sadiq, your keen intellect and unflinching support kept me from wandering off the doctoral path in spite of life's tumultuous shifts and turns. To Dr. Kasun Hewage, your astute technical feedback and hearty sense of humour were both much appreciated. Special thanks to my Supervisory Committee for allowing me to move forward with a research idea that was unconventional to the discipline of engineering.

To Michael McSweeney and his team at the Cement Association of Canada, I owe you a debt of gratitude for fulfilling the countless information requests, and, allowing me to fashion my research around an unassuming but incredibly relevant industry.

My family and friends were a source of encouragement and gave me those kind words and pats on the back when I needed them the most, thank you. To William and Lorne, it is my honour to share this with you.

Lastly, but in no way least, to my sweetheart Jaimey. I could question the judgement of God in bringing us together for your sake, but, as your partner in life I am boundlessly blessed. Although completing a doctorate will be an accomplishment, there will be no greater joy for me than when you become my wife, if you'll have me.

for my love, Jaimey

Chapter 1: Introduction

1.1 Background and Problem Formulation

Governments around the world are tasked with developing sound environmental policy to protect and enhance the quality of their local, regional or national ambient air quality. However, prior to developing environmental policy, decision-makers must first ascertain existing air quality conditions, the relative contribution of emission sources, and identify key priorities. Once this initial data gathering and prioritizing is complete the next step is to carry out multi-criteria decision analysis (MCDA) to develop policies and ultimately legislation to effect change.

As an important contributor to air pollution, heavy industry is accessible for policy makers given they are stationary and the emissions typically emanate from concentrated sources (i.e., through stacks) which make them easier to monitor and potentially mitigate. Consequently, many countries require monitoring of air emissions from industrial sources. In Canada, the *Canadian Environmental Protection Act, 1999* (CEPA) requires industrial operations which exceed defined threshold limits, or are directly named, to report total annual air emissions of listed toxic substances through the national pollutant release inventory (NPRI). As a mandated sector, Portland cement manufacturing facilities across Canada report air emissions into NPRI. In Canada, the NPRI program provides a valuable source of data for policy makers. As it pertains to domestic cement manufacturing NPRI data indicates the industry contributes an estimated 1.4% of total (anthropogenic) greenhouse gases (GHGs) and 1% of total air pollutant emissions in Canada (ECCC, 2016).

As with most industrial processes, cement manufacturing generates air emissions. These emissions are produced throughout the life cycle of cement production from quarrying limestone to packaging and transporting the finished product. The largest contributors to air emissions from cement manufacturing are carbon dioxide (CO_2), oxides of nitrogen (NOx), sulphur dioxide (SO_2) and particulate matter (PM) (WBCSD, 2005).

Other substances that may be emitted from cement manufacturing include volatile organic compounds, acid gases, trace metals and organic micro pollutants. However, these other substances are only emitted in trace quantities (WBCSD, 2005).

The national contribution of cement manufacturing to total air emissions may evoke the need for action. However, total emissions can be a misleading determinant of environmental performance. Total emissions provides no indication of the amount of cement consumed relative to other building materials, the strategic need for cement as a component of concrete, or the long-term lifecycle benefits of concrete. Also, total emissions do not provide an accurate gauge of environmental performance of Canadian cement manufacturing in the global context.

It is important to emphasize that cement manufacturing is truly a global industry with manufacturing plants in almost every country. One reason cement manufacturing is global is that the principal raw materials of limestone, clay and shale are common lithologies and are widely distributed in most parts of the world. As well, cement has a relatively low cost per unit weight making ground transportation an expensive externality. These factors, combined with an insatiable demand for concrete in urban development, support the need for domestic production on a global scale. According to the Cement Association of Canada (CAC) the global demand for concrete is second only to that of water (CAC, 2010).

In light of this, and excluding a suitable alternative to cement, total emissions are a poor way to measure the Canadian cement sector's environmental performance or to develop environmental policy. Rather, an intensity-based approach is needed to understand the environmental performance of Canadian cement manufacturing and to gauge performance in the global context. In terms of sustainability emerging markets face greater challenges than developed countries. By virtue of lower cost, the flow of production for many industries, and consumer demand for cost savings, production follows the cost. In emerging markets, energy, labour and transport subsidies make them a prime target for production leakage. Along with production leakage emissions follow. However, in overpopulated countries (like China and India) with already intense production the environmental and health effects may be potentiated.

1.2 Goal and Objectives

The principal goal of this research is to develop a framework for which policy and supporting mechanisms can be derived to minimize emissions leakage from energy intensive and trade exposed (EITE) industries such as the Portland cement manufacturing sector. The specific objectives presented in this thesis include:

1. A critical review and content analysis of the environmental performance of the Canadian Portland cement sector based on the primary air emissions of carbon dioxide (CO_2), oxides of nitrogen (NOx), sulphur dioxide (SO_2) and particulate (PM);

2. Application of life cycle impact assessment (LCIA) methodology to compare Portland cement produced in China to that of Canada (using regional nocuous air emissions of carbon monoxide (CO), NOx, SO_2, and PM); and,

3. An evaluation of policy options and supporting mechanisms to minimize emissions leakage from EITE industry in developed markets to emerging markets.

The approach of this research utilizes both quantitative and qualitative methodologies. The first quantitative aspect of the research revolves around establishing the environmental performance of Portland cement manufacturing in Canada. The air emission intensities of CO_2, NOx, SO_2 and PM are tantamount to environmental performance and statistical analysis can be applied in order to compare datasets. The second phase of quantitative research applies LCIA methodology for Portland cement produced in China and Canada.

Maintaining objectivity in the quantitative phase is critical. It is anticipated that erroneous and missing data will occur in China given there are not similar requirements for reporting as in Canada. In China, data from credited universities and internationally recognized bodies such as World Health Organization (WHO) will be given priority over other sources (e.g., government organizations).

The qualitative aspect of the research evaluates policies through MCDA. Applying Analytic Hierarchy Process (AHP) in conjunction with the actionable solidarities of Cultural Theory the policies and their supporting mechanisms are evaluated.

Deductive logic would suggest that Portland cement manufacturing in developed countries will have better environmental performance than emerging markets due to increased regulatory control. However, the intention of the research is not to highlight potential deficiencies in the governance of China. To the contrary, if there is a notable difference in the environmental performance, Canadian regulators need to account for this in their decision making otherwise pollution will simply be transferred to China, particularly in the case of EITE industry. This is further complicated by health/risk factors associated with individuals living in heavily industrialized areas with limited control mechanisms.

1.3 Research Motivation

In developed democratic societies, such as Canada, elected governments are beholden to their citizens. Laws and regulations governing the protection of human health and the environment from industrial pollution result from the awareness of potential harmful impacts and the will of the people represented through the elected government to take action and mitigate these sources. However, compliance with legislation often requires the implementation of source control measures with considerable capital investment as well as ongoing operational costs. These compliance costs are absorbed as part of production costs and ultimately raise consumer prices.

Ideally, the compliance process will result in cleaner industrial production and potentially lead to product innovation that may further reduce environmental impact. That said, regulatory compliance does not extend beyond the jurisdictional border. Given this, consumers may access the global market in search of more competitive pricing. Unfortunately, reduced pricing is typically associated with countries that have weak or unenforced regulation, such as emerging markets. In the scenario that consumer demand shifts consumption from domestic producers to those in emerging markets with weak pollution control requirements, the local regulation becomes ineffective and the pollution is simply relocated to the emerging market.

1.4 Thesis Structure and Organization

There are six chapters in this thesis. The thesis structure is represented graphically in Figure 1.1 below. Chapter 1 identifies the motivation for the research and presents the goal, objectives and structure of the research. Chapter 2 outlines the materials and methods used in the thesis. In Chapter 3 the EITE Portland cement manufacturing sector in Canada is characterized for both production capacity and environmental performance. Chapter 4 applies LCIA impact methodology to compare the environmental performance of Portland cement manufacturing between China and Canada. In Chapter 5 plausible policies and supporting mechanisms are evaluated to minimize the potential for emissions leakage. Lastly, Chapter 6 summarizes the research carried out and provides conclusions and recommendations.

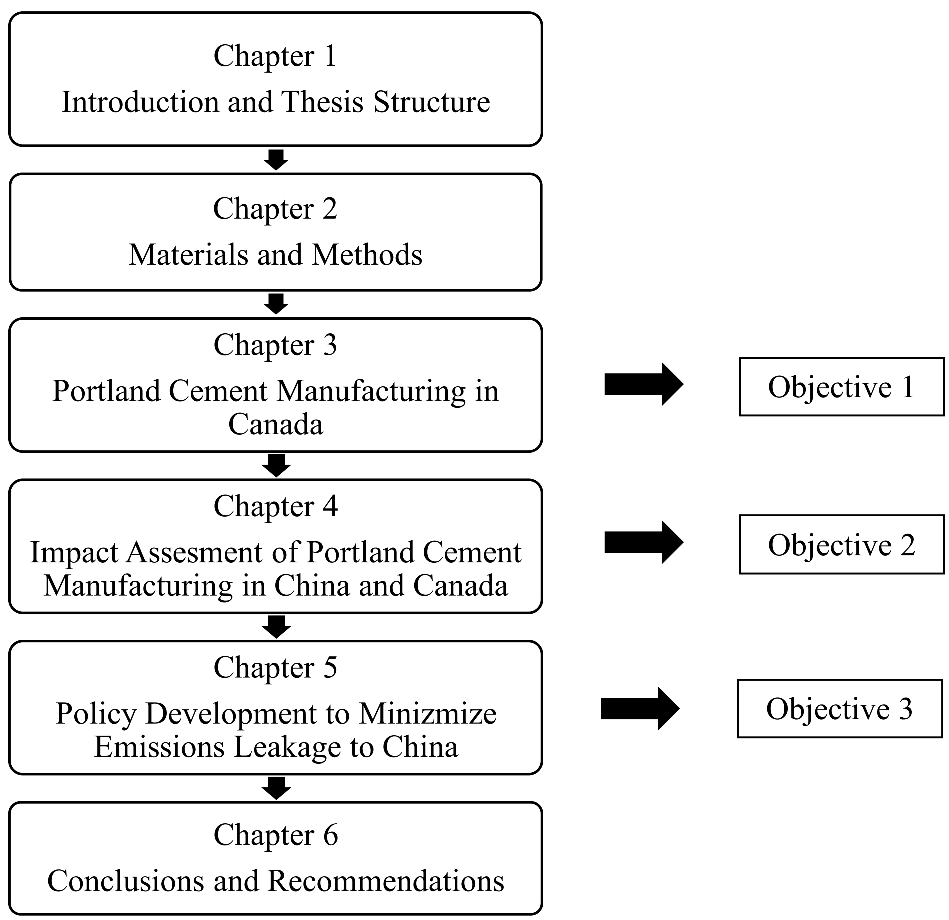

Figure 1.1: Research flow diagram

Chapter 2: Materials and Methods

As indicated in Chapter 1 this research involved the use of both quantitative and qualitative methodology to achieve the three objectives. Objective 1 was completed by characterizing the breadth of grey cement manufacturing in Canada, identifying key air emissions, quantifying total production and total emissions, and, expressing performance indicators in intensities. Total Portland cement production was obtained from the CAC, and, emission totals were retrieved from NPRI. Chapter 3 details the review of grey cement manufacturing in Canada.

In order to complete Objective 2, life cycle assessment (LCA) was applied to comparatively evaluate the environmental performance of Portland cement manufacturing in China and Canada. The LCA process is described in detail in Section 2.1 of this chapter. With regard to the comparative evaluation, the LCA culminated at the LCIA phase. For LCIA methodology, Eco-Indicator 99 was implemented to quantitatively evaluate impact per tonne of Portland cement produced. Other LCIA methods which were considered included CML 2001 and EDIP 2003. However, Eco-Indicator 99 was preferred given endpoints are provided, and, it is the most widely used method. The comparative LCIA for Portland cement manufacturing in China and Canada is provided in Chapter 4.

MCDA was carried out to complete Objective 3. For MCDA, AHP was applied. Other MCDA methods including WSM, WPM, TOPSIS and ELECTRE, PROMETHEE were also considered, however, AHP was selected because it allows for decomposition of the problem into component parts, priorities are based on pair-wise comparisons, and, the method validates consistency. Differing from the traditional approach to AHP in which experts are solicited to complete pair-wise comparisons, the research relies on the actionable solidarities of Cultural Theory to provide an unbiased perspective to evaluate the plausible policies and their supporting mechanisms. The AHP process and information on Cultural Theory is provided in Section 2.2 and 2.3, respectively. The development and evaluation of policies is discussed in Chapter 5.

2.1 Life Cycle Assessment (LCA)

The International Organization for Standardization (ISO) collaborates with standards groups across the globe to develop streamlined procedural requirements. This work is carried out by technical representatives assigned to committees. The ISO 14040:2006 standard that details the principles and framework for LCA was prepared by Technical Committee ISO/TC 207, *Environmental Management*, Subcommittee SC 5, *Life Cycle Assessment*. The ultimate goal of LCA is to better understand the impact of product or process through the individual or cumulative stages of its life cycle. Subsequently, this information can be used to make more informed decisions.

According to ISO there are four phases to an LCA, which include: 1) the goal and scope definition phase; 2) the inventory phase; 3) the impact assessment phase; and, 4) the interpretation phase (see Figure 2.1, ISO 14040:2006, 2016).

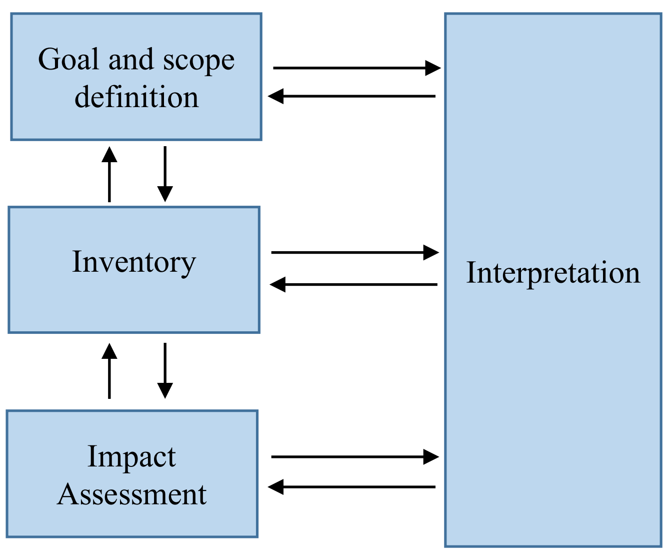

Figure 2.1: Life cycle assessment framework

As indicated by Figure 2.1, the stages of an LCA are not simply linear. Instead, each phase can shape and inform other phases. In respect of this, it is important to note that the ISO 14040:2006 standard does not prescribe techniques or methodologies for completing the individual phases.

As it pertains to the LCIA phase, ISO 14044:2006 provides four procedural steps (ISO 14044:2006, 2016). These steps include two mandatory and two optional steps: 1) selection of impact categories; 2) characterization; 3) normalization; and, 4) weighting (Figure 2.2, ISO 14044:2006, 2016).

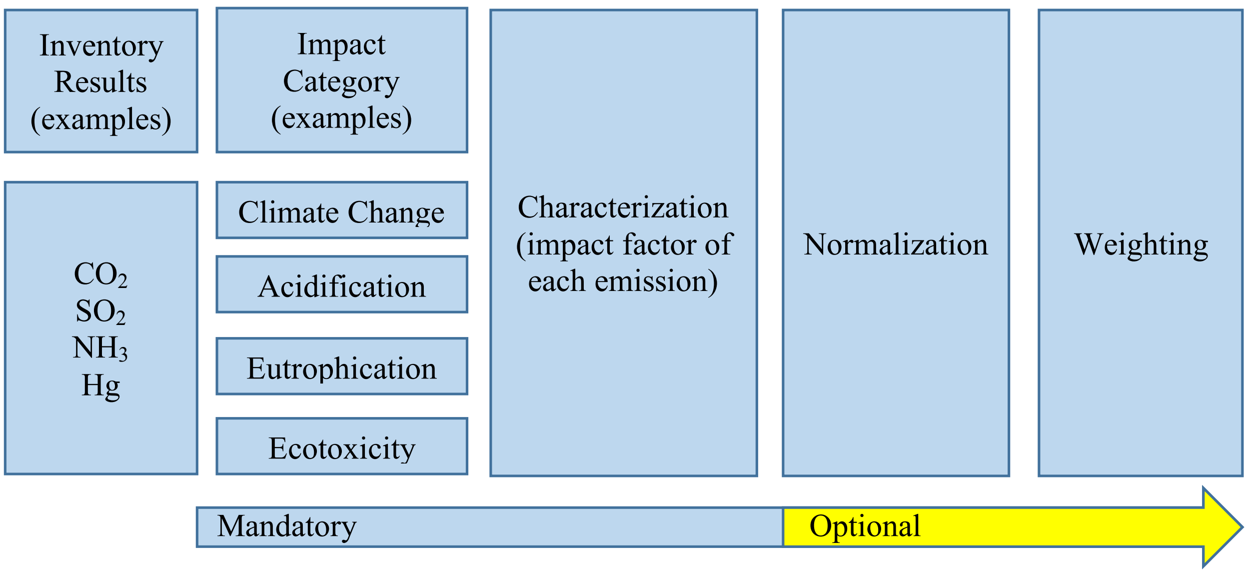

Figure 2.2: Life cycle impact assessment steps

The results of the life cycle inventory (LCI) are applied to the selected impact categories. In the characterization step the impact of each emission is assigned a factor relative to its contribution to the impact category. Through the characterization step a cumulative impact / damage score can be tabulated. In the first optional step, normalization, the impact of the product or process are associated with a common reference. Lastly, the second optional step of weighting provides a means rank the relative importance of the individual impact or impact category.

2.2 Analytic Hierarchy Process (AHP)

Initially developed by Thomas L. Saaty in the 1970s AHP is a multi-criteria decision making method for prioritizing alternatives to complex problems. Saaty (2008) indicates AHP is a theory of measurement based on a fundamental scale that evaluates pair wise comparisons of elements to establish priorities.

The key steps of AHP include: 1) defining the problem and the preferred outcome or goal; 2) developing a hierarchical structure which includes a goal, criteria and alternatives (Figure 2.3); 3) performing pair-wise comparisons between the elements of the hierarchical structure (Figure 2.4); and, 4) obtaining weights for the elements of the hierarchical structure including those which determine the preferred alternative (Saaty, 2008).

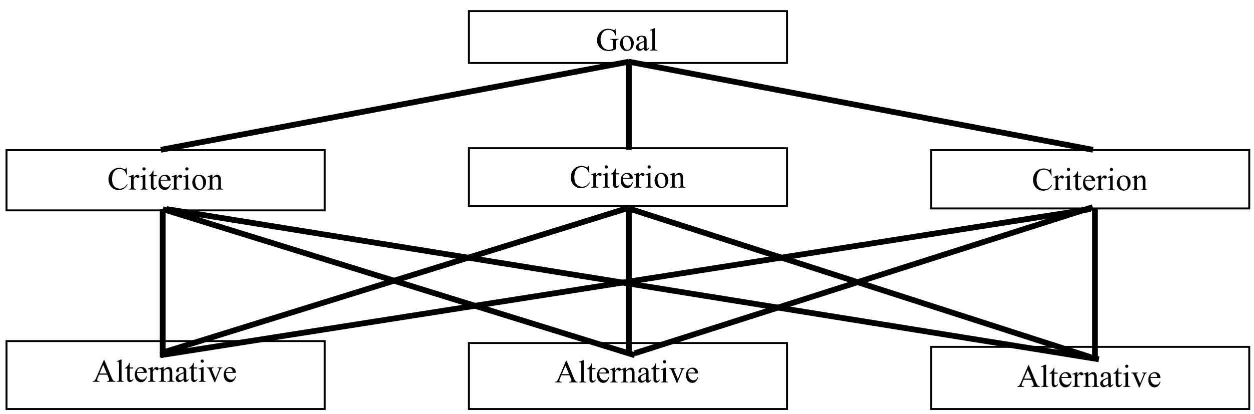

Figure 2.3: Example of a hierarchical structure

The scoring of the pair-wise comparisons is based on the fundamental scale of absolute numbers (Saaty, 2008) (Figure 2.4). The scale ranges from 1/9 (indicating an extremely weak preference) to 9 (indicating an extremely strong preference). The value of 1 indicates the two alternatives are of equivalent preference.

Alternative	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9	Alternative
1																		2
1																		3
2																		3

Figure 2.4: Example of a pair-wise comparison

For analysis the results of all the pair-wise comparisons are averaged and compiled into a single reciprocal matrix (A). This matrix is normalized to a value of 1 and the Principal Eigenvector (priority vector) w is calculated averaging across the rows (Saaty, 1980). The priority vector shows the relative weights for each of the three alternatives. These weights are simply converted to percentages.

$$A = \begin{bmatrix} 1 & x & y \\ 1/x & 1 & z \\ 1/y & 1/z & 1 \end{bmatrix} \qquad w = \frac{1}{3}\,[\hat{A}] = \begin{bmatrix} Alternative\ 1 \\ Alternative\ 2 \\ Alternative\ 3 \end{bmatrix} = 1$$

In order to understand the validity of the priority vector the Principal Eigenvalue (λ_{max}) is first calculated from adding the products each column of the reciprocal matrix and corresponding priority vector (Saaty, 1980).

$$\lambda\max = \left(1 + \frac{1}{x} + \frac{1}{y}\right) Alternative1 + \left(x + 1 + \frac{1}{z}\right) Alternative2 + (y + z + 1) Alternative3$$

Next, the consistency index (CI) is calculated using the Principal Eigenvalue and the size of the matrix (in this instance n=3) (Saaty, 1980).

$$\text{CI} = \frac{\lambda\max - n}{n - 1}$$

Finally, the Consistency Ratio is determined by comparing CI to the Random Consistency Index (RI) as developed by Saaty (1980).

$$\text{CR} = \frac{\text{CI}}{\text{RI}}$$

If CR $\leq$ 10% then the amount of inconsistency in the judgement is acceptable (Saaty, 1980)

2.3 Cultural Theory

Described by Thompson (2000) the Cultural Theory identifies four main solidarities of how people perceive nature, these include: individualist; egalitarian; hierarchist, and fatalist.

Graphically represented in Figure 2.5, each solidarity has a unique approach to the environment and society (Schwarz and Thompson, 1990).

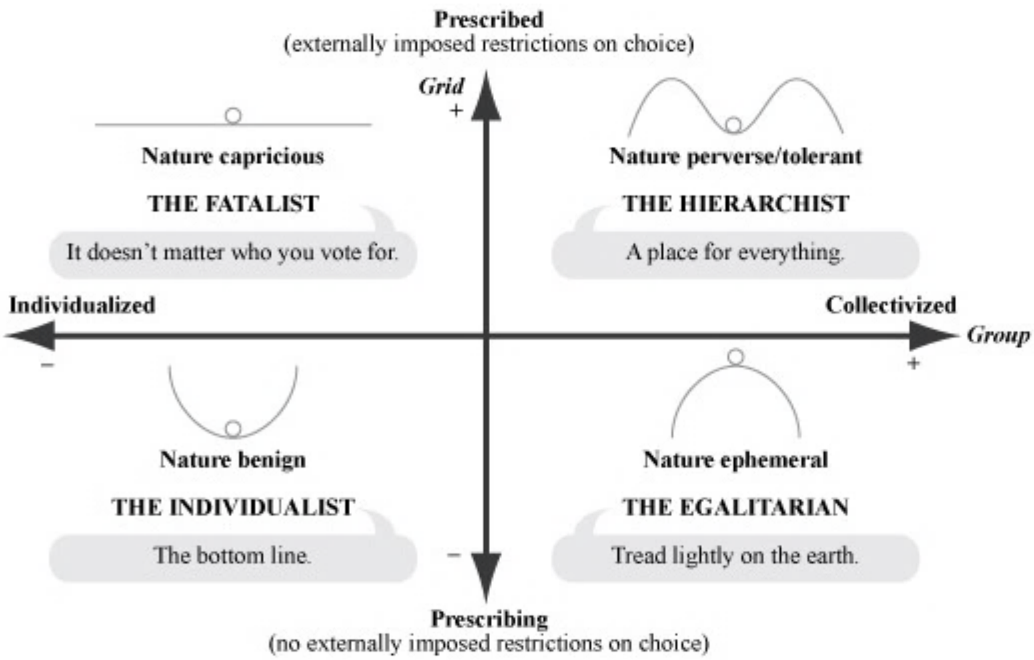

Figure 2.5: Cultural theory grid

The individualist is characterized as the self-seeking solidarity that believes the natural environment is robust enough to absorb and recover from any impact humans create (Thompson, 2000; Schwarz and Thompson, 1990). Ultimately, the individualist is concerned with personal wealth and success. They recognize the value of relationships to advance their personal gain and retaliate against those that work against them. They are not opposed to risk and believe that whoever puts the most in deserves to get the most out.

They egalitarian solidarity is opposite of the individualist. Egalitarians believe the natural environment is fragile, interconnected, and, people genuinely care for each other and recognize the importance of the collective (Thompson, 2000; Schwarz and Thompson, 1990). They do not readily accept risk, instead, they cling to the precautionary principle. Egalitarians believe in equality for all people, and, the equal distribution of wealth.

Hierarchists take a more neutral approach as compared to the individualist or egalitarian. This solidarity views the natural environment as resilient, but with limitations, and believes the collective is important but cannot function without control in the form of rank and position (Thompson, 2000; Schwarz and Thompson, 1990). Hierarchists can accept some level of risk, but, that risk would firstly be tied to the hierarchical structure and then to the collective. In short, they would need assurance they aren't upsetting the apple cart.

The last of the four solidarities is the fatalist. This solidarity is both disconnected from the natural environment and non-participating in society (Thompson, 2000; Schwarz and Thompson, 1990). The fatalist solidarity would not consider contributing a point of view given their belief that they have no ability to influence, and, that nothing really matters.

In terms of participation for the pair-wise comparisons carried out as part of the policy evaluations in Chapter 5, only the individualist, egalitarian, and hierarchist are considered actionable. As previously indicated, these actionable solidarities were applied in place of expert opinions for the AHP. Given the characteristics of the fatalist, which would see the entire process as futile, they are not considered an actionable solidarity or included in the pair-wise comparisons.

Chapter 3: Portland Cement Manufacturing in Canada

A version of this chapter has been published in *Clean Technologies and Environmental Policy* entitled “An overview of air emission intensities and environmental performance of grey cement manufacturing in Canada” by Brown, D., Sadiq, R., Hewage, K. (Brown et al., 2014).

3.1 Background

Portland cement is one of the most widely used substances on the planet. It is estimated that each man, woman and child utilize an equivalent of 350 kg of cement each year (WBCSD, 2005). In 2008, global cement production was approximately 2.8 billion tonnes (WBCSD, 2011). Despite the incredible need and consumption of cement for use in concrete to build housing and infrastructure there is also an awareness of the environmental sustainability issues associated with the manufacturing process (WBCSD, 2005).

Cement manufacturing involves four general activities: quarrying; raw material preparation; clinker production; and, grinding and distribution. The general process flow of cement manufacturing is illustrated in Figure 3.1 (Huntzinger and Eatmon, 2009). This illustration, adapted from the US Environmental Protection Agency (EPA), describes where particulate and gaseous emissions are generated in the manufacturing process.

Intuitively, given the whole process ultimately involves turning large rock into powder, it is reasonable to expect PM emissions have presence throughout. However, the bulk of air emissions generated in cement manufacturing result from the pyroprocessing of raw materials. Chen and co-authors identified in their LCIA that direct kiln emissions were the main contributors to air quality impact categories (Chen et al., 2010).

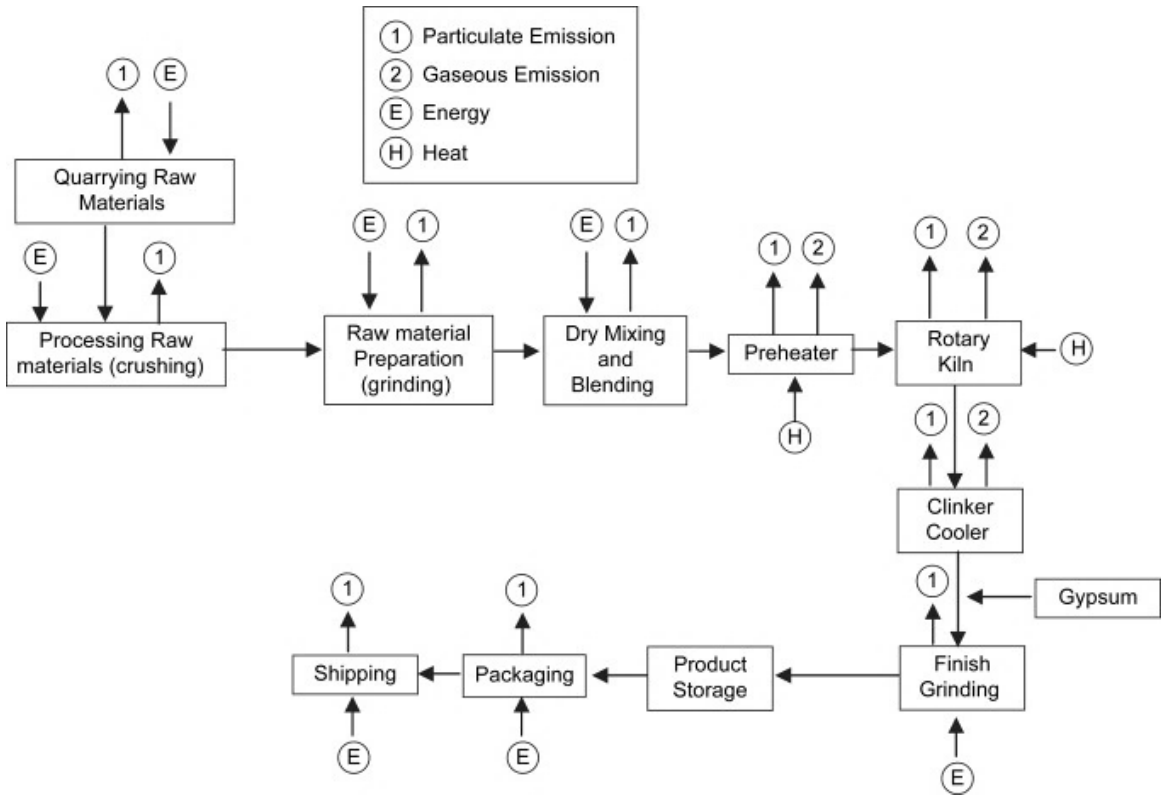

Figure 3.1: Portland cement manufacturing process flow diagram

In quarrying, limestone and other materials are extracted by drilling and blasting. The quarry is typically located at or near the cement manufacturing facility to keep transportation costs low. Following extraction, the quarried material is reduced in size by a crusher. These raw materials are then transported to the cement plant by truck, conveyor or rail car for preparation.

At the cement plant the limestone, clay, and other raw materials are mixed and homogenized. This mixture is then further pulverized in the raw mill into a fine ground material. In the next step, clinker production, this fine ground material is heated in a kiln to 1450-1500˚C where it becomes transformed into a molten product called clinker (referred to as pyroprocessing). The clinker is cooled as it exits the kiln system and stored in silos. The clinker is finely ground and mixed with gypsum to become cement. In addition to gypsum, ground limestone and other supplemental cementitious materials may be added to the mix, such as fly ash or slag. The final cement product is then distributed in bags or a as bulk powder by truck, ship and rail car.

3.2 Air Emissions and Related Effects

Air emissions generated during cement manufacturing originate primarily from the combustion of fossil fuels required to heat the kiln and the chemical reaction of raw materials in the pyroprocessing phase. Given that the kiln system is enclosed, air emissions discharge from a single point source kiln stack. Unlike other industries, the point source kiln stack enables the cement sector to accurately monitor and record total emissions. The largest contributors to air emissions from cement manufacturing are CO_2, NOx, SO_2 and dust / PM.

Table 3.1: Major air emissions from cement manufacturing and associated effects

Pollutant	Formation	Human Health Risks	Environmental Risks
Carbon dioxide (CO_2)	Combustion reaction of fuel (e.g., Coal): $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ Calcination of Limestone: $CaCO_3 \rightarrow CaO + CO_2$ Approximately 40% of CO_2 emissions from Portland cement manufacturing are generated through fuel combustion; approximately 60% are generated through the limestone calcining process.	CO_2 is not a toxic substance, although at high concentrations (in excess of 100x normal outdoor air concentrations of 360 PPM) it can act as an asphyxiant.	There is broad consensus in the scientific community that the earth's atmospheric CO_2 concentration has increased as a result of human industrial activity over the past 200 years, and this increase is linked to climate change.
Oxides of Nitrogen (NOx)	Thermal: $N_2 + O \rightarrow NO + N$ Fuel: $N + O_2 \rightarrow NO + O$ Prompt: $N + OH \rightarrow NO + H$ NOx are generated during fuel combustion by oxidation of chemically-bound nitrogen in the fuel (Thermal/Fuel NOx), and by the thermal fixation of nitrogen in the air to hydrocarbon radicals ("Prompt" NOx).	NOx can react with atmospheric ammonia, VOCs and moisture to form particles such as Ozone that can damage lung tissue if inhaled.	Atmospheric NOx reacts with water molecules to form acid rain, which damages ecosystems, buildings and infrastructure. Also strongly associated with smog formation.

Pollutant	Formation	Human Health Risks	Environmental Risks
Sulphur dioxide (SO_2)	$2CaSO_4 + 2\ SiO_2 + C \rightarrow 2CaSiO_3 + 2\ SO_2 + CO_2$ Sulphur dioxide (SO_2) may be generated both from the sulphur compounds in the raw materials during pyroprocessing, and from the combustion of sulphur-containing fuels such as coal and petroleum products.	Concentrations of ambient SO_2 of as low as 1 ppm have been linked to temporary reduction in lung function and difficulty breathing. SO_2 is also strongly associated with incidence of bronchitis and other respiratory illnesses, particularly among children. Also an eye irritant.	Atmospheric SO_2 reacts with water molecules to form acid rain, which damages ecosystems, buildings and infrastructure. Also strongly associated with smog formation.
Coarse Particulate Matter (PM_{10})	Compounds commonly associated with particulate matter (PM) include Sulfate (SO_4), Nitrate (NO_3), elemental carbon, and various organic compounds (e.g. PAHs, PNAs) and heavy metals (lead, zinc, copper, nickel etc.), along with suspended water particles.	A bronchial/ respiratory irritant; exposure is linked to bronchitis, chronic cough and respiratory symptoms, reduced lung function, and respiratory and cardiac hospital admissions.	Harmful compounds commonly associated with PM include Sulfate (SO_4), Nitrate (NO_3), elemental carbon, and various organic compounds (e.g. PAHs, PNAs) and heavy metals (lead, zinc, copper, nickel etc.)
Fine Particulate Matter ($PM_{2.5}$)	The largest emission source of PM in cement manufacturing is the pyroprocessing system (includes the kiln and clinker cooler exhaust stacks), though there are emissions at every production stage, from quarrying and grinding to packaging.	The same health risks as Coarse PM, though Fine PM also typically contains a higher proportion of toxic metals and acid species, and due to its size and shape it can penetrate more deeply into the respiratory tract.	Harmful compounds commonly associated with PM include Sulfate (SO_4), Nitrate (NO_3), elemental carbon, and various organic compounds (e.g. PAHs, PNAs) and heavy metals (lead, zinc, copper, nickel etc.)

3.2.1 Carbon Dioxide

The coal example provided in Table 3.1 shows the reaction combustion of methane in the presence of oxygen that produces CO_2 and water. The calcining process thermally decomposes $CaCO_3$ to CaO and CO_2. Typically, Portland cement contains the equivalent of about 63.5 %

CaO. Consequently, about 1.135 units of $CaCO_3$ are required to produce 1 unit of Portland cement, and the amount of CO_2 released in the calcining process is about 500 kilograms (kg) per tonne of Portland cement produced. Total CO_2 emissions from the pyroprocess depend on energy consumption and generally fall in the range of 850 to 1135 kg of CO_2 per tonne of clinker.

3.2.2 Oxides of Nitrogen

NOx is generated during fuel combustion by oxidation of chemically-bound nitrogen in the fuel and by thermal fixation of nitrogen in the combustion air. As described in Table 3.1, there are three principal mechanisms for NOx formation in Portland cement manufacturing operations: thermal NOx; fuel NOx; and, prompt NOx. Thermal NOx results from the oxidation of nitrogen in air at temperatures above 1200°C. As flame temperature increases, the amount of thermally generated NOx increases. In cement manufacturing operation, thermal NOx is only generated at large amounts within the kiln itself, but not within the preclaciner.

Thermal NOx results from the oxidation of molecular nitrogen in air at high temperature. This phenomenon occurs in and around the flame in the burning zone of a cement kiln at a temperature greater than 1200◦C. The three principal reactions (the extended Zeldovich mechanism) that produce thermal NOx are:

$N_2 + O \rightarrow NO + N$

$N + O_2 \rightarrow NO + O$

$N + OH \rightarrow NO + H$

Fuel NOx results from the oxidation of nitrogen in fuel and occurs at any temperature. Fuel NOx will be generated within a cement kiln and within a preclaciner, as well as within any ancillary device (transportation equipment, coal mill, etc.) where fuels may be combusted. The amount of NOx generated from fuel increases with the quantity of nitrogen in the fuel. In the Portland cement manufacturing process, NOx is generated in both the burning zone of the kiln and the burning zone of a precalcining vessel. Fuel use affects the quantity and type of NOx generated.

A third and generally less important source of NOx formation is Prompt NOx, which forms from the rapid reaction of atmospheric nitrogen with hydrocarbon radicals. Prompt NOx is generally very minor compared to the overall quantity of NOx generated from cement manufacturing operations.

Due to the fact that NOx is only present when in combination with a variety of other combustion-related pollutants, the specific adverse health effects of NO_2 are somewhat difficult to gauge – health risks may stem from the molecule itself, or its reaction products (i.e. Ozone (O_3) and secondary particles). WHO (2016) states that "the levels encountered in the ambient outdoor air, direct effects of NO_2 alone on the lungs (or any other system) are minimal or undetectable". EPA (2016) states that NO_2 exposure is associated with eye, nose and throat irritation, with extremely high-dose indoor exposure associated with pulmonary edema and diffuse lung injury. Asthmatics, young children, and individuals with pre-existing lung diseases are thought to be at a higher risk for respiratory harm related to NO_2 exposure, though evidence remains inconclusive. The greater threat posed by NO_2 is almost certainly its propensity to transform into nitric acid, one of the principal components of acid rain. Acid rain is damaging to plants and wildlife, and in particular to aquatic ecosystems.

3.2.3 Sulphur Dioxide

SO_2 may be generated both from the sulphur compounds in the raw materials and from sulphur in the fuel. Sulfide or elemental sulphur contained in raw materials (e.g. limestone) is "roasted" or oxidized to SO_2 during pyroprocessing where sufficient oxygen is present and the material temperature is in the range of 300-600°C (Miller et al., 2001). In fuel, the sulfide or elemental sulphur (e.g. coal) is oxidized to SO_2 at temperatures in the range of 300 to 600°C. However, the alkaline nature of the Portland cement provides for direct absorption of SO_2 into the product, thereby mitigating the quantity of SO_2 emissions in the exhaust stream. Depending on the process and the source of the sulfur, SO_2 absorption ranges from about 70-95%. Unless the fuel source is heavily contaminated, on mass balance, the main source of SO_2 emissions for modern kilns comes from the raw materials.

Unlike NOx emissions then, SO_2 generation is much more variable (even within the same kiln technology) as it is highly affected by the raw materials used in the manufacturing process, and therefore the geographical locations of the plants. Within Canada, cement kilns generate extremely low levels of SO_2, as the sulphur content in limestone tends to be extremely low in Western Canada, increasing considerably in concentration in Central Canada. Even within Central Canada, however, while sulphur concentrations in limestone are considerably higher than in Western Canada, there remain distinct quarry to quarry variations.

Sulfur dioxide is a particularly foul-smelling air pollutant associated with a wide range of negative environmental and human health impacts. At low levels of outdoor exposure, humans are generally able to block the majority of SO_2 from entering the respiratory system, as it is absorbed by the natural mucous layer in the throat and nose. However, concentrations of ambient SO_2 of as low as 1 ppm have been linked to temporary reduction in lung function and difficulty breathing. The Agency for Public Health and Education Accreditation (APHEA) project on ambient air pollution in Paris notably found a direct correlation between the daily ambient concentration of SO_2 and both hospitalizations and mortality from respiratory causes (Dab et al., 1996). SO_2 is also strongly associated with incidence of bronchitis and other respiratory illnesses, particularly in children.

In light of recent findings suggesting that the health risks associated with SO_2 exposure are more severe than was originally thought, in 2011 the WHO revised their 24-hour guideline value for SO_2 exposure from 125 down to 20 $\mu g/m^3$ (WHO, 2016).

3.2.4 Particulate Matter

Compounds commonly associated with PM include sulfate (SO_4), nitrate (NO_3), elemental carbon, and various organic compounds (e.g., PAHs) and heavy metals (lead, zinc, copper, nickel etc.), along with suspended water particles. Though the specific chemical composition of PM may vary widely, it is by its very nature a respiratory and bronchial irritant, with the ability of the lung to clear itself of inhaled particles being the primary determinant in PM's specific health risks. This in turn varies based on the average size and composition of inhaled particles, with "coarse" PM_{10} (particulate matter with an aerodynamic diameter of 2.5-10 micrometres) less strongly associated with incidence of cardiopulmonary or lung cancer than the pernicious "fine" $PM_{2.5}$ particles (diameter of less than 2.5 micrometers). Fine particulate matter typically contains a higher proportion of toxic metals and acid species, and due to its size and shape it can penetrate more deeply into the respiratory tract.

Numerous studies have also indicated a strong relationship between both PM_{10} and $PM_{2.5}$ exposure and bronchitis, chronic cough and respiratory symptoms, reduced lung function, and respiratory and cardiac hospital admissions. Predictably, those with pre-existing lung or respiratory conditions, young children, and the elderly are thought to be at a higher risk for PM-related injury or premature death.

There is a considerable body of scientific research investigating the risks posed by CO_2, NOx, SO_2, and PM to human health and the health of natural ecosystems. While some of these alleged risks remain contentious, there is certainly broad agreement that at sufficiently high ambient concentrations, each of these pollutants can lead to adverse health outcomes and that regulating industrial emissions of these pollutants should be a priority for governments.

3.3 Environmental Performance of Canadian Portland Cement Manufacturing

3.3.1 Landscape

According to the Cement Association of Canada (CAC, 2010) there are 15 Portland cement plants and one white cement plant operating in Canada. In 2008, the Canadian cement industry produced 15 million tonnes of cement (valuing over $1.7 billion) and provided more than 2,000 jobs (CAC, 2010). Based on data from 2008, 65% of Canada's cement is produced for the Canadian market and 35% is exported to the United States (CAC, 2010). Combined with the concrete industry, cement and concrete collectively employ 27,000 Canadians and contribute over $3.2 billion to Canada's gross domestic product (CAC, 2010). As demonstrated in Table 3.2, Canada's cement manufacturing operations are relatively modern and efficient, especially when compared to operations in nearby U.S. States.

In 2008, the last of Canada's wet kiln facilities (Lafarge Woodstock) suspended operations. Meanwhile, as of the end of 2007, nearly 30% of all cement kilns operating in the United States were less-efficient wet kilns, constructed prior to 1960 (CAC, 2010).

Table 3.2: Portland cement manufacturing operations in Canada

Company	Plant	# of kilns	Process	Year Began or Modernized	Fuel[1]	Clinker Capacity *000 tonnes*
Lafarge	Brookfield, NS	2	Dry Dry	1964 1978	C, A	520
Lafarge	St. Constant, QC	2	Dry Dry	1966 1975	K, A	956
Ciment Quebec	St. Basile, QC	1	Dry (precalciner)	1982 2002 - 2008	C,O,G,A	1150
Colacem	Calumet, QC	1	Dry	2004[2]	C	265
Holcim Canada	Joliette, QC	4	Dry Dry Dry Dry	1965 1965 1970 1973	C,K,A	900
Lafarge	Bath, ON	1	Dry (preheater)	1973	C,K,G	1064
Essroc	Picton, ON	2	1 Dry 1 Dry (preheater)	1965 1975	C,K,G	1,250
Holcim Canada	Mississauga, ON	1	1 Dry (preheater / precalciner)	1988	C, A	1,380
St. Marys	Bowmanville, ON	1	1 Dry (preheater & precalciner)	1991	C, K	1,966
Lafarge	Woodstock, ON	2	Wet	1956 1957	C, K	526
St. Marys	St. Mary's, ON	1	Dry (preheater)	1976	C,K	754

[1] C- coal, G- gas, K – petroleum coke, A – Alternative source (e.g. tires, biosolids, construction and demolition removals, etc. , O – Oils (e.g. Bunker C fuel oil)

[2] While starting operations as a cement manufacturing facility in 2004, the Colacem facility is not a new, modern cement facility, but rather an upgraded former brick manufacturing kiln.

Company	Plant	# of kilns	Process	Year Began or Modernized	Fuel[1]	Clinker Capacity *000 tonnes*
Lafarge	Exshaw, AB	2	1 Dry 1 Dry (preheater / precalciner)	1976 1981	C, G	1,209
Lehigh Cement	Edmonton, AB	1	1 Dry (precalciner)	1997	C, G	1,082
Lafarge	Kamloops, BC	1	1 Dry	1970	C, K, A	193
Lafarge	Richmond, BC	1	1 Dry (preheater / precalciner)	1999	C,G, K, A	1,260
Lehigh Cement	Delta, BC	1	1 Dry (preheater)	1978 / 1992	C, G, O, A	1,207

3.3.2 Environmental Performance Indicators

The Cement Association of Canada's 2012 Environmental Performance Report provides total production numbers for cement, CO_2, NOx, SO_2, and PM totals for 2003-2010 (see Table 3.3). In addition to total values the report also provides emission intensity values for CO_2, NOx, SO_2, and PM. These emission intensity values are provided in both units of clinker and cement. Table 3.3 forms the basis of discussion on the individual air quality parameters as well as the subsequent figures.

Table 3.3: Cement performance indicators

Year	2003	2004	2005	2006	2007	2008	2009	2010
Production Indicators								
Clinker Production (Mt)	13.20	13.81	13.88	14.12	13.75	12.45	9.58	10.81
Cement Production (Mt)	15.13	16.05	16.47	16.55	16.29	15.00	11.54	13.48
Clinker to Cement Ratio	87%	86%	84%	85%	84%	83%	83%	80%
CO_2 and Climate Change Indicators								
Direct CO_2 Emissions (Mt CO_2)	11.81	12.51	12.61	12.77	12.30	11.04	8.39	9.53
Direct CO_2 Emissions Intensity (kg CO_2 / tonne cement)	781	779	766	772	755	736	727	707
Air Quality Indicators								
Total NO_X Emissions (tonnes / year)	40431	43415	44295	31108	32004	28908	24350	25669
NO_X Emissions Intensity (kg / tonne clinker)	3.06	3.14	3.19	2.20	2.33	2.32	2.54	2.38
NO_X Emissions Intensity (kg / tonne cement)	2.67	2.71	2.69	1.88	1.96	1.93	2.11	1.90
Total SO_2 Emissions (tonnes / year)	37359	42768	38355	31992	28381	22309	17773	16760
SO_2 Emissions Intensity (kg / tonne clinker)	2.83	3.10	2.76	2.27	2.06	1.79	1.85	1.55
SO_2 Emissions Intensity (kg / tonne cement)	2.47	2.67	2.33	1.93	1.74	1.49	1.54	1.24
Particulate Matter (PM) Emissions (tonnes / year)	3927	4382	4369	4572	5330	4250	3280	2819
PM Emissions Intensity (kg / tonne clinker)	0.30	0.32	0.31	0.32	0.39	0.34	0.34	0.26
PM Emissions Intensity (kg / tonne cement)	0.26	0.27	0.27	0.28	0.33	0.28	0.28	0.21

3.3.3 Intensity-based Environmental Performance (2003-2010)

Total cement production reflects historic economic cycles. During the housing boom period in Canada and the United States cement production peaked at 16.55 Mt. When the crash occurred in 2008 the subsequent cement production in 2009 was down five million tonnes from 2006.

Interestingly, the clinker to cement ratio has trended down from 87% in 2003 to 80% in 2010, reflecting increased use of ground limestone and supplemental cementitious materials such as fly ash or slag.

Since 2003 total annual CO_2 emissions from the Canadian cement manufacturing sector have varied from 8.39 Mt to 12.77 Mt (see Figure 3.2). Given the primary formation of CO_2 is relative to the amount of fuel consumed and $CaCO_3$ calcined, total CO_2 emissions increase with total cement production. However, the CO_2 intensity demonstrates a decrease of 9.5% from 2003 to 2010 (see Figure 3.2).

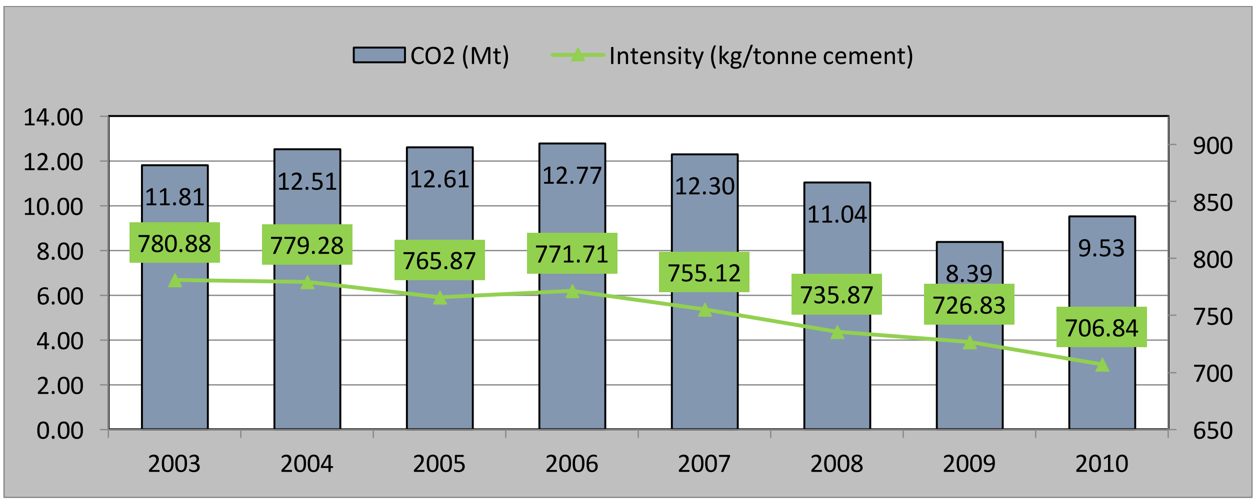

Figure 3.2: Total CO_2 and CO_2 intensity (2003-2010)

Since 2003 total annual NOx emissions from the Canadian cement manufacturing sector have varied from 24,350 tonnes to 44,295 tonnes (see Figure 3.3). Unlike CO_2 there are three modes of NOx formation and fuel type and technology can strongly influence the amount of NOx generated. As such, total NOx production may not be as directly correlated to total cement production. However, the NOx intensity has also decreased from 2003 to 2010. In 2003 NOx intensity was 2.67 kg/tonne cement and in 2010 NOx intensity was 1.90 kg/tonne cement, a 28% decrease.

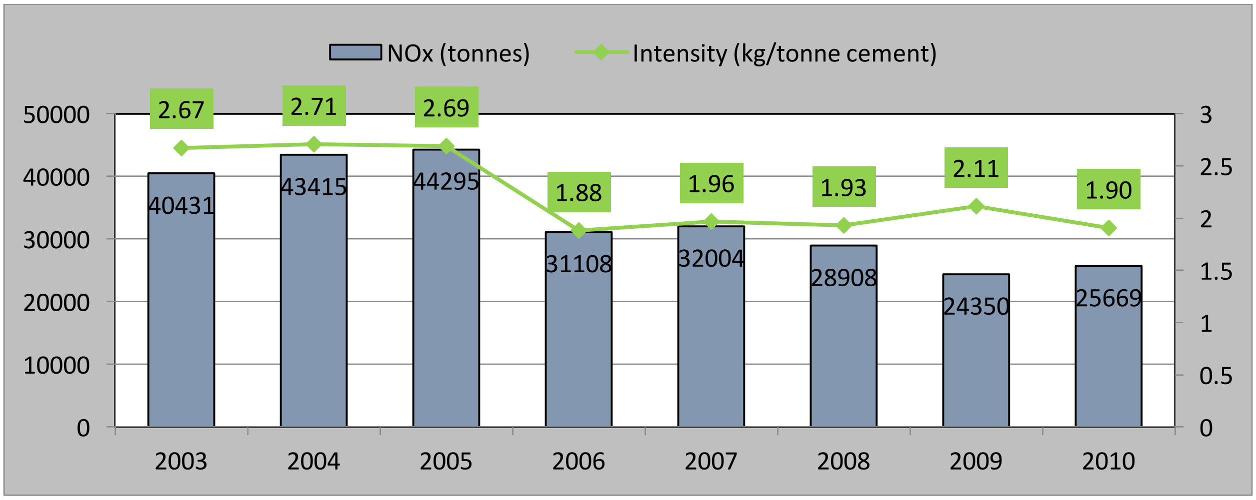

Figure 3.3: Total NOx and NOx intensity (2003-2010)

Since 2003 total annual SO_2 emissions from the Canadian cement manufacturing sector have varied from 16,760 to 42,767 tonnes (see Figure 3.4). In spite of total cement production total SO_2 shows as downward trend from 2003 to 2010. This is strongly reinforced by SO_2 intensity which has dropped considerably between 2003 and 2010. In 2003 SO_2 intensity was 2.47 kg/tonne cement and in 2010 SO_2 intensity was 1.24 kg/tonne cement, a 49.8% decrease.

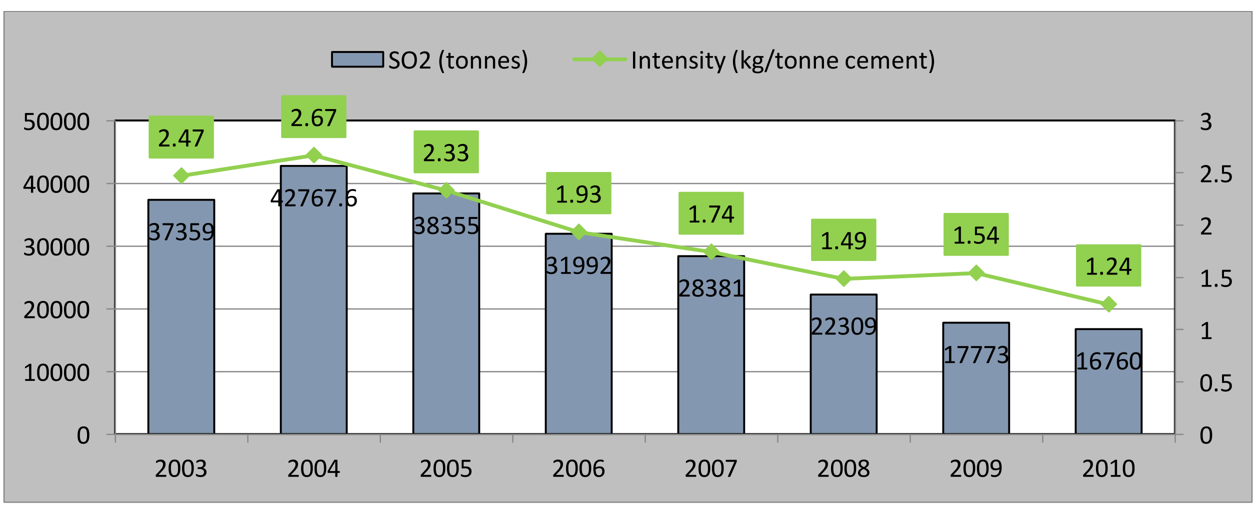

Figure 3.4: Total SO_2 and SO_2 intensity (2003-2010)

Since 2003 total annual PM emissions from the Canadian cement manufacturing sector have varied from 2,819 tonnes to 5,330 tonnes (see Figure 3.5). As with CO_2, PM emissions fluctuate with total cement production as demonstrated between 2003 and 2010. However, the intensity of PM has generally remained consistent fluctuating between 0.21 kg/tonne cement 0.33 kg/tonne cement.

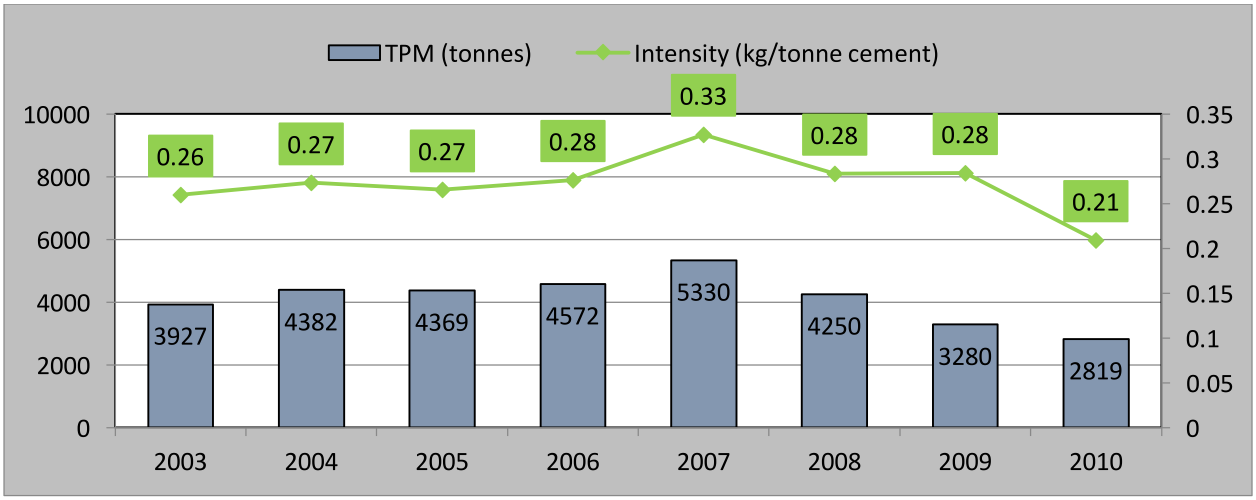

Figure 3.5: Total PM and PM intensity (2003-2010)

3.4 Interpretation

Based on a review of total emissions and intensities for CO_2, NOx, SO_2 and PM it is clear that total emissions are not a reliable way to measure cement manufacturing environmental performance. Total emissions generally fluctuate with total production and fail to provide a benchmark whereby performance can be measured. For intensity-based values, with the exception of PM, there is a downward trend from 2003-2010. It is unclear why PM intensity has not also notably decreased during this timeframe given the implementation of fabric filter bag houses at many of the facilities. However, in efforts to reduce CO_2 emissions facilities have attempted to supplant fossil fuels with alternative and renewable fuels. Cristea and Cinti (2010) suggest that the use of alternative and renewable may actually increase PM.

The reduction in CO_2 intensity for cement can be attributed to three factors: 1) increased use of alternative and renewable fuels which supplant fossil-based fuels; 2) incorporation of supplemental cementitious materials (e.g., fly ash, slag) which reduce clinker content; and, 3) increase use of ground limestone to further reduce the clinker content in cement. Reduction in NOx intensities result from process modification and the implementation of control measures such as selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR). Interestingly, using end of life tires for fuel can reduce NOx emissions by 15-30% (Corti & Lombardi, 2004).

Similar to NOx, the decrease in SO_2 intensity is attributable to both process and secondary control measures. Managing combustion efficiency and using excess oxygen in the kiln has a major impact on fuel-based SO_2. Lime injected into the kiln system reacts with SO_2 to form calcium sulphate which is generally incorporated into the clinker product. Wet scrubbing technology can also be used to remove SO_2 from the exhaust gases in the stack (Bradley et al., 2011).

Despite this improved environmental performance, the latest information from Environment and Climate Change Canada (ECCC) (2016) indicates that domestic cement manufacturing is responsible for 1.4% of total anthropogenic GHGs and 1% of total air pollutant emissions in Canada. Consequently, we need to expand the picture to flesh out what these emissions means nationally and where Canadian cement manufacturing is situated in the context of global environmental performance.

3.5 Global Context

According the WHO (2016), and looking primarily at PM pollution, Canadian air quality is the third best in the world. Emerging markets such as China and India are considerably worse off. According to He et al. (2002) in the early 1990s less than 1% of the 500 cities in China reach Class I of the Chinese National Ambient Air Quality Standards (CNAAQS)[3].

---

[3] Class I of CNAAQS are comparable to good air quality standards in developed countries.

In India the country-wide annual average for PM 10 is over 100 μg/m^3, which is five times the recommended limit of 20 μg/m^3 (WHO, 2016).

With the exception of CO_2 the emissions intensities for NOx, SO_2 and PM fall within the ranges provided by the European Integrated Pollution Prevention Control Bureau (WBCSD, 2005). Cement CO_2 intensity in Europe has been below 700 kg / tonne of CO_2 since year 2000. Although clinker intensity is comparable to that of the Canadian cement sector. The reason for the disparity between cement CO_2 intensity between Canada and Europe is likely due to the higher proportion of blended cements that can take advantage of more ground limestone and supplemental cementitious materials, reducing the amount of clinker in the product (WBCSD, 2011).

Accurate emission intensities from emerging markets such as China are much harder to come by given there are data gaps, data inaccuracies and production and emissions coverage by the Cement Sustainability Initiative (CSI) is limited to member companies with new and modernized plants in the region (WBCSD, 2011). However, an inventory completed by Lei et al. (2011) at Tsinghua University provides total cement production and emissions data from 2008 (Table 3.4).

Table 3.4**:** Canadian and China's environmental performance intensities (2008)

Air Quality Indicators Emissions Intensity (kg/tonne cement)	Canada	China
CO_2	736	642.75
NO_X	1.93	1.38
SO_2	1.49	0.87
PM	0.28	2.54

Although Table 3.4 indicates that national intensities for CO_2, NOx and SO_2 are lower in China, it is difficult to reconcile this better performance with the fact the China produces one third of its cement from vertical shaft kilns (Lei et al., 2011). Vertical shaft kilns are the oldest, dirtiest and least efficient kiln systems in cement manufacturing. There are no shaft kilns in Canada and the last wet kiln was suspended in 2008. Given that the Canadian cement manufacturing industry has a modern fleet of plants one would expect to see better environmental performance. With respect to PM intensity this considerable difference aligns with both what would be expected given the mixed kiln technology and the WHO air quality ranking of China.

In terms of production, the Canadian cement manufacturing sector is easy eclipsed by China and India as the largest world-wide producers. In 2008 China alone produced 1.38 billion tonnes of cement (European Chamber, 2009). China's investment into cement manufacturing in 2009 suggests that current (2011) overcapacity is in excess of 1 billion tonnes (European Chamber, 2009). The European Chamber (2009) indicate that the overcapacity in the cement sector, compared with Chinese overcapacity in the aluminum industry, is thought to be caused by market forces, subsidized energy prices, easy access to technology and funding, and stimulus spending.

Consequently, Canadian cement manufacturers are under considerable competitive strain from Asia-based producers. In Canada, higher production costs of result from increased environmental regulatory control, expensive fuel and labour. Based on the Economic Chamber's projections, the entire Canadian cement production as of 2008 could be replaced by 1.5% of China's overcapacity. It is possible the reason that complete market takeover has not already occurred is that cement has a low cost per unit weigh ratio, making ground transportation very expensive.

3.6 Energy Intensive & Trade Exposed (EITE) Industry and Emissions Leakage

Over the past decade concerns around GHGs, particularly CO_2, have prompted governments at regional, national and international levels to develop and implement emissions reduction programs. The cement industry is acutely aware of these measures given it contributes approximately 5% of global CO_2 emissions (WBCSD, 2011). In 2005 the European Economic Commission (EEC) introduced the European Union Emissions Trading Scheme (EUETS). In 2007 select Canadian provinces and US states signed onto the Western Climate Initiative (WCI) with the purpose of developing a North American emissions trading system (cap and trade). In

2008 the province of British Columbia in Canada implemented a carbon tax on fuel emissions and in 2011 Australia followed suit with introducing their own carbon tax.

A few years after the implementation of EUETS the European Commission recognized an oversight with the program. EITE industry in countries covered by EUETS were at a competitive disadvantage to foreign imports from industry in unregulated countries. The resulting effect was carbon leakage. In 2009 the European Commission issued a directive identifying and allowing protection for sectors with trade exposure to countries not subject to EUETS (EEC, 2010). In June 2010, the WCI released a report on the risk of carbon leakage associated with electricity imports and exports from non-WCI jurisdictions calling for first-jurisdictional delivery to mitigate these effects. These actions taken by EUETS and WCI recognize that emissions leakage must be thoroughly considered in order to genuinely reduce global GHG emissions.

Applying the concept of carbon leakage to NOx, SO_2 and PM follows the same logic. If stringent regulation increases cement production costs locally, the production may be shifted to a non-regulated country and cement imported. The result would be local decrease in emissions because production decreases while global emissions remains unchanged, if not increased due to poorer standards in emerging markets. Simply put, emissions leakage refers to the change in emission A externally (ΔAx^{ext}) divided by the absolute value of local or internal emissions reductions (ΔAx^{int}). This result is then expressed to denote relative percent leakage (L). For example, if the L = 25% this suggests that A*x* emissions have increased by 25% in the non-regulated country (Chen, 2009).

$$L = \frac{\Delta Ax^{Ext}}{|\Delta Ax^{Int}|} * 100\% \qquad (3.1)$$

Studies on Annex B countries complying with their commitment to the Kyoto Protocol suggest that carbonleakage will range from 5% - 20% (Kallbekken et al., 2007; Barker et al., 2007). In evaluating the EUETS transition path to 2020, Bernard and Vielle (2009) indicate some industries may incur carbonleakage over 10%. Disparity between Regional Greenhouse Gas

Initiative (RGGI) states and non-RGGI states in the US demonstrate leakage may be up to 30% (Chen, 2009). Despite the fact that NOx, SO_2 and PM generate regional air quality issues they are a ‘global-local’ concern.

3.7 LCA Applications

Increased public concern for environmental degradation has put pressure on the construction industry to move towards sustainable business practices. In response to this pressure the construction industry has begun to reshape its *modus operandi*. This transformation is exemplified by the development of environment and energy certification systems such as those associated with the International Organization for Standardization (ISO) or the Leadership in Energy and Environmental Design (LEED) developed by the United States Green Building Council.

The cornerstone of both ISO and LEED certification is life cycle assessment (LCA). LCA has become the principal assessment methodological tool for determining the complete environmental footprint of a product or process. The holistic approach considers all aspects of a product’s development from cradle to grave. In the example of cement manufacturing an LCA may consider all the environment impacts starting from the initial geological survey to find a suitable limestone source to the packaging and transporting the finished product.

Cement and its primary end-use product concrete are widely used building materials with an average one tonne of concrete produced each year for every human being on earth (Van den Heede and De Belie, 2012). Given cement and concrete’s extensive use, accurately determining the environmental impact of these materials is critical to understanding their role in sustainable construction practices. Despite the emissions intense nature of cement LCA research may demonstrate the environmental performance of cement and concrete over its lifetime are higher than other building materials such as timber, steel, polymers, glass and bitumen.

3.8 Multi-criteria Decision Analysis (MCDA)

Industrial air emissions are a major concern for the protection of human health and the environment. Development of standards and control mechanisms to reduce industrial emissions is important to protecting air quality. In order to developing sound environmental policy to air quality governments typically undertake some form of MCDA. MCDA attempts to combine social, environmental and economic assessment criteria into a single performance measure (Ascough et al., 2008).

In light of the awareness around carbon leakage it is important to consider emissions leakage and its role on the effectiveness of a policy or program to genuinely reduce emissions (Chen, 2009; Barker et al., 2007). Unlike CO_2 emissions which add to global GHGs, NOx, SO_2 and PM emissions create local impacts. If creating environmental policy, simply transfers regional air pollution to an unregulated jurisdiction it defeats the purpose of developing said policy.

In a policy development scenario that considers regional air emissions, and applies MCDA to develop the appropriate standard, social (*s*) environmental (*en*) and economic (*ec*) criteria are considered:

$$\text{Standard for air emission } S_A = \frac{1}{n}\sum_{i=1}^{n} g_\text{i} = \frac{g1(s) + g2(en) + g3(ec)}{n} \tag{3.2}$$

However, if Equation 3.2 fails to consider leakage effects there may be not net reduction in emission A because production may simply decrease locally and increase in an unregulated jurisdiction. In this instance a leakage factor (*Lf*) would need to be applied:

$$\text{Standard for air emission } S_A = \frac{1}{n}\sum_{i=1}^{n} g_\text{i} = \frac{g1(s) + g2(en) + g3(ec)}{n} \times (Lf) \tag{3.3}$$

The value of the *Lf* would likely be proportional to productions costs. As an EITE industry cement manufacturing would require a greater *Lf* due to the high energy and labour costs. In a study of the environmental effects of exports and imports, Wang and Xie (2011) found that considerable strain is being placed on China's environment because of the expansion of heavy industry designated for the export market. The lack of environmental regulation and cheap labour allow China to outcompete domestic producers in the developed world. In order to improve the quality of the environment in China, Wang and Xie (2011) suggest that environmental regulation needs to be strengthened and the scale of exports needs to be reduced.

Considering the actions taken by the European Commission to acknowledge and address emissions leakage of GHGs from EITE industry, and, the noted strain of export manufacturing on the environment in China, the next step is to comparatively evaluate the life cycle of an exported product to that of domestically manufactured product. As an EITE industry in both China and Canada, Portland cement manufacturing is an ideal candidate for the assessment. Given this research focuses on regional nocuous emissions, the environmental performance of cement produced in either country would be based on those emissions rather than GHGs.

Consequently, in the next chapter a health-based comparative LCIA is carried out between Portland cement produced in China and Canada. The purpose of the assessment is to further understand the environmental performance of cement production in China and Canada and to translate this performance into actual impact. Depending on the outcome of the LCIA results, MCDA methodology can be applied to adjust or strengthen policy and legislation to minimize emissions leakage.

Chapter 4: LCIA Investigation of Cement Manufacturing in China and Canada

A version of this chapter has been accepted by *Clean Technologies and Environmental Policy*. The paper, entitled "A health-based life cycle impact assessment (LCIA) for cement manufacturing: a comparative study of China and Canada", was prepared by Brown, D., Sadiq, R., Hewage, K. (Brown et al., 2017).

4.1 Industrial Pollution and State of the Industry

Environmental awareness and the impact of pollution are becoming increasingly known. This is reflected in government policies and regulations as well as the prominence of the environment in news, electronic print and social media. In day-to-day activities, the general public may be directly aware of the environment and pollution while sorting their garbage as part of a municipal waste management program, moderating outdoor activities based on air quality advisories, or, deciding to take public transport instead using their vehicle. What is less likely known is the environmental impact associated with inter-jurisdictional trade.

As previously mentioned cement manufacturing is a true global enterprise. This is largely due to the abundance of the principal raw material, limestone, which covers approximately 10% of the earth's surface (PCA, 2004). The wide availability of raw materials for cement production and cement's primary use in the major building material, concrete, supports a strong demand. Recent estimates indicate that annual consumption of cement on a per person basis is 450 kg (WBCSD, 2012).

Unfortunately, the process of cement manufacturing generates by-products, in particular, undesirable gaseous emissions. The most recognized of which is carbon dioxide (CO_2). According to the World Business Council for Sustainable Development (WBSCD) Cement Sustainability Initiative (CSI) the cement sector accounts for up to 6% of global anthropogenic CO_2 emissions (WBCSD, 2012). Apart from CO_2, the other main and more acutely nocuous emissions are NOx, SO_2, PM, and CO (WBCSD, 2012). Minor constituents include volatile organic compounds, acid gases, trace metals, and organic micro pollutants (WBCSD, 2012).

Given the demand for cement, the challenge of regulating and reducing air emissions has become a priority for governments and industry alike. Historically, before regulatory intervention, maximizing product output and minimizing costs associated with energy drove innovation. Consequently, initial emission reductions were achieved through the advancement of kiln technology (PCA, 2004). Low output vertical shaft kilns were replaced with rotary kilns, the less energy efficient wet process was replaced with the dry process, and, preheater kilns transitioned to ultra-efficient precalciner kilns.

In recent history, awareness of the direct impact of air emissions on human health and the environment prompted some governments to regulate industrial emissions closely. In these countries, antiquated kilns have been decommissioned and scrubbing technology and operational controls have become mandatory to reduce the primary emissions (e.g., NOx, SO_2, PM, and CO).

Currently, public concern over global warming has resulted in GHG reduction initiatives such as carbon tax, cap and trade and mandated performance limits. In these jurisdictions, industry is responding to reduce CO_2 emissions by using supplemental cementitious materials (e.g., fly ash, slag), increasing the use of ground limestone, seeking alternatives to traditional fossil fuels, and, further focussing on energy efficiency.

In so much as the cement sector can be acknowledged for adapting to human health and environmental concerns, the apparent challenge to a wholesale transformation of the industry lies with having ubiquitous production parameters. As discussed in Chapter 3 an EITE industry market advantage is given to cement producers who operate in countries not subject to the same level of scrutiny. This EITE worst-case scenario is exemplified by the cement industry in China. As the world's largest producer, in 2014 China manufactured 2.476 billion tonnes, which is approximately 60% of global production (Xu et al., 2015). Weak environmental regulations, fuel and raw material subsidies, and low labor costs all contribute to a favourable price for export (Xu et al., 2015; Song et al., 2015).

Given the ability for China to produce and export cement at lower costs, cement manufacturers in countries that are well regulated, such as Canada, are susceptible to production leakage. Along with production leakage are the associated air emissions. As demonstrated in their review of EUETS to reduce GHGs, the European Economic Commission (EEC) recognized the program did not account for emissions leakage associated with EITE industry (EEC, 2010). In general, studies indicate that GHG emissions leakage between regulated and non-regulated jurisdictions could be up to 30% (see Chapter 3).

Although the emissions leakage is important, the ultimate concern is the connection between emissions leakage and environmental performance of the industry within the jurisdiction. With regards to GHGs, if the intensity of CO_2 emissions per tonne of imported cement is equivalent to that of the domestically produced cement, including transportation, the impact is the same. However, if the CO_2 intensity is greater in the imported cement there will be a net increase in global CO_2 emissions. Without extending the same standards to the importer, the regulated jurisdiction has inadvertently caused an increase in emissions.

Recognition of the global concern surrounding GHGs is well understood and several countries are moving towards emission reduction initiatives. At the 2015 Paris climate conference (COP21), 195 countries adopted the legally binding Climate Paris Agreement. Even emerging economies, such as China, ratified the agreement. In order to meet their obligation, China has committed to reducing GHG emissions per unit of gross domestic product by 60-65% below 2005 levels. This commitment alone may address the concerns of consistency with other global cement producers for CO_2 emission intensity and modernization.

However, what is less publicized with a unified global approach are initiatives to address the other primary air emissions of cement manufacturing which are more directly harmful. Unlike CO_2 emissions and their contribution to global warming, other gases such as NOx, SO_2, PM and CO are regional pollutants with local effects. Coincidently, SO_2 and suspended PM in conjunction with NOx, organic substances and CO are known to cause what is referred to as winter smog (Guo, 2012). The most widely recalled instance of winter smog occurred in London in December of 1952. The London smog, generated from home heating with coal, was linked to approximately 12,000 deaths (Guo, 2012). In recognition of, and in response to, the deadly event the United Kingdom passed the *Clean Air Act* (CAA) of 1956.

Given the limited attention of research into emissions leakage of regional pollutants, and the serious potential for impact on air quality in emerging markets with EITE industry, cement manufacturing in China and Canada are comparatively evaluated for their national cement emission intensities of NOx, SO_2, PM and CO. This comparative evaluation will highlight the importance of emissions leakage and identify the potential for increased emissions associated with importing cement from producers with poor emission profiles. However, with emission intensities, the discussion on the adverse effects of the pollutants on human health is limited to exposure limits of the individual parameters.

In order to meaningfully assess the impact of the emissions, their interactions and fate in the environment must be incorporated. In the life cycle thinking (LCT) approach, the individual emissions are considered beyond their initial release and exposure limits, and, are evaluated as contributing factors to an impact category that directly quantifies damage to human health. Using LCIA methodology, the environmental performance of cement production is assessed in terms of the winter smog impact category.

Both emissions intensities and the LCIA results will provide a means of comparing environmental performance between the two countries, the potential for increased emissions from trade, and the potential for impacts to human health. Following this analysis, the emissions intensities and LCIA results will be used to highlight the pollution challenges and assess policy differences between emerging markets and developed markets. Given the traditional approach to regulating air pollution focuses on setting individual contaminant limits, the multi-pollutant impact approach of LCIA may also be considered.

4.2 Approach

This LCIA adheres to the ISO standard for LCA (ISO 14040:2006 / ISO 14044:2006). Although the scope of the LCIA is more narrowly focused than the traditional LCA, all the essential phases have been addressed. As previously mentioned, the main objective of the LCIA is to perform a comparative study to evaluate cement manufacturing processes in China and Canada. The overarching goal is to serve as a tool for policy makers developing regulation, addressing EITE industry, and minimizing the potential for emissions leakage.

4.2.1 Scope

Identifying a functional unit to encompass all cement types is problematic. As explained in Chapter 3 the intermediate product clinker, that embodies the majority of emissions associated with cement manufacturing, varies in concentration depending on the cement type. Different applications of cement in concrete can also vary in clinker concentration. As well, countries and jurisdictions may differ in their building material standards. Lastly, the incorporation of supplemental cementitious material such as fly ash or slag into cement further complicates consistency.

Ideally, clinker would be the preferred metric to directly determine environmental performance of the cement plant. However, the consumable is cement. Additionally, much of the cement industry in developed countries are focused on reducing the environment impacts of cement by specifying applications that require lower clinker cement, and, supplanting some of the clinker concentration with other pozzolans. That said, the bulk of the globally produced cement occurs in developing countries and is Portland cement, which consists of 95% clinker. As such, the functional unit used in this assessment is 1 tonne of Portland cement.

In Canada, the NPRI requires cement manufacturing facilities to report emissions for several contaminants including NOx, SO_2 PM, and CO. However, the upstream activities of quarrying and crushing, and their associated emissions, are not included. As well, the downstream activities after the cement product has left the plant, until the final use in concrete, are not included. Given the NPRI provides the principal source of output data for the life cycle inventory (LCI), for the purpose this LCIA the system boundaries are limited to the cement manufacturing plant (i.e., gate-to-gate).

In reviewing the emissions data from China, it has been identified that there is not an equivalent monitoring system to NPRI in Canada. Inventory data for China's cement manufacturing is drawn from diverse sources including research papers and international reporting systems (e.g., CSI). As such, it is difficult to determine the exact system boundaries of the life LCI data from China. However, given that the cement manufacturing facility phase generates the bulk of emissions for cement, and different kiln technology emission profiles are well understood, it is assumed that emissions inventory from China will be consistent with NPRI data. Inconsistencies in data will identified and discussed.

Although multiple impact categories are affected by the main regional emissions of cement manufacturing (NO, SO_2, PM, and CO), the focus of this LCIA concerns local air quality impacts on human health. Consequently, the impact category selected for comparative purposes is winter smog. In Eco-indicator 99, winter smog is equivalent to the damage category of respiratory effects on humans caused by inorganic substances (Pré, 2001). In Table 4.1 the list of substances contributing to winter smog are identified. The damage factors are expressed as per kg emission and the unit of damage is Disability Adjusted Life Years (DALYs).

Table 4.1**:** Respiratory effects from inorganic substances per kg emission (E,E) (Pré, 2001)

Substances in Air	Damage Factor	Normalised Damage Factor	Weighted Damage Factor
ammonia	8.50E-05	5.48E-03	1.65E+00
CO	7.31E-07	4.72E-05	1.41E-02
dust (PM_{10})	3.75E-04	2.42E-02	7.26E+00
dust ($PM_{2.5}$)	7.00E-04	4.52E-02	1.35E+01
TSP	1.10E-04	7.10E-03	2.13E+00
NO	1.37E-04	8.84E-03	2.65E+00
NO_2	8.91E-05	5.75E-03	1.72E+00
NOx	8.91E-05	5.75E-03	1.72E+00
NOx (as NO_2)	8.91E-05	5.75E-03	1.72E+00
SO_2	5.46E-05	3.52E-03	1.06E+00
SO_3	4.37E-05	2.82E-03	8.46E-01
SOx	5.46E-05	3.52E-03	1.06E+00
SOx (as SO_2)	5.46E-05	3.52E-03	1.06E+00

DALYs refer to years of life lived with disability or years of life lost due to overall disease burden. The damage factor column in Table 4.1 is consistent with other LCA databases and is applied to the each associated substance to produce DALYs. However, the normalised and weighted damage factors are unique to Eco-Indicator 99.

In Eco-Indicator 99 there are three cultural perspectives that affect the normalisation and weighting of the damage factor: individualists; hierarchists; and, egalitarians. Individualists would be considered short term thinkers, need proven cause and effect, and value human health more during productive years. The hierarchists are balanced between short term and long term thinking, accept evidence-based facts, and will accept some risk. Lastly, the egalitarians are the long term thinkers, they adhere to the precautionary principle, and are risk adverse.

In Table 4.1 the damage, normalised and weighted factors reflect the egalitarian perspective (E,E) (Pré, 2001). As the precautionary approach, the egalitarian perspective for winter smog has the highest damage factors and includes the most number of contributing substances. However, in normalising and weighting they put less emphasis on human health and more on ecosystem quality and resources (Table 4.2). As such, the egalitarian perspective provides the most conservative valuation of impact to human health from winter smog.

Table 4.2**:** Normalisation and weighting by cultural perspective (derived from Pré, 2001)

Category	Individualist		Hierarchist		Egalitarian	
	Normalisation	Weights	Normalisation	Weights	Normalisation	Weights
Human Health	8.25E-03	550	1.54E-02	400	1.55E-02	300
Ecosystem Quality	4.51E+03	250	5.13E+03	400	5.13E+03	500
Resources	1.48E+02	200	8.41E+03	200	5.94E+03	200

4.2.2 Life Cycle Inventory (LCI)

In accordance with the scope, the system boundaries of this LCI are limited to the gate-to-gate of the cement production facility (Figure 4.1). Energy and raw materials are brought into the plant, processing occurs, and cement and emissions are created. As indicated previously, upstream and downstream activities are not included in the LCI because the bulk of emissions are generated from the manufacturing phase. As well, data availability and data consistency are key factors in the comparative study. However, it is important to note that upstream and downstream activities between producers can significantly vary. The variations can include: type and origin of electric and thermal energy; distance and mode of transportation between raw material sources and the plant; distance and mode of transportation between the plant and the consumer; and, the type of cement and the concrete application.

In cement manufacturing there are no two identical systems. Even with consistent technology the configuration will vary across the facilities of the world. It is recognized that differences in technology, energy, raw materials, additives and operational efficiencies all factor into emission totals and intensities. It may be possible to use probabilistic or fuzzy logic methodology to discretely characterize the cement manufacturing systems. However, for the purpose of evaluating national level cement manufacturing performance all that is required is total Portland cement production and associated emission totals and intensities for NOx, SO2, PM, and CO.

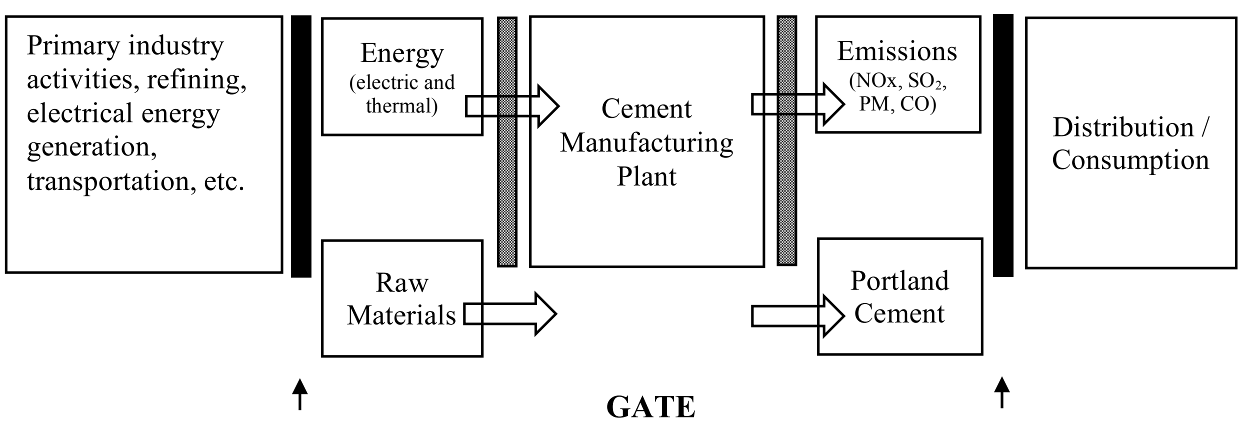

Figure 4.1: System boundaries of LCI

Unlike Canada, data gathering from China's cement industry provides considerable challenge. The data available from CSI is very limited and reflects larger companies with modern facilities. Research papers also provide limited information in that only a subset of the sector is included, and/or, the data is not presented in useable form (e.g., SO_2 emissions from coal combustion alone, excluding raw material SO_2 emissions), and/or, the data conflicts between papers. In light of these limitations, and for the purpose of consistency, a single inventory paper was selected for the LCI. Although dated, the inventory completed by Lei et al. (2011) assesses the entire cement industry, presents useable data, and, demonstrates consistency.

Mandatory data reporting through the NPRI provides complete emission totals for the cement sector in Canada. Additionally, the CAC has compiled cement production, emission totals, and intensities in their environmental performance report (CAC, 2012). Although data is available up to 2015 through NPRI, the inventory in China completed by Lei et al. (2011) only provides data up to 2008. However, in their study Lei et al. (2011) offers a projection of emissions for a high production scenario in 2015. Given there was high production in 2015, and, no other exhaustive inventory is available, the projection will be used for the purposes of comparison. In Table 3.3 both the total emissions and intensities have been reported.

With respect to DALYs, NOx, SO_2, and CO are assigned a single damage factor as per Table 4.1. However, PM is fractioned into three damage categories (total suspended particulate (TSP) or total PM, PM_{10} and $PM_{2.5}$). In Table 4.3, only total PM emissions and PM intensity are provided. However, when determining impact, each PM fraction is evaluated separately.

In Canada, recent efforts to reduce GHGs have resulted in an increase production of Portland limestone cement (PLC). With PLC, ground limestone can substitute up to 15% of the clinker concentration. Unfortunately, it is not possible to separate the emissions reported from the plants between PLC and Portland cement. That said, Portland cement is still the main cement product, and, the influence of PLC will only result in reducing emissions. In China, Portland cement is the main product.

Table 4.3: Portland cement production, emission totals and intensities (2015)

Country	Portland Cement	NOx		SO_2		PM		CO	
	(Mt)	(Mt)	(kg/t)	(Mt)	(kg/t)	(Mt)	(kg/t)	(Mt)	(kg/t)
China	2010[a]	3.07[a]	1.53	1.12[a]	0.557	2.33[a]	1.16	9.42[a]	4.69
Canada	12.28[b]	2.804 E-02[c]	2.283	1.504 E-02[c]	1.225	3.330 E-03[c]	0.2711	8.478 E-03[c]	0.6904

[a] Lei et al. (2011)
[b] Cement Association of Canada (2016)
[c] National Pollution Release Inventory (2016)

4.3 Analysis

According to the emissions intensities indicated in Table 4.3, China outperforms Canada in both NOx and SO_2. In Canada, NOx emissions intensity is 49% higher and SO_2 intensity is increased by 120%. Conversely, PM and CO are considerably lower in Canada. PM intensity is 77% lower and CO intensity is 85% lower.

4.3.1 Life Cycle Impact Assessment (LCIA)

In terms of environmental performance, the outcome of the LCI does not provide a simple answer. According to available data if cement were imported to Canada from China the embodied emissions would be lower for NOx and $SO_{2,}$ while higher for PM and CO. Conversely, cement exported to China from Canada would have lower PM and CO while having increased NOx and SO_2. Ultimately, the impact of the individual parameters must be assessed in order to qualify the discussion on performance.

As part of the LCIA, damage factors are applied to the individual emissions in order to determine the corresponding impact (DALYs). In this instance, the Eco-Indicator 99 factors for winter smog are applied (see Table 4.1). These factors are normalised and weighted according to the egalitarian perspective (E.E). The sum of all damage contributions are expressed as DALYs per tonne of Portland cement (see Table 4.4).

Table 4.4: Disability adjust life years (DALYs) per tonne of Portland cement (2015)

Country	Emission	Intensity (kg/tonne of cement)	Eco-Indicator 99 (E,E) Weighted damage factor (per kg emission)	DALYs (per tonne cement)	Total DALYs (per tonne cement)
China	NOx	1.53	1.72	2.63	14.2
	SO2	0.557	1.06	0.59	
	$PM_{>10}$	0.219	2.13	0.466	
	PM_{10}	0.358	7.26	2.60	
	$PM_{2.5}$	0.582	13.5	7.86	
	CO	4.69	0.0141	0.0661	
Canada	NOx	2.283	1.72	3.93	7.02
	SO2	1.225	1.06	1.30	
	$PM_{>10}$	0.1140	2.13	0.243	
	PM_{10}	0.09249	7.26	0.671	
	$PM_{2.5}$	0.06467	13.5	0.873	
	CO	0.6904	0.0141	9.73 E-03	

According to Table 4.4 the damage generated from 1 tonne of Portland cement manufactured in China at 14.2 DALYs. This is more than double that of Canada at 7.02 DALYs. In spite of Canada having higher intensity values for NOx and SO_2, the increased PM intensity in China has far greater impact, in particular the PM_{10} and $PM_{2.5}$ fractions. The damage caused from China's $PM_{2.5}$ intensity alone is more than Canada's total DALYs per tonne of Portland cement.

In consideration of added emissions during trade based on emissions intensity, either country will lose or gain depending on the parameter. However, in considering health impacts, China generates more than twice the damage per tonne of Portland cement produced. Given these pollutants may cause regional impacts, the production and associated emissions leakage to China will potentiate the damage. Based on the LCIA results, China generates 7.18 DALYS per tonne of cement more than Canada.

The change in damage (ΔD) measured in DALYs is a result of the leaked cement production (P_L)

multiplied by the difference between the exporting country product damage (D_{EXP}) and the importing country product damage (D_{IMP}) in DALYs per tonne of cement.

$$\Delta D = P_L \bullet (D_{EXP} - D_{IMP}) \tag{4.1}$$

As such, if Canada imports one million tonnes of Portland cement there is an increase damage of 7.18 million DALYs. Conversely, if China imported one million tonnes of cement from Canada the result would be a decrease of 7.18 million DALYs (denoted by a negative value). It is important to note this value does not include impacts outside of the system boundaries or from transportation.

4.3.2 Interpretation

The results of the LCI and LCIA provide unique perspectives on environmental performance. The LCI intensity results summarized in Table 4.5 suggest that neither China nor Canada have distinct advantage in performance. Where China gains in NOx and SO_2 performance they lose with PM and CO. Although, it is important to state the China's values are based on projections from 2008 whereas the Canadian values are field collected and verified through the NPRI.

Table 4.5**:** LCI emissions intensity results in kg/tonne of Portland cement (2015)

Country	NOx	SO_2	PM	CO
	(kg/t)	(kg/t)	(kg/t)	(kg/t)
China	1.53	0.557	1.16	4.69
Canada	2.283	1.225	0.2711	0.6904
% change	↑49%	↑120%	↓77%	↓85%

As discussed in Chapter 3, China's 2008 reporting-based intensity values for NOx and SO_2 were also lower than Canada's values. The increased value for NOx in Canada can be explained as an unintended effect of enhanced kiln technology.

As opposed to older vertical shaft kilns that operate inefficiently, the high temperatures of the more efficient rotary kilns generate thermal NOx. It is expected, as China transitions to modern kiln technology NOx will increase. However, the operational efficiencies and technologies such as selective catalytic reduction (SCR) can minimize NOx.

The lower SO_2 intensity in China is more difficult to account for. In 2008, vertical shaft kiln technology accounted for one third of China's cement production (Lei et al., 2011). Unlike preheater or precalciner kilns where fuel-based elemental sulphur or sulphide is largely incorporated in to the product, vertical shaft kilns release SO_2 emissions from both fuel and the raw materials. That said, as discussed in Chapter 3, production in Canada is significantly smaller scale than China, and, approximately half the plants consume limestone with heavy pyrite (FeS_2) concentrations.

Differing from the LCI results, the LCIA clearly indicates that Canadian manufacturers produce lower impact cement than China. The Eco-Indicator 99 damage factors for PM_{10} and $PM_{2.5}$ demonstrate their potentially serious impact on human health, and, remove ambiguity associated with the varying intensities. This does not dismiss the impacts of NOx, SO_2, and CO, however, as it pertains to respiratory effects and contribution to winter smog, the smaller fractions of PM play a significant role. Other impact categories may be influenced by the individual parameters. As an EITE industry the cement producers are especially susceptible to production leakage and associated emissions leakage. However, Equation 4.1 can apply to any industry. Even if there is no domestic production capability the foreign production and impact thereof can still be measured. The equation is simply reduced to $\Delta D = P_L \bullet D_{EXP}$. That said, the LCI and LCIA of the industry would need to be first assessed.

4.3.3 Limitations and Next Steps

As previously mentioned the spatial parameters of the LCIA are limited to gate-to-gate of the cement manufacturing phase as indicated in Figure 4.1. A complete LCIA would include initial raw material extraction and preparation, electrical generation, thermal fuel extraction and refinement, and, transportation. As well, post process handling and transportation are not included. There are two principal reasons for the exclusions: 1) large data gaps; and, 2) variability of material source and product endpoints contributions. In spite of the challenges of completing a full LCIA, cradle and post-processing impacts should be included.

It is recognized that winter smog is only one of the LCA impact categories. Given the focus of this LCIA is health-based effects and regional air pollutants associated with cement manufacturing, the impact category is appropriate. That said, an assessment that includes all impact categories would provide a complete health and environmental characterization. Moreover, the information could be utilized to develop an environmental product declaration (EPD) for cement that could be universally applied.

Of note, no sensitivity analysis was carried out as part of this study. Given the egalitarian perspective is the most conservative of the three solidarities used in Eco-Indicator 99, sensitivity analysis could only depict a larger impact.

In spite of these limitations, there is clear cause to evaluate the effectiveness of existing policy and legislation to reduce offshoring of Portland cement production to China. In terms of regionally important air emissions the relative impact of cement production in China per tonne of cement is disconcerting. Given China already has significant industrial capacity for their domestic consumption, adding production for the export market can only exacerbate air pollution. Establishing effective trade policy in Canada could have a real impact on minimizing emissions leakage to China.

In the next chapter, the potential for emissions leakage is further evaluated. As well, MCDA is applied to assess policies and their supporting mechanisms for the purpose of minimizing emissions leakage.

Chapter 5: Reducing Emissions Leakage to China

A version of this chapter is under review with *Environmental Management*. The paper, entitled "Investigating the impacts of plausible Canadian policies and their supporting mechanisms on export-based regional air pollution in China: A case of cement manufacturing", was prepared by Brown, D., Sadiq, R., Hewage, K. (Brown et al., 2017).

5.1 Existing Legislative Framework

CEPA was developed for the dual purpose of pollution prevention and the protection of the environment and human health in Canada (ECCC, 2014). In Part 7, Division 6 of CEPA, the Minister has the authority to act if Canadian sources are generating air pollution outside of Canada, or, if the air pollution violates an international binding agreement on Canada (ECCC, 2014). As an example of the latter, Canada entered into the '*Agreement Between the Government of Canada and the Government of the United States of America on Air Quality*' (ECCC, 2013). The purpose of the agreement is to minimize transboundary air pollution between the two countries for mutually beneficial purposes.

Although Canada recognizes international air pollution issues, and has provided a legislated mechanism for intervention, this is limited to the movement of air pollution across a physical border. However, regional air pollution generated during the manufacturing of goods, which are imported to Canada, are not considered. Naturally, Canada has no direct control over how foreign jurisdictions operate. That said, if an imported product is manufactured in a manner that is not consistent with Canadian air pollution standards then a contradiction may occur. Moreover, the unintended effect of trade could potentiate pollution in the exporting country.

Intuitively, trade with developed markets pose lower risk of pollution displacement than emerging markets. As one of Canada's largest trading partners, and a developed market, the United States has a strong federal regulatory system to manage and control air pollution. The *Clean Air Act* (CAA) administered by EPA is authorized to limit emissions from industrial operations and requires that individual states meet the National Ambient Air Quality Standards

(NAAQS) (EPA, 2016). In Canada, the regulatory approach is analogous with ECCC and the Canadian Ambient Air Quality Standards (CAAQS) (ECCC, 2013).

As a result of similar regulatory frameworks there is a reasonable expectation that products are manufactured with comparable impacts. However, with an emerging market such as China that has no demonstrable equivalent, the uncertainty and associated risks increase. In the absence of equivalency, other mechanisms are needed to verify some level of confidence as to the embodied impact of the product. Moreover, if the process of assessment identifies additional impacts to air quality from manufacturing, the government may need to implement policy or regulation to dissuade the importation of such products.

5.2 Impact of Increasing Exports on China's Air Quality

Regional air pollution in China causes a major health risk. It estimated that poor air quality contributes to 1.6 million deaths per year in China (Rohde and Muller, 2015). Although the percentage of deaths with respect to the total population is relatively low, what China experiences annually in air pollution mortality is equivalent to approximately 5% of Canada's total population (StatCan, 2015). Furthermore, in 2012 China accounted for roughly 23% of the 7 million air pollution linked deaths world-wide (WHO, 2016).

As an economic powerhouse China has become the largest exporter in the world (Wang et al., 2015). In 2012, China exported over two trillion in US dollars by volume (Song et al., 2015). However, this market dominance has not been achieved without a serious impact on air quality. Huo et al. (2014) postulate that the embodied emissions of the exports contributed to 24% of total NOx emissions, 25% of total SO_2 emissions, and, 23% of total $PM_{2.5}$ emissions in China.

These estimates exclude emissions from capital project development and international transportation. Huo et al. (2014) further suggest that major factors in China's poor air quality can be attributed to high emissions per unit product and a high proportion of emissions intense industry.

The reason that China has become the world's factory is largely attributed to the pollution haven hypothesis, in that emissions intense industry relocate from developed countries to take advantage of lower production costs and less stringent environmental regulations in emerging markets (Wang et al., 2015). As discussed in Chapter 3, this also aligns with the concept of carbon leakage between regulated and non-regulated jurisdictions in consideration of EITE industry. However, unlike GHGs which add to the global concentration emissions leakage associated with regional air pollutants such as NOx, SO_2, PM, and CO have localized effects.

5.3 EITE Cement Manufacturing Industry

As an EITE industry cement manufacturing provides a unique opportunity to study the potential for increasing regional air pollution in the exporting country. Given the cement industry is global and energy intense (which is tantamount to emissions intense), relocating manufacturing to emerging markets would be expected. Consequently, China has become the largest producer of cement with billions of tonnes of capacity and accounts for approximately 60% of global production (Xu et al., 2015). By contrast, Canada's relatively small cement industry with a total capacity under 20 million tonnes, operating in a more stringent regulatory environment, is under considerable competitive pressure from imported cement.

This competitive pressure on the cement manufacturing industry is demonstrated by the implementation of the carbon tax in British Columbia (BC). In 2008, the Government of BC introduced a tax on the fossilized carbon component of fuels. Initially at $10 per tonne of carbon dioxide equivalent (CO_{2e}) emissions the carbon tax incrementally increased by $5 each year to its present rate of $30 per tonne of CO_{2e}. As indicated in Table 5.1 the tax rate is based on the CO_{2e} emissions intensity of the fuel.

Since the inception of the carbon tax in 2008, the British Columbia, Canada, cement industry has experienced considerable deterioration of domestic market share to imported cement (see Figure 5.1). In 2005, imported cement accounted for approximately 5.9% of total domestic cement consumption (CAC, 2016). At the end of 2015, with carbon tax at $30 per tonne CO_{2e}, imports accounted for approximately 50% of total domestic cement consumption (CAC, 2016).

Table 5.1: Selected carbon tax rates by fuel (July 1, 2012)

Fuel	Units	Tax Rate
Gasoline	¢/litre	6.67
Diesel (light fuel oil)	¢/litre	7.67
Jet Fuel	¢/litre	7.83
Natural Gas	¢/cubic metre	5.70
Propane	¢/litre	4.62
Coal - high heat value	$/tonne	62.31
Coal - low heat value	$/tonne	53.31

http://www.fin.gov.bc.ca/tbs/tp/climate/A4.htm

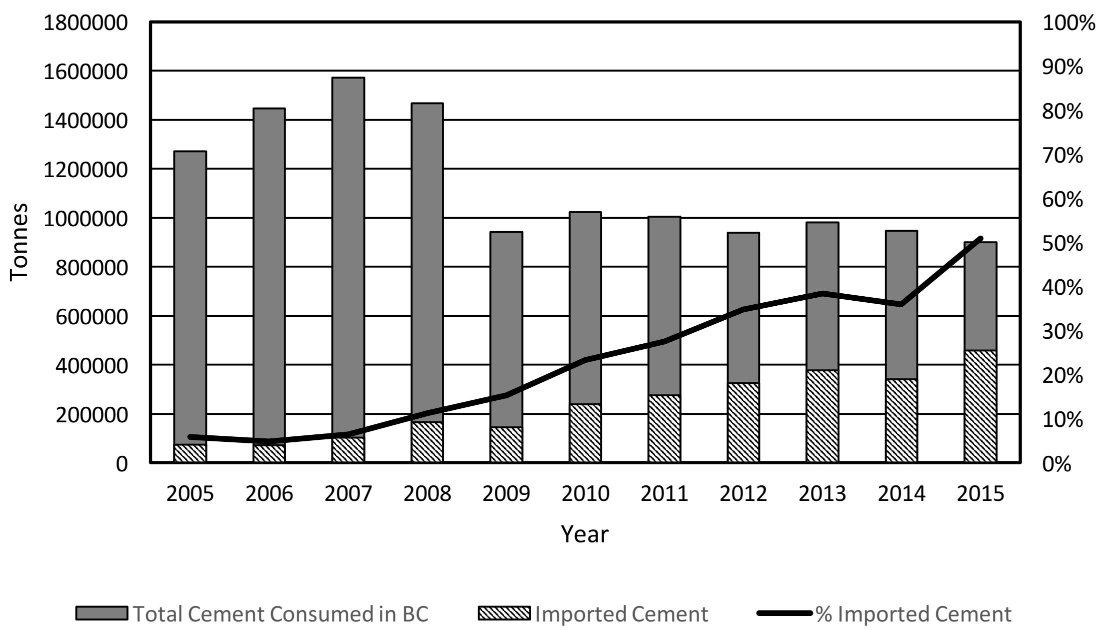

Figure 5.1: Cement consumption in BC (Canada) by Year (CAC, 2016)

Although there may be several factors that influence market share, Figure 5.1 clearly shows a trend between the percentage of imports and the increase in the tax from $10 per tonne in 2008 to $30 per tonne of CO_{2e}. Since 2012, with carbon tax at a fixed price of $30 per tonne CO_{2e}, imports have not dropped below 35% of total domestic cement consumption. The critical difference being exploited is that imported cement is not subject to carbon tax because the tax only applies to the fuel combustion CO_{2e} associated with manufacturing.

Along with the drop in domestic cement production will be an apparent drop in total CO_{2e}. However, this is only due to the fact that imported cement, and its embodied CO_{2e}, is not accounted for by BC GHG reporting mechanisms. It is plausible, in the case of the EITE cement industry, the intended purpose of the carbon tax to reduce GHGs is ineffective. Moreover, if the CO_{2e} intensity of the exporting manufacturing facilities is higher than domestic producers then the carbon tax has resulted in a net increase in global CO_{2e} emissions.

Extending the scope of leakage beyond production and CO_{2e} emissions to include regional nocuous air pollutants (NOx, SO_2, PM and CO) the issue is further exacerbated. According to the results of Chapter 4, the impact to regional air quality from cement production in China, in terms of disability adjusted life years (DALYs) from these four regional pollutants, is twice that of Canada. Based on this, unchecked importation of cement from China will have a net increase on the health and environmental impact of cement production.

5.4 Emissions Leakage Protection: Plausible Policy Scenarios

For Canada, there are three general policy directions that can be taken to minimize the potential for emissions leakage associated with the international trade of cement. These policies include the following (Table 5.2):

Policy 1 - provide direct support for local cement manufacturing to cut costs and increase competitiveness;

Policy 2 - create barriers for importation such that foreign manufacturers either comply with Canadian standards or are dissuaded from exporting; and,

Policy 3 – a combination of 1 and 2.

Table 5.2: Plausible policy scenarios for emissions leakage protection

Policy	Border	Domestic Cement Producers
Policy 1	Open	Supported
Policy 2	Restricted	Not supported
Policy 3	Selective	Partially Supported

Within each policy, there are various supporting mechanisms available to achieve the intended outcome. For Policy 1, these mechanisms may include relaxation of emission standards, subsidies, and/or, direct funding. In support of Policy 2, mechanisms may include prohibiting cement imports, environmental tariffs, and/or a verification process, such as LCIA that can demonstrate equivalency with Canadian standards. Lastly, Policy 3 may include a combination of Policy 1 and Policy 2 mechanisms.

This paper utilizes the cement manufacturing sector to evaluate the efficacy of these three plausible policy scenarios and their supporting mechanisms. The ideal outcome of this process will be a well-supported policy and mechanisms that best mitigates emissions leakage of the regional nocuous air pollutants to foreign jurisdictions. At the same time the policy will maintain an economically strong trading partnership. However, minimizing regional air pollution loading in emerging markets, such as China, is the key objective. Ultimately, valuation of imported products needs to incorporate the potential impacts generated from manufacturing (TTH, 2009).

5.4.1 Problem Decomposition

This phase of the thesis builds on Chapter 3 and Chapter 4 as indicated in Figure 5.2. The initial assessment characterized the environmental performance of cement manufacturing on a national scale in Canada. In Chapter 3, the emission intensities for regional nocuous air pollutants were developed for the Canadian cement sector. In the evaluation component of Chapter 3 there was discussion that emissions leakage associated with carbon policy could expand to include regional air pollutants, particularly in emerging markets such as China.

In Chapter 4, a comparative evaluation of national cement production in China and Canada was carried out based on emission intensities for NOx, SO_2, PM and CO, and LCIA. As an outcome of the comparison it was found that the embodied emissions of cement manufactured in China had much greater impact on regional air quality and human health than cement manufactured in Canada. In the conclusion of Chapter 4 it is further postulated that the regional air pollution was occurring in China as a result of production leakage.

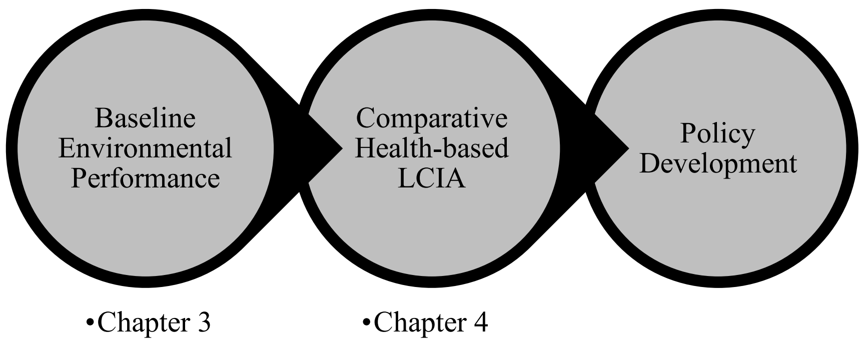

Figure 5.2: Research flow diagram

In this chapter, MCDA is used to investigate and evaluate the three policy scenarios. Specifically, AHP methodology has been applied as detailed in Chapter 2. Considering the potential ramifications of a policy which may impact international trade, and in light of Canada's export market which accounts for more than 30% of gross domestic product (GDP), the main criteria of evaluation are: health/environment; cost; and, trade retaliation (StatCan, 2016). The decomposition of the problem into the hierarchal structure of the goal, criteria, and alternatives is presented in Figure 5.3.

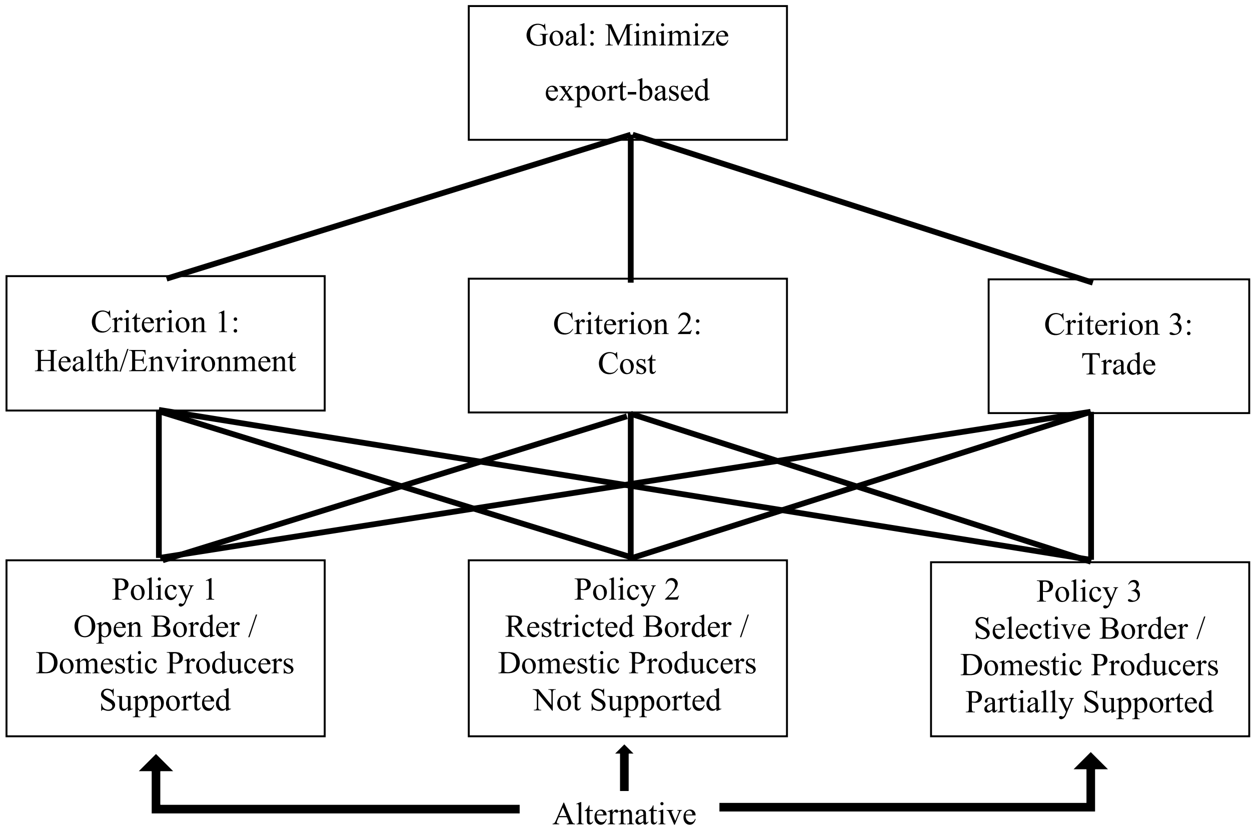

Figure 5.3: AHP – Minimizing export-based regional air pollution in China

Although not directly included in the AHP structure, the mechanisms that may in part support each policy alternative are presented in Table 5.3. The mechanisms indicated for each policy scenario are not prioritized, and, it is possible that more than one mechanism could be implemented. That said, the mechanisms presented are confined to the policy parameters of border status and the level of support for domestic cement producers.

Table 5.3: Policy scenario mechanisms

Policy	Border	Domestic Cement Producers	Mechanisms		
1	Open	Supported	Relaxation of emission standards	Subsidies (e.g., tax breaks, fuel, raw materials)	Capital Investment ($$$)
2	Restricted	Unsupported	Embargo	Environmental tariff	Verification process (e.g., LCIA, EPD* Agreement**)
3	Selective	Partly Supported	Environmental tariff	Verification process (e.g., LCIA, EPD*, Agreement**)	Capital Investment ($)

* Environmental product declaration (EPD)
** Agreement as per CEPA

Differing from the standard approach in AHP where pair-wise comparisons determine the proportional weight of the criteria, in this study each criterion is automatically assigned one third of the weight. The purpose of evenly distributing the weight across the criteria is to ensure a balanced approach to selecting the alternative to minimize export-based regional air pollution in China. Additionally, as discussed in Chapter 2, in place of expert opinions for the pair-wise comparisons, the data is derived from the application and averaging of the three actionable solidarities of the Cultural Theory framework: individualist; egalitarian; and, hierarchist (Thompson, 2000). Adapted from Pré (2001) and Thompson (2000), the approach of each 'solidarity' to the pair-wise comparisons is explained in Table 5.4.

Table 5.4: Cultural Theory solidarity perspectives (Pré, 2001; Thompson, 2000)

Solidarity	Perspectives		
	View on Environment	Societal Thinking	Time Horizon
Individualist	Adaptable	Self-seeking	Short term
Egalitarian	Fragile and interconnected (precautionary principle)	Collective	Long Term
Hierarchist	Controllable	Hierarchical	Balanced

Given the perspectives of the solidarities, and based on the criteria in Figure 4.3, the following relational expressions form the basis of decision making:

Individualist - Cost > Trade Retaliation >> Health/Environment;

Egalitarian - Health/Environment >> Trade Retaliation > Cost; and,

Hierarchist - Trade Retaliation > Cost >= Health/Environment.

In addition to these expressions, each 'solidarity' considers the policy mechanisms provided in Table 5.3. The ranking or judgement scale for the pair-wise comparison adheres to the fundamental scale of absolute numbers (Saaty, 2008). The qualitative scale ranges from the weakest relative preference (1/9) to the strongest relative preference (9), and, a score of 1 indicates an equal importance (Saaty, 2008).

Figure 5.4 provides an example of the scoring format for a solidarity applied to the paired alternatives. As denoted by the arrows in Figure 5.4, a score of 9 in the first pairing would indicate an extremely strong preference for Policy 2. Conversely, a score of 1/9 would indicate a very weak preference for Policy 2, but, an extremely strong preference for Policy 1.

Solidarity	Policy	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9	Policy
x	1	⇐								=								⇒	2
	1	⇐								=								⇒	3
	2	⇐								=								⇒	3

Figure 5.4: Format for pair-wise comparison of alternatives

5.5 AHP Results

The individual scoring for the pair-wise comparisons are presented in Table 5.5. Intuitively, the individualist prioritizes cost and then trade retaliation, whereas the egalitarian focuses primarily on the health/environment and to a lesser extent trade retaliation (with respect to supporting the collective). Lastly, the hierarchist attempts to balance the interests while recognizing the potential impact of trade retaliation. Ultimately, all solidarities are directed toward the goal of implementing an effective solution of export-based regional air pollution in China.

Table 5.5: Solidarity based pair-wise comparisons of alternatives

Solidarity	Policy	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9	Policy
Individualist	1											√							2
	1											√							3
	2							√											3
Egalitarian	1													√					2
	1													√					3
	2									√									3
Hierarchist	1					√													2
	1							√											3
	2													√					3
Average	1											√							2
	1											√							3
	2										√								3

In averaging the pair-wise comparisons, the values were rounded to the nearest whole number. Based on the averaged values of the alternate policies the reciprocal matrix, normalized matrix and priority vector are calculated.

$$A = \begin{bmatrix} 1 & \frac{1}{3} & \frac{1}{3} \\ 3 & 1 & \frac{1}{2} \\ 3 & 2 & 1 \end{bmatrix}$$

$$\text{SUM} = 7 \quad \frac{10}{3} \quad \frac{11}{6}$$

$$A = \begin{bmatrix} \frac{1}{7} & \frac{1}{10} & \frac{2}{11} \\ \frac{3}{7} & \frac{3}{10} & \frac{3}{11} \\ \frac{3}{7} & \frac{6}{10} & \frac{6}{11} \end{bmatrix}$$

$$\text{SUM} = 1 \quad 1 \quad 1$$

$$w = \frac{1}{3} \begin{bmatrix} \frac{1}{7} & \frac{1}{10} & \frac{2}{11} \\ \frac{3}{7} & \frac{3}{10} & \frac{3}{11} \\ \frac{3}{7} & \frac{6}{10} & \frac{6}{11} \end{bmatrix} = \begin{bmatrix} 0.1416 \\ 0.3338 \\ 0.5248 \end{bmatrix}$$

The Principal Eigenvalue was 3.065 and the consistency ratio was 5.6%, indicating consistency in judgement for the Policy 3 preference. Given each criterion has been assigned equal weighting of one-third, therefore no further analysis is required to determine the final weightings. Figure 5.3 provides the AHP structure and the proportional weightings are 0.1416 for Policy 1, 0.3338 for Policy 2 and 0.5248 for Policy 3. Based on the analysis carried out, and converted to percentages, Policy 3 is strongly favoured at approximately 52.5% following by Policy 2 at 33.4%. The least favoured is Policy 1 at 14.2%.

In order to evaluate the robustness of the results two additional scenarios were evaluated. In the first scenario each solidarity provided a less assertive opinion in the pair-wise comparisons and the rankings moved towards equal importance by two levels (i.e., a score of 5 became 3, and a score of 1/5 became 1/3). In this conservative evaluation Policy 3 was still favoured at 50%, however, the Policy 1 and 2 were equally favoured at 25%. The consistency ratio of 0% indicates no inconsistency in judgement, although, it also indicates the proximity of the scoring to 1.

In the second scenario the opposite occurred. Each 'solidarity' had a stronger opinion in the pair-wise comparisons moving away from equal importance by two levels. In this exaggerated evaluation support for Policy 3 increased to approximately 60% and the gap widened between Policy 2 at 30% and Policy 1 at 10%. However, the consistency ratio increased to 16% indicating the judgement was no longer consistent. Consequently, the results of the primary analysis are well situated within the 10% limit.

5.6 Interpretation

It is not surprising that Policy 3 was the preferred alternative among the three options given it provides middle ground between Policy 1 and 2. However, the overwhelming support for Policy 3 suggests there are key influencing factors. Less expected, given the direct impact on trade, was support for Policy 2 more than doubled that of Policy 1. Particularly, since the Canadian government would likely select Policy 1 to avoid potential impact to the export industry and its contribution to GDP.

5.6.1 Cultural Theory Review

In reviewing the mechanisms that support the policies there are clearly those that can be removed. The egalitarian solidarity, and to a lesser extent the hierarchists, would not accept the relaxation of regulatory standards indicated in Policy 1. As well, none of the solidarities would support the embargo mechanism in Policy 2. The individualists would be concerned about the opportunity cost, egalitarians would prefer to avoid impacting the global community, and most strongly opposed would be the hierarchists and their sensitivity to trade retaliation.

Although capital investment and subsidies are practicable, they are less than desirable mechanisms. The main influencing factor for the individualist to select Policy 3 over Policy 1 was to minimize costs associated with the implementation of the program. The egalitarian supported Policy 3 over Policy 1 for two reasons: firstly, relaxing emission standards is completely counter to the precautionary principle; and, secondly, domestic capital investments and subsidies have no direct influence on reducing export-based regional air pollution in China.

It is possible embodied emissions in the cement from China may increase as a result of a shift to lower pollution safeguards to be more cost competitive.

The two remaining mechanisms, environmental tariff and verification process are supported by the AHP analysis through the policy preferences. From the individualist perspective either mechanism puts the cost and responsibility on the exporter. Egalitarians are satisfied that the domestic emission standards are maintained, and, for either mechanism there is incentive for cement manufacturers in China to improve on emissions performance.

While hierarchists prefer an environmental tariff or a verification process to embargoing non-compliant cement, there is still is concern with trade retaliation. It is possible both mechanisms may be viewed as a barrier to trade, and challenged at the World Trade Organization (WTO). That said, the verification process mechanism would likely be preferred given it implicitly provides a procedure for achieving compliance and not a fee. Table 5.6 provides a summary of solidarity review of the policy mechanisms.

Table 5.6: Review of policy mechanisms by solidarity

Solidarity	Mechanisms					
	Relaxation of Standards	Embargo	Environmental Tariff	Subsidies	Capital Investment	Verification Process
Individualist	√	×	√	×	×	√
Egalitarian	×	×	√	×	×	√
Hierarchist	×	×	×	√	√	√

5.6.2 Verification Process Mechanism

Based on the analysis, the most accepted policy mechanism is the verification process. This is substantiated by the support for Policy 3 in the AHP analysis and in the review of policy mechanisms in Table 5.6. As previously indicated, the verification process mechanism can be approached more than one way, however, the underlying requirement is at minimum there is equivalency with Canadian standards and performance. As such, Canada could pursue: an agreement under CEPA with China that is similar to the existing arrangement with the United States; or, a robust EPD; or, a cement-based LCIA.

In respect of the cement sector, it is unlikely that the Canadian government would allocate time and resources for a single industry agreement under CEPA. However, in terms of the broader picture an overarching agreement on trade an agreement may be appropriate. Procedures could be incorporated in the agreement to evaluate imported products for their embodied emissions. This framework could be applied universally.

An EPD provides the most thorough evaluation of the environmental impact of a product. Tantamount to a nutritional label on food an EPD details the environmental aspects of a product based on a full life cycle assessment (LCA) (ISO 14025:2006, 2015). The purpose of an EPD is to allow for comparison between products that provide the same function (ISO 14025:2006, 2015). The challenge with an EPD is that the data collection phase requires considerable effort to address the complete life cycle of the product. That said, the product category rules (PCR) which define the required data for the LCA can be incorporated into a Canada-China agreement prior to the development of an EPD (ISO 14025:2006, 2015).

As indicated in Chapter 3 and 4, the bulk of NOx, SO_2, PM, and CO emissions are generated at the cement manufacturing facility and emitted from the stack. As such, these emissions can be efficiently monitored and quantified. With production volumes, the emissions intensity per tonne of cement can be calculated and used for comparative purposes between China and Canada. However, comparing emission intensities alone provides limited understanding of the potential impact.

In Chapter 4, the health-based comparative LCIA combined the cement emission intensities for NOx, SO_2, PM and CO into a single impact category for winter smog. Although the constituents contribute to other impact categories, the focus of this research is to limit export-based regional air pollution. Interestingly, data from China indicated that their cement manufacturing sector produced lower emissions intensities than Canada's cement industry for NOx and SO_2. However, the $PM_{2.5}$ intensities were much higher in China, and, had much greater impact on air quality than NOx and SO_2.

5.6.3 Synthesis

Given the preference for Policy 3 the parameters of the Canadian approach should be confined to at most a selective border and partial support for domestic cement manufacturers. Drilling down to the preferred policy mechanisms more emphasis is placed on border adjustments than capital investment. With regard to possible border adjustments a verification process is favoured over an environmental tariff. In review of the verification process tactics a universal strategy is considered in addition to a cement-specific approach.

From a universal perspective on trade with China an air quality agreement under CEPA should be established. In the agreement a framework which provides procedures for evaluating products for their embodied emissions / environmental impact should be built-in. Ultimately, the agreement will include product EPDs, however, in the interim uniform PCR that follows ISO 14025:2006 must be defined in the document. As a base requirement of the agreement both countries need to acknowledge regional air pollution extends beyond jurisdictional boundaries.

With specific regard to establishing requirements for exporting cement to Canada, manufacturers in China will need to provide emission intensities for the main regional nocuous pollutants (NOx, SO_2, PM, CO). These intensities will be comparatively evaluated to national intensities in Canada and assessed collectively in terms of impact applying standardized LCA damage factors for winter smog. At minimum the exporting manufacturers must demonstrate that both emission intensities and impact do no exceed that of Canadian manufacturers.

Eventually this process evaluation process would be matured and incorporated under a Canada-China agreement as an EPD for cement.

5.6.4 Limitations

In AHP, data for the pair-wise comparisons are typically collected from experts or decisions makers in a survey format. In this study no survey was carried out. Instead, the three actionable solidarities of Cultural Theory (individualist, egalitarian, hierarchist) and their corresponding perspectives were applied as a surrogate for the survey. Although this may be considered a data limitation, unlike the less reliable response of survey participants who may be influenced by external factors, the solidarities remain consistent (Rindermann et al., 2016; Lin and Lu, 2012). Serenko and Dohan (2011) found that experts may show biased judgement based on their current research. Given the solidarities are roughly analogous to perspectives on policy working group, the recommendation expressed may be more realistic.

In addition to forgoing the survey, the criteria weighting was not developed as a result of pair-wise comparisons in accordance with AHP. Instead, each criterion was arbitrarily assigned one third of the weighting. Even though this reduces the extent of the analysis, the benefit of equal weighting is that it minimizes the potential for a systematic error.

Ultimately, the limitations expressed simply reflect a novel approach to decision-making. The application of the Cultural Theory with MCDA may be considered a viable alternative to expert review. Although the literature for this approach may not be directly available for evidentiary discussion, there is possible linkage to artificial intelligence paradigms. To the contrary, there is considerable evidence to suggest the expert survey approach is subject to bias. Interestingly, future debate and research on the relative importance of surveying may be an indirect benefit of this work.

Chapter 6: Conclusions and Recommendations

6.1 Summary and Conclusions

As indicated in Chapter 1, most industrial processes Portland cement manufacturing generates air emissions. These emissions are produced throughout the life cycle of cement production from quarrying limestone to packaging and transporting the finished product. The largest contributors to air emissions from cement manufacturing are CO_2, NOx, SO_2 and PM (WBCSD, 2005). Other substances that may be emitted from cement manufacturing include volatile organic compounds, acid gases, trace metals and organic micro pollutants. However, these other substances are only emitted in trace quantities (WBCSD, 2005).

It is important to stress that cement is one of the most widely used man-made substances on the planet, second only to water. It is estimated that each man, woman and child consume 350 kg of cement each year (WBCSD, 2005). In 2008 global cement production was approximately 2.8 billion tonnes (WBCSD, 2011). Despite the incredible need and consumption of cement for use in concrete to build housing and infrastructure there is also an awareness of the environmental sustainability issues associated with the manufacturing process (WBCSD, 2005).

In developed countries with strong environmental regulatory systems consideration must be given offshoring production of industry. Emerging markets such as China that assume production for other markets, further impact their already degraded air quality, particularly in heavily industrialized areas. Apart from the well documented CO_2 leakage, regional air pollution leakage should also be considered.

As a global industry, cement manufacturing provides unique insight into the effects of competition between emerging markets and developed markets. Cement is an intermediate product that serves as the main binding agent in concrete. Given the product quality is generally analogous the market advantage is limited to the cost of production and the cost of transportation to the consumer. Emerging markets like China typically have an advantage on cost due to less stringent environmental regulation, subsidies and lower labour costs.

Unfortunately, the market success puts a serious strain on China's environment. Industrial air emissions have serious impact on air quality. According to the WHO, in 2014, of the 209 cities and towns assessed for air quality in China, 67% were above an annual mean concentration of 70 $\mu g/m^3$ for PM_{10}, and, 79% were at or above an annual mean concentration of 35 $\mu g/m^3$ $PM_{2.5}$ (WHO, 2016). At those concentrations, individuals are subject to a long term mortality risk of 15% higher than the recommended guideline of 20 $\mu g/m^3$ for PM_{10} and 10 $\mu g/m^3$ for $PM_{2.5}$.

While China is profiting from controlling the market, the cost of externalities appears to be overlooked. Xi et al. (2013) calculated that in China the cost (US dollars) of environmental damage per tonne of PM_{10}, NO_x and SO_2 are $7,714, $1,006 and $902, respectively. In the example of PM10, for every 1 million tonnes of Portland cement produced in China, with an intensity of 3.58×10^{-4} tonnes of PM_{10}/tonne of cement, at $7,714 per tonne, the environmental cost is approximately $2.76 million. Although, the cost seems considerable, at an arbitrary $100 US per tonne of cement, the cost is only 2.76% of the revenue.

The environmental challenges China faces result from both failures in domestic policy and failure in the policy of its trading partners. Clearly, complete dismantling of antiquated technology, creation of a strong 'national emissions reporting system', and, improved regulation and enforcement must be carried out. With China's economic strength, all cement manufacturing should be state-of-the-art kiln technology, full implementation of emissions control technologies, and assurance that operators are highly skilled. Even with marginal increases in cost per tonne of cement to cover costs, China will continue to supply the bulk of global cement.

At the same time, developed countries such as Canada with stronger environmental regulation, minimal subsidies, and high labour costs, need to address the issue of production leakage and associated regional air emissions. Without protection measures, domestic cement production, other EITE industries, and industries in general will not be able to compete. Moreover, Canada and other developed countries have an ethical duty to not simply push pollution onto emerging markets. Effective regulatory framework needs to be established to account for the potential adverse environmental impact of trade.

Export-based regional air pollution is not well acknowledged. Understandably, jurisdictions prioritize minimizing regional air pollution within their own borders. Unfortunately, as an unintended consequence of a strong regulatory environment, industries may relocate to jurisdictions with less stringency to avoid compliance costs. These jurisdictions are typically emerging markets, such as China.

As an importer of products from emerging markets it is important that Canada recognizes the potential impact to these jurisdictions. The purpose and intent of regulating air emissions from industry in Canada is to protect the health of Canadians and their environment. Failing to extend these values to the global community, while knowingly importing emissions intense products, signals a tiered approach to the value of human life.

Canada has a unique opportunity to create international policy that positively influences the quality of life in emerging markets. Additionally, the regulatory framework and policy mechanisms discussed in this research can be universally applied. Consequently, Canada would be viewed globally as taking a leadership role in reducing export-based regional air pollution.

6.2 Limitations and Future Recommendations

In completing the three objectives of this research the main concern was obtaining reliable emissions data available from Portland cement manufacturing in emerging markets. As an example, a direct comparison between Canadian environmental performance and China's environmental performance is problematic. Firstly, the amount of production in Canada is far more manageable to monitor in comparison to China's massive inventory. Data inventory and monitoring requirement are poor. The CSI provides some analysis of China's cement production, however, these are new facilities and only cover 80 million tonnes of the ≈ 1.5 billion tonnes of cement produced in China.

Despite the data quality challenge, the recommendations provided as a result of this research consists of two parts. The overarching and longer term component is an agreement between China and Canada that deals with air pollution generated from trade (see Figure 6.1) and the second and shorter term component is a process to mitigate emissions leakage from the Portland cement manufacturing sector (see Figure 6.2).

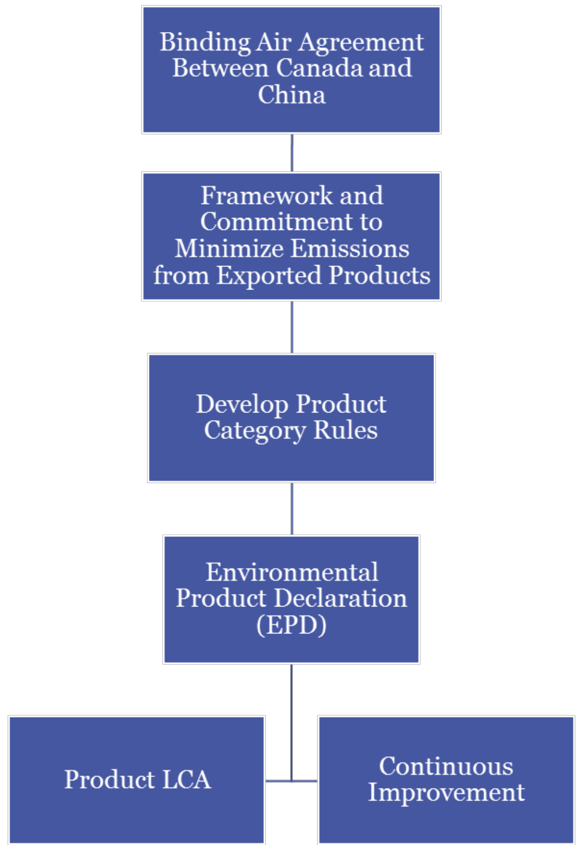

Figure 6.1: China/Canada air quality agreement

As depicted in Figure 6.1, the agreement between China and Canada would be created based on the following recommendations:

1. Canadian government, in accordance with Part 7, Division 6 of CEPA, take appropriate action to develop an internationally binding agreement with China on air quality;

2. Chinese and Canadian policy makers cooperatively develop an overarching framework for the binding document that acknowledges, and agrees to, the need to minimize air pollution from products manufactured for the export market;

3. In accordance ISO 14025:2006, Chinese and Canadian policy makers, with scientific experts, cooperatively develop PCR for all traded products in support of LCA for EPDs;

4. Once established, the EPD for each product from the best performing jurisdiction becomes the minimum requirement for exporting, and, is incorporated into the legally binding agreement. If only one jurisdiction provides the product then that EPD becomes the default unless a comparable international standard is available; and,

5. Incorporate a provision within the legally binding agreement to allow for continuous improvement of product EPDs.

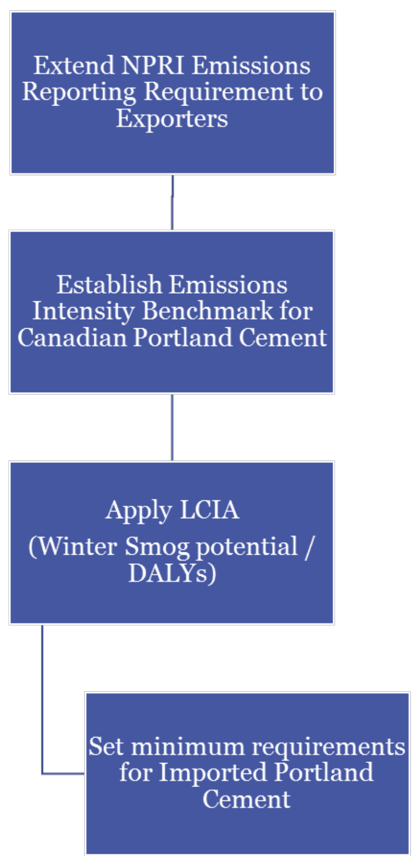

Figure 6.2: Process for mitigating emissions leakage from Portland cement manufacturing

The second component, described in Figure 6.2, is an approach to specifically mitigate emissions leakage from Portland cement manufacturing. For this process, the following recommendations are provided:

1. In accordance with CEPA, extend the emissions reporting requirement under NPRI for Canadian Portland cement manufacturing to export manufacturers in China;

2. Develop an emissions intensity benchmark from NPRI data for the Canadian Portland cement manufacturing sector for the main regional nocuous pollutants (NOx, SO_2, PM, PM_{10}, $PM_{2.5}$ and CO);

3. Apply LCIA methodology to the emissions intensities of the Canadian benchmark and determine the winter smog potential and associated DALYs per tonne of Portland cement; and,

4. In advance of establishing a China-Canada agreement, and incorporating an EPD for Portland cement, set minimum requirements for imported cement such that embodied emissions (winter smog potential / DALYs per tonne of Portland cement) do not exceed the Canadian benchmark value.

6.3 Research Significance and Originality

The most significant aspect of this work is the awareness that industrial air pollution reduction or prevention measures cannot be limited to jurisdictional boundaries. In the example of Portland cement manufacturing, the imported product from China had more than twice the impact to human health over the domestic product. Although it is important to protect and enhance local air quality, the global community must also be considered.

Efforts to minimize industrial pollution domestically, without considering the international market, particularly in the case of EITE industry, will simply result in pollution dumping to emerging markets.

Establishing international air pollution agreements that set minimal standards for the embodied impact of products (e.g., EPD) will minimize emissions leakage and enhance air quality in emerging markets.

In review of the available scientific literature there is considerable discussion on emissions leakage as it pertains to GHG abatement policy and programs. That said, leakage of regional nocuous emissions is not well understood or discussed.

Interestingly, environmental burden on emerging markets from manufacturing for the export industry is well known. However, this export-based pollution often attributed to the lack of relevant legislation / control in the emerging market and not to the gap in the regulatory framework of the developed market.

References

Ascough II, J. C., Maier, H. R., Ravalico, J. K., Strudley, M. W. (2008). Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. *Ecological Modelling,* 219 (3-4), 383-399.

Baldauf, R. W., Lane, D. D. (2001). Air quality impacts from hazardous waste combustion at portland cement manufacturing plants. *Ninth International Conference on Modelling, Monitoring and Management of Air Pollution, Air Pollution IX, September 12, 2001 - September 14,* 10, 325-334.

Barker, T., Junankar, S., Pollitt, H., Summerton, P. (2007). Carbon leakage from unilateral environmental tax reforms in europe, 1995-2005. *Energy Policy,* 35(12), 6281-6292.

Bernard, A., Vielle, M. (2009). Assessment of European Union transition scenarios with a special focus on the issue of carbon leakage. *Energy Economics,* 31, S274-S284.

Boughton, B., Horvath, A. (2006). Environmental assessment of shredder residue management. *Resources, Conservation and Recycling,* 47(1), 1-25.

Bradley, A., Chen, B., Jackson, K., Moore, R., Baloga, S. (2011). Multi-pollutant control for the portland cement industry. *2011 IEEE-IAS/PCA 53rd Cement Industry Technical Conference, CIC 2011, May 22, 2011 - May 26.*

Brown, D., Sadiq, R., Hewage, K. (2014). An overview of air emissions intensities and environmental performance of grey cement manufacturing in Canada. *Clean Technologies and Environmental Policy*, 16(6), 1119-1131.

Brown, D., Sadiq, R., Hewage, K. (2017). A health-based life cycle impact assessment (LCIA) for cement manufacturing: a comparative study of China and Canada. *Clean Technologies and Environmental Policy* [accepted]

Brown, D., Sadiq, R., Hewage, K. (2017). Investigating the impacts of plausible Canadian policies and their supporting mechanisms on export-based regional air pollution in China: A case of cement manufacturing. *Environmental Management* [under review]

Canpolat, B. R., Atimtay, A. T., Munlafalioglu, I., Kalafatoglu, E., Ekinci, E. (2002). Emission factors of cement industry in turkey. *Water, Air, and Soil Pollution,* 138(1-4), 235-252.

Cement Association of Canada. (2010). *2010 Canadian cement industry sustainability report*. Ottawa-Ontario, Canada: Cement Association of Canada.

Cement Association of Canada. (2012). *2012 environmental performance report*. Ottawa-Ontario, Canada: Cement Association of Canada.

Cement Association of Canada (2016). *2016 annual report*. Ottawa-Ontario, Canada: Cement Association of Canada.

Chattopadhyay, D., Dhar, G. (1988). Air pollution control in the indian cement industry - an overview. *Journal of the Institution of Engineers (India): Chemical Engineering Division,* 68 (2), 39-42.

Chen, C., Habert, G., Bouzidi, Y., Jullien, A. (2010). Environmental impact of cement production: Detail of the different processes and cement plant variability evaluation. *Journal of Cleaner Production,* 18(5), 478-485.

Chen, C., Habert, G., Bouzidi, Y., Jullien, A.,Ventura, A. (2010). LCA allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete. *Resources, Conservation and Recycling,* 54(12), 1231-1240.

Chen, Y. (2009). Does a regional greenhouse gas policy make sense? A case study of carbon leakage and emissions spillover. *Energy Economics,* 31(5), 667-675.

Corti, A., Lombardi, L. (2004). End life tyres: Alternative final disposal processes compared by LCA. 29(12-15), 2089-2108.

Cristea, D., & Cinti, G. (2010). Cement Kilns. Industrial Combustion Testing. Chapter 31, 615-669.

Dab, W., Medina, S., Quenel, P., Le Moullec, Y., Le Tertre, A., Thelot, B., Monteil, C., Lameloise, P., Pirard, P., Momas, I., Fest, B. (1996). Short term respiratotry health effects of ambient air pollution: results of the APHEA project in Paris. *Journal of Epidemiol Community Health*, 50(1), 42-46.

De Gorter, H., & Drabik, D. (2011). Components of carbon leakage in the fuel market due to biofuel policies. *Biofuels,* 2(2), 119-121.

Deja, J., Uliasz-Bochenczyk, A., Mokrzycki, E. (2010). CO2 emissions from polish cement industry. *International Journal of Greenhouse Gas Control,* 4(4), 583-588.

ECCC (2013). Canadian ambient air quality standards. Retrieved from http://www.ec.gc.ca/default.asp?lang=En&n=56D4043B-1&news=A4B2C28A-2DFB-4BF4-8777-ADF29B4360BD

ECCC (2013). Canada – United States air quality agreement. Retrieved from http://www.ec.gc.ca/Air/default.asp?lang=En&n=1E841873-1

ECCC (2014). Canadian environmental protection act, 1999. Retrieved from http://www.ec.gc.ca/lcpe-cepa/26A03BFA-C67E-4322-AFCA-2C40015E741C/lcpe-cepa_201310125_loi-bill.pdf

EPA (2016). National ambient air quality standards. Retrieved from https://www.epa.gov/regulatory-information-topic/regulatory-information-topic-air#criteriapollutants

European Economic Commission. (2010). Commission decision of December 2009 determining pursuant to directive 2003/87/EC of the European parliament and of the council, a list of sectors and subsectors which are deemed to be exposed to a significant risk of carbon leakage. *Official Journal of the European Union,* L1, 10-18.

Eddings, E. G., Pershing, D. W. (1996). Hydrocarbon emissions due to raw materials in the manufacture of portland cement. *Proceedings of the 1996 Air & Waste Management Association's 89th Annual Meeting & Exhibition, June 23, 1996 - June 28,* 16-16.

Ehrlich, C., Noll, G., Kalkoff, W., Baumbach, G., Dreiseidler, A. (2007). PM10, PM2.5 and PM1.0-emissions from industrial plants-results from measurement programmes in germany. *Atmospheric Environment,* 41(29), 6236-6254.

European Chamber. (2009). Overcapacity in china, causes, impacts and recommendation.

European Economic Commission. (2010). Commission decision of december 2009 determining pursuant to directive 2003/87/EC of the european parliament and of the council, a list of sectors and subsectors which are deemed to be exposed to a significant risk of carbon leakage. *Official Journal of the European Union,* L1, 10-18.

Fisher, S. (2010). EPA sets mercury limits for cement industry. *Pollution Engineering,* 42(8).

Gäbel, K., Forsberg, P., Tillman, A. (2004). The design and building of a lifecycle-based process model for simulating environmental performance, product performance and cost in cement manufacturing. *Journal of Cleaner Production, 12*(1), 77-93.

Goyal, P., Singh, M. P., Gulati, A. (1996). Air quality assessment of the environment over a cement industrial complex. *Atmospheric Environment,* 30(7), 1159-1166.

Greer, W. L., Hawkins, G. J. (2004). A qualitative examination of the control of major gaseous pollutants generated in portland cement kilns. *Proceedings of the A and WMA's 97th Annual Conference and Exhibition; Sustainable Development: Gearing Up for the Challenge, June 22, 2004 - June 25,* 3787-3817.

Guardigli, L., Monari, F., Bragadin, M. A. (2011). Assessing environmental impact of green buildings through LCA methods:Acomparison between reinforced concrete and wood structures in the european context. *2011 International Conference on Green Buildings and Sustainable Cities, GBSC 2011, September 15, 2011 - September 16,* 21, 1199-1206.

Guo. M. (2012). Life cycle assessment (LCA) of light-weight eco-composites. *Springer Theses*. Berlin, Germany.

Gupta, R. K., Majumdar, D., Trivedi, J. V., & Bhanarkar, A. D. (2012). Particulate matter and elemental emissions from a cement kiln. *Fuel Processing Technology,* 104(0), 343-351.

He, K., Huo, H., Zhang, Q. (2002). Urban air pollution in china: Current status, characteristics, and progress. *Annual Review of Energy and the Environment*, 27, 397-431.

Horton, J., Linero, A., Miller, F. M. (2006). Use of SNCR to control emissions of oxides of nitrogen from cement plants. *2006 IEEE Cement Industry Technical Conference Record, April 9, 2006 - April 14, 2006,* 316-344.

Houillon, G., Jolliet, O. (2005). Life cycle assessment of processes for the treatment of wastewater urban sludge: Energy and global warming analysis. *Environmental Assessments and Waste Management,* 13(3), 287-299.

Hung, M., Ma, H.,Yang, W. (2007). A novel sustainable decision making model for municipal solid waste management. *Waste Management*, 27(2), 209-219.

Huntzinger, D. N., Eatmon, T. D. (2009). A life-cycle assessment of portland cement manufacturing: Comparing the traditional process with alternative technologies. *Journal of Cleaner Production,* 17(7), 668-675.

Huo, H., Zhang, Q., Guan, D., Su, X., Zhao, H., He, K (2014). Examining air pollution in China using production- and consumption-based emissions accounting approaches. *Environmental Science and Technology*, 48, 14139-14147.

ISO 14025:2006. (2015). Environmental labels and declarations — type III environmental declarations — principles and procedures. Retrieved from https://www.iso.org/obp/ui/#iso:std:38131:en

ISO 14040:2006. (2016). Environmental management – life cycle assessment – principles and framework. Geneva, Switzerland: International Organisation for Standardization.

ISO 14044:2006. (2016). Environmental management – life cycle assessment – requirements and guidelines. Geneva, Switzerland: International Organisation for Standardization.

Josa, A., Aguado, A., Cardim, A., Byars, E. (2007). Comparative analysis of the life cycle impact assessment of available cement inventories in the EU. *Cement and Concrete Research,* 37(5), 781-788.

Josa, A., Aguado, A., Heino, A., Byars, E., Cardim, A. (2004). Comparative analysis of available life cycle inventories of cement in the EU. *Cement and Concrete Research,* 34(8), 1313-1320.

Kabir, G., Madugu, A. I. (2010). Assessment of environmental impact on air quality by cement industry and mitigating measures: A case study. *Environmental Monitoring and Assessment,* 160(1-4), 91-99.

Kallbekken, S., Flottorp, L. S., & Rive, N. (2007). CDM baseline approaches and carbon leakage. *Energy Policy,* 35(8), 4154-4163.

Koroneos, C. J., Dompros, A. T. (2009). Environmental assessment of the cement and concrete life cycle in greece. *International Journal of Environmental Technology and Management, 10*(1), 71-88.

Kuik, O., Hofkes, M. (2010). Border adjustment for european emissions trading: Competitiveness and carbon leakage. *Energy Policy,* 38(4), 1741-1748.

Kuramochi, T., Ramírez, A., Turkenburg, W., & Faaij, A. (2012). Effect of CO2 capture on the emissions of air pollutants from industrial processes. *International Journal of Greenhouse Gas Control, 10*(0), 310-328.

Kwok, R. C., Ma, J., Zhou, D. (2002). Improving group decision making: A fuzzy GSS approach. *IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews*, 32(1), 54-63.

Lee, K., Park, P. (2005). Estimation of the environmental credit for the recycling of granulated blast furnace slag based on LCA. *Resources, Conservation and Recycling,* 44(2), 139-151.

Lei, Y., Zhang, Q., Nielsen, C., He, K. (2011). An inventory of primary air pollutants and CO2 emissions from cement production in china, 1990-2020. *Atmospheric Environment,* 45(1), 147-154.

Li, L., Xu, G., Lu, X. (2010). A novel fuzzy route selection method based on multi-norm decision making. *2010 2nd International Conference on Computer Engineering and Technology, ICCET 2010, April 16, 2010 - April 18*, 3, V3619-V3623.

Lin, S-W., Lu, M-T. (2012). Characterizing disagreement and inconsistency in experts' judgements in the analytic hierarchy process. *Management Decision*, 50(7), 1252-1265.

Liu, S., Lin, Z., Kang, M. (2000). Environmental impact assessment of cement-concrete system. *Journal Wuhan University of Technology, Materials Science Edition,* 15(4), 7-11.

Maria, C. D., Van, D. W. (2008). Carbon leakage revisited: Unilateral climate policy with directed technical change. *Environmental and Resource Economics*, 39(2), 55-74.

Matthews, H. S., Lave, L., MacLean, H. (2002). Life cycle impact assessment: A challenge for risk analysts. *Risk Analysis*, 22(5), 853-860.

McKee, D. J., Rodriguez, R. M. (1993). Health effects associated with ozone and nitrogen dioxide exposure. *Water, Air and Soil Pollution*, 67(1-2), 11-35.

National Pollution Release Inventory (2016). Retrieved on June 23 from https://www.ec.gc.ca/inrp-npri/

Oggioni, G., Riccardi, R., Toninelli, R. (2011). Eco-efficiency of the world cement industry: A data envelopment analysis. *Energy Policy,* 39(5), 2842-2854.

Ontario Regulation 194/05 - Industry Emissions - Nitrogen Oxides and Sulphur Dioxide (2005).

Ortiz, O., Castells, F., Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials,* 23(1), 28-39.

PCA. (2004). Innovations in portland cement manufacturing. Skokie, United States: Portland Cement Association.

Peters, G. P. (2010). Policy update: Managing carbon leakage. *Carbon Management,* 1(1), 35-37.

PRé. (2001). The eco-indicator 99 – a damage oriented method for life cycle impact assessment – methodology report. Amersfoort, Netherlands.

Rhode, R., Muller, R. (2015). Air pollution in China: mapping of concentrations and sources. *Plose One*, 10(8).

Riccardi, R., Oggioni, G., Toninelli, R. (2012). Efficiency analysis of world cement industry in presence of undesirable output: Application of data envelopment analysis and directional distance function. *Energy Policy,* 44(0), 140-152.

Rindermann, H., Becker, D., Coyle, T.R. (2016). Survey of expert opinion on intelligence: causes of international differences in cognitive ability tests. *Journal of Frontiers in Psychology*, 7(399).

Saaty T. L. (1980). *The Analytic Hierarchy Process*. New York: McGraw Hill.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Sciences*, 1(1), 83-98.

Salmento, J. S., Shenk, R. E. (2004). Accurately predicting cement plant emissions. *Conference Record - IEEE-IAS/PCA 2004 Cement Industry Technical Conference, April 25, 2004 - April 30, 2004,* 333-343.

Santacatalina, M., Reche, C., Minguillon, M. C., Escrig, A., Sanfelix, V., Carratala, A. (2010). Impact of fugitive emissions in ambient PM levels and composition. A case study in southeast spain. *Science of the Total Environment,* 408(21), 4999-5009.

Schreiber Jr., R. J., Kellett, C. D., Streitman, F. (2009). Development of a quantitative, predictive mercury model for a cement kiln. *2009 IEEE Cement Industry Technical Conference Record, may 29, 2009 - June 5*.

Schwarz, M., Thompson, M. (1990). Divided we stand: redefining politics, technology and social choice. Philadelphia, Pennsylvania: University of Pennsylvania Press.

Serenko, A., Dohan, M. (2011). Comparing the expert survey and citation impact journal ranking methods: example from the field of artificial intelligence. *Journal of Informetrics*, 5(2011), 629-648.

Sheth, S. H. (1992). SO2 emissions history and scrubbing system. *IEEE Transactions on Industry Applications,* 28(4), 970-980.

Sikkema, J. K., Alleman, J. E., Kee Ong, S., Wheelock, T. D. (2011). Mercury regulation, fate, transport, transformation, and abatement within cement manufacturing facilities: Review. *Science of the Total Environment,* 409(20), 4167-4178.

Singh, A., Berghorn, G., Joshi, S., Syal, M. (2011). Review of life-cycle assessment applications in building construction. *Journal of Architectural Engineering,* 17(1), 15-23.

Song, P., Mao, X., Corsetti, G. (2015). Adjusting export tax rebates to reduce the environmental impacts of trade: lessons from china. *Journal of Environmental Management,* 161, 408-416.

StatCan (2015). Population and demography. Retrieved from http://www.statcan.gc.ca/pub/11-402-x/2012000/chap/pop/pop-eng.htm?fpv=3867

StatCan (2016). Gross domestic product at basic prices, by industry (monthly). Retrieved from http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/gdps04a-eng.htm

Strazza, C., Del Borghi, A., Gallo, M., & Del Borghi, M. (2011). Resource productivity enhancement as means for promoting cleaner production: Analysis of co-incineration in cement plants through a life cycle approach. *Journal of Cleaner Production*, 19(14), 1615-1621.

TTH (2009). Morning moon – we are the same. Retrieved from http://www.thehip.com/albums/We+Are+The+Same/Morning+Moon/

Thompson, M. (2000). Understanding environmental values: a cultural theory approach. Retrieved from http://www.carnegiecouncil.org/publications/articles_papers_reports/710.html/_res/id=sa_File1/711_thompson.pdf

Valderrama, C., Granados, R., Cortina, J. L., Gasol, C. M., Guillem, M., Josa, A. (2012). Implementation of best available techniques in cement manufacturing: A life-cycle assessment study. *Journal of Cleaner Production,* 25, 60-67.

Van, D. H., De Belie, N. (2012). Environmental impact and life cycle assessment (LCA) of traditional and 'green' concretes: Literature review and theoretical calculations. *Cement and Concrete Composites,* 34(4), 431-442.

Vares, S., Hakkinen, T. (2009). LCA tool for cement manufacturers for system optimization and for environmental reporting. *Symposium on Life Cycle Assessment of Products and Technologies, LCA, October 6, 2009 - October* 6, (262), 122-133.

Wang, K., Xie, S. (2011). The environment effect embodied in export and import of china's industry: An analysis based on the industrial data. *International Conference on Management and Service Science, MASS 2011, August 12, 2011 - August 14*.

Wang, S., Hao, J. (2012). Air quality management in china: issues, challenges, and options. *Journal of Environmental Sciences,* 24(1), 2-13.

Wang, Z., Bin, Z., Zeng, H. (2015). The effect of environmental regulation on external trade: empirical evidences from chinese economy. *Journal of Cleaner Production*, 114 (2016), 55-61.

WBCSD. (2005). Cement sustainability initiative - guidelines for emissions monitoring and reporting in the cement industry (1.0). Conches-Geneva, Switzerland: World Business Council for Sustainable Development.

WBCSD. (2011). Cement sustainability initiative - CO_2 and energy accounting and reporting standard for the cement industry (3.0). Conches-Geneva, Switzerland: World Business Council for Sustainable Development.

WBCSD. (2012). Cement sustainability initiative - guidelines for emissions monitoring and reporting in the cement industry (2.0). Conches-Geneva, Switzerland: World Business Council for Sustainable Development.

WHO (2016). WHO global urban ambient air pollution database (update 2016). Retrieved from http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/

WHO (2016). Media centre: 7 million deaths annually linked to air pollution. Retrieved from: http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/

Xu, D., Cui, Y., Li, H., Yang, K., Xu, W., Chen, Y. (2015). On the future of chinese cement industry. *Cement and Concrete Research*, 78, 2-13.

Xi, Y., Fei, T., Gehua, W. (2013). Incorporating environmental co-benefits into climate policies: a regional study of the cement industry in china. *Applied Energy*, 112, 1446-1453.

Yin, C., Li, T., Liu, F., Yin, S. (2010). Decision-making framework model for networked outsourcing resources selection. *Jixie Gongcheng Xuebao/Journal of Mechanical Engineering,* 46(19), 133-139.

Young, G. L. (2002). NOx formation in rotary kilns producing cement clinker applicable NOx control techniques and cost effectiveness of these control techniques. *IEEE-IAS/PCA 2002 Cement Industry Technical Conference: Conference Record, May 5-9, 2002*, 239-254.

Zaim, K. K. (1996). Emissions due to fossil-fuel consumption and cement production in turkey (1970-1991). *Energy,* 21(4), 325-331.