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Industrial Ecology and Development of Production Systems

Analysis of the CO₂ Footprint of Cement

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Cover photos:

Photos on the cover and the back are taken on March 2011 during site visit to Kollenbach cement plant in Germany. On the front is the view of the nearby town observed from the roof of the plant. The back shows a view of the local limestone quarry.

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Abstract

This research is an attempt to create a comprehensive assessment framework for identifying and assessing potential improvement options of cement production systems.

From an environmental systems analysis perspective, this study provides both an empirical account and a methodological approach for quantifying the CO₂ footprint of a cement production system. An attributional Life Cycle Assessment (LCA) is performed to analyze the CO₂ footprint of several products of a cement production system in Germany which consists of three different plants. Based on the results of the LCA study, six key performance indicators are defined as the basis for a simplified LCA model. This model is used to quantify the CO₂ footprint of different versions of the cement production system.

In order to identify potential improvement options, a framework for Multi-Criteria Assessment (MCA) is developed. The search and classification guideline of this framework is based on the concepts of Cleaner Production, Industrial Ecology, and Industrial Symbiosis. It allows systematic identification and classification of potential improvement options. In addition, it can be used for feasibility and applicability evaluation of different options. This MCA is applied both on a generic level, reflecting the future landscape of the industry, and on a production organization level reflecting the most applicable possibilities for change. Based on this assessment a few appropriate future-oriented scenarios for the studied cement production system are constructed. The simplified LCA model is used to quantify the CO₂ footprint of the production system for each scenario.

By integrating Life Cycle Assessment and Multi-Criteria Assessment approaches, this study provides a comprehensive assessment method for identifying suitable industrial developments and quantifying the CO₂ footprint improvements that might be achieved by their implementation.

The results of this study emphasize, although by utilizing alternative fuels and more efficient production facility, it is possible to improve the CO₂ footprint of clinker, radical improvements can be achieved on the portfolio level. Compared to Portland cement, very high reduction of CO₂ footprint can be achieved if clinker is replaced with low carbon alternatives, such as Granulated Blast Furnace Slag (GBFS) which are the by-products of other

industrial production. Benchmarking a cement production system by its portfolio product is therefore a more reasonable approach, compared to focusing on the performance of its clinker production.

This study showed that Industrial Symbiosis, that is, *over the fence* initiatives for material and energy exchanges and collaboration with non-traditional partners, are relevant to cement industry. However, the contingent nature of these strategies should always be noted, because the mere exercise of such activities may not lead to a more resource efficient production system. Therefore, in search for potential improvements, it is important to keep the search horizon as wide as possible, however, assess the potential improvements in each particular case. The comprehensive framework developed and applied in this research is an attempt in this direction.

Keywords

industrial ecology, industrial symbiosis, industrial development, life cycle assessment, multi-criteria assessment, CO₂ footprint, cement

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Finally, I wish to thank my family for their care, devotion, and patience. In particular, my father and my late mother whose love and prudence have shaped my being.

List of Appended Papers

This thesis is based on the three following articles (see Appendix):

Article I- Feiz, R., Ammenberg, J., Baas, L., Eklund, M., Helgstrand, A., Marshall, R., 2014a. Improving the CO₂ performance of cement, Part I: Utilizing life-cycle assessment and key performance indicators to assess development within the cement industry. *Journal of Cleaner Production*.

Article II- Feiz, R., Ammenberg, J., Baas, L., Eklund, M., Helgstrand, A., Marshall, R., 2014b. Improving the CO₂ performance of cement, Part II: Framework for assessing CO₂ improvement measures in the cement industry. *Journal of Cleaner Production*.

Article III- Ammenberg, J., Feiz, R., Baas, L., Eklund, M., Helgstrand, A., Marshall, R., 2014. Improving the CO₂ performance of cement, Part III: The relevance of Industrial Symbiosis and how to measure its impact. *Journal of Cleaner Production*.

These articles are developed from earlier versions presented at Greening of Industry Network (GIN) conference in October 2012 at Linköping, Sweden.

My Contribution to the Papers

The three articles are written in close relationship to each other and I have been actively involved in all stages of their development. As co-authors as well as my supervisors, Jonas Ammenberg and Mats Eklund have provided comments on all the articles on many occasions, while I have also benefited from the advisory input of Leenard Baas and Richard Marshall in all articles.

- Article I: Along with Anton Helgstrand, I have had a major contribution in data collection, LCA modeling, analysis and writing of this article. I have developed the simplified LCA model based on a few key performance indicators.

- Article II: I have had major contribution in all parts of this article, including data collection, analysis, development and application of the multi-criteria assessment framework, and writing.
- Article III: While Jonas Ammenberg is the leading author of this article, I have made major contributions to it, specifically in relation to developing the scenarios, applying both the quantitative and qualitative methods developed in Article I and Article II to them, and performing the synthetic analysis based on the results.

In addition, I have played a major role in establishing the integrative methodology which encompasses these three articles.

Other Related Publications

- Feiz, R., 2011. Improving climate performance of cement production; developing an assessment framework and applying it to a CEMEX cement production cluster in Germany (Master thesis). Linköping University, Sweden.
- Ammenberg, J., Feiz, R., Helgstrand, A., Eklund, M., Baas, L., 2011. Industrial Symbiosis for improving the CO₂ -performance of cement production. Linköping University, Sweden.

Nomenclature

Glossary

Blended cement	Cement types such as CEM III which contain more than 5% clinker substitutes.
CEM I	Portland cement with clinker content between 95% to 100%
CEM II	Blended cement with clinker content between 65% to 94%
CEM III/A	Blended cement (blast-furnace cement) with clinker content between 35% to 64%
CEM III/B	Blended cement (blast-furnace cement) with clinker content between 20% to 34%
CEM III/C	Blended cement (blast-furnace cement) with clinker content between 5% to 19%
Clinker	A basic component of Portland cement, produced by calcification of limestone
CO ₂ footprint	Greenhouse gas emissions of a product over its life cycle expressed in CO ₂ -eq (100-year global warming potential: IPCC, 2007b). Because in cement industry the greenhouse gas emissions are predominantly CO ₂ this term is selected.

Abbreviations

BFS	Blast-furnace slag
CP	Cleaner Production
GBFS	Granulated blast-furnace slag
GGBFS	Ground granulated blast-furnace slag
GWP	Global Warming Potential
IE	Industrial Ecology
IS	Industrial Symbiosis
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
ALCA	Attributional Life Cycle Assessment
CLCA	Consequential Life Cycle Assessment
LCRE	Life-Cycle Resource Efficiency
MCA	Multi-Criteria Assessment
OPC	Ordinary Portland Cement
SCM	Supplementary Cementitious Materials

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Thesis Outline

The content of this thesis is structured as follows:

Chapter 1 (Introduction) focuses on cement production, its challenges, and existing industrial and academic approaches for tackling them. It provides a background for the aim and research questions, with considerations to its scope.

A short summary of cement production and key trends in the cement industry is presented in Chapter 2 (Cement Production). In addition, a few of the special characteristics of cement production which differentiate it from many other forms of industrial production are presented.

The theoretical foundations of this research are presented in Chapter 3 (Theoretical Framework) where concepts such as Life Cycle Assessment and Resource Efficiency are introduced.

In Chapter 4 (Methodology) the research process, the studied case, and the methods used for data collection and analysis are presented.

The main results of the research is presented in Chapter 5 (Results) followed by critical reflections on its methodological perspective, and results in Chapter 6 (Discussion).

The conclusions of this study are summarized in Chapter 7 (Conclusions) and a few of the possible ways that this research can be continued are discussed in Chapter 8 (The Way Forward).

Finally, the full texts of the three articles (accepted for publication) are appended (see Appendix).

Preface

Our industrial activities and capabilities have placed us in a unique situation. Modern technologies have empowered us in unprecedented ways and at the same time have created unwanted consequences with alarming ecological implications such as resource depletion and global warming (IPCC, 2007a). We cannot undo the past: going backward in time and into a pre-industrial era, even if possible, is not a reasonable path to take. Given the physical and ecological limits of our planet¹ continuing the status quo modes of industrial production and consumption is also not a realistic option. Therefore, a fundamental question that needs to be asked, is whether (and how) we can maintain and strengthen the bright side of our industries, while abating and effectively reducing their dark consequences.

Skeptics may argue that it is not possible, while an array of technological optimists may claim that there is not much to worry about and that existing industrial systems will steer their way out of the problem deterministically and all we have to do is to infest our societies with more technological artifacts. It may be rather easy not to be an outright pessimist, but it is extremely difficult to avoid falling into the deep-rooted idolatries such as *technicism* or *economism* and their various manifestations. Yet, some may maintain that although it is likely that solutions exist, there is no given and pre-determined path toward them. There may be a possible way out of this seemingly downward spiral, but it needs to be constructed deliberately and meticulously with the best of our collective knowledge and abilities.

One can also claim that although it may be possible to summarize the main problems that we are facing today in a universally acceptable manner, it is not possible to formulate universal solutions to those problems. Solutions are often particular and contingent depending on the idiosyncrasies of each time and place. This argument is probably true, but even so, it does not mean that we should not try to identify similar problem patterns and formulate common methodologies and tool sets for approaching them.

One of the concepts that can underline most of the problems of existing industrial systems is *sub-optimization*. The word optimization resonates a

¹For an example of recent attempts to identify and quantify these limits see the study by Rockström et al. (2009). Such studies are often widely acknowledged, but are also seriously criticized (Blomqvist et al., 2012).

positive meaning: “an act, process, or methodology of making something (as a design, system, or decision) as fully perfect, functional, or effective as possible” (Merriam-Webster, 2014). However, in practice, optimization of a small system from a narrow perspective often creates undesirable situations in other systems or possibly even within the same system. Therefore, if we want to avoid shifting problems into other modes, scales, times, or spaces we need to move from the sub-optimization paradigm, that is, optimization of a small system from a narrow perspective, into what is also called co-optimization paradigm, defined as measures and initiatives that aim “to achieve multiple goals without sacrificing one for another, that is, reaching an optimum described as achieving *a proper balance*, that is, a compromise among goals” (Ashford and Hall, 2011).

Our industrial society and its technological systems are subject to change. However, influencing technological development in order to go in the direction of co-optimization needs concepts, approaches and tools that allow us to be empowered in three contrapuntally related problem domains. First is *the diagnosis*, which can be simply defined as increasing our understanding of where we are and what areas have been over-optimized at the expense of other areas being neglected or under-optimized. The second problem domain is *the prognosis* because we need foresight about possible ways in which things can be improved and how important aspects can be co-optimized so that we can influence the construction of better socio-technical systems in the future. The third is *the prescription* which relates to actual decisions about things that need to be done.

In this thesis, performed in relation to the cement industry, it has been assumed that the main issues related to this industry are already diagnosed. So, the point of departure is the existing challenges of the cement industry which can be chiefly characterized by high material and energy intensity and CO₂ emissions. Therefore, the core of this thesis is related to the second problem domain, that is, a prognostic study: How can we systematically identify and prioritize options for improvement in cement production systems? How might improved cement production systems appear in the future? How can we quantify the CO₂ performance of these hypothetical improved systems?

Chapter 1

Introduction

This chapter introduces the background of this study, its aim and research questions, as well as its scope.

Cement is an important material for construction of buildings, roads and various structures. Its production has been increasing during the last century, but since the mid-20th century the increase has been dramatic and continues to grow in most parts of the world. (U.S. Geological Survey, 2005). Cement production has more than doubled during the last two decades, and it has grown by 60% during the years 2005–2012 despite the financial crisis which affected many parts of the world. In 2009, about 0.5 tonnes of cement were produced per person living on the earth. This amounted to about 3 billion tonnes and this number has continued to increase, to 3.6 and 3.7 billion tonnes in 2011 and 2012 respectively (U.S. Geological Survey, 2013). Production of cement is energy and material intensive (van Oss and Padovani, 2002; WBCSD/CSI, 2012) and therefore has significant environmental impacts. Considerable amounts of SO₂, NO₂, and other pollutants are caused by cement production, however its CO₂ emissions which often receive the most attention are estimated to be more than 5% of global anthropogenic CO₂ emissions (EIPPCB, 2013; IEA/WBCSD, 2009; van Oss and Padovani, 2003). In short, cement production has a very high CO₂ footprint¹ and a key imperative for cement industry is to find ways to reduce it.

In recent decades and in many parts of the world, especially in industri-

¹ CO₂ footprint is defined in relation to the concepts of *carbon footprint*, that is, “a measure of the total amount of carbon dioxide (CO₂) and methane (CH₄) emissions of a defined population, system or activity, considering all relevant sources, sinks and storage within the spatial and temporal boundary of the population, system or activity of interest. It is calculated as carbon dioxide equivalent (CO₂-eq) using the relevant 100-year global warming potential (GWP100)” (Wright et al., 2011). In addition, *improving the CO₂ performance of cement* is used as a synonym for *reducing its CO₂-eq footprint*.

alized regions such as northern Europe, the rise of environmental awareness combined with technological advances and more stringent legal frameworks have influenced the cement industry significantly and continues to do so (CP/RAC, 2008, p. 13). This is most visible in the increasing popularity of *Cleaner Production* (CP) (UNEP, 1994) which includes preventive strategies such as *product modification*, *input substitution*, *technology modification*, *good housekeeping*, and *on site recycling* (van Berkel, 2000) in the cement industry.

Traditionally the focus of the producers has been primarily on production plants and their key suppliers and customers. Cleaner Production emphasizes the importance of proactive approaches and reducing environmental impacts by improving the production process itself, as opposed to *end of pipe*² fixes. These strategies correspond to improved management practices and technical enhancements within the cement production plants. Generally, they provide possibilities for reducing many pollutants of cement production, however CO₂ improvements are harder to achieve even if some housekeeping and management practices have CO₂ reduction effects³.

Therefore, the initiatives which demand taking wider system perspectives and participation with new actors when devising the future development plans of a facility may provide new possibilities for reducing the CO₂ footprint of cement. Concepts such as Industrial Ecology (IE) and Industrial Symbiosis (IS)⁴ emphasize the opportunities that can arise by looking outside the traditional supply chains.

In other words, industries should not only look at their back and front, that is, their traditional supply chain, but also peer sideways (Bansal and Mcknight, 2009). Therefore, a thorough approach for identifying and assessing the potential CO₂ improvement options in the cement industry might *a*) include both facility-centered improvement measures and *b*) synergistic solutions involving other industrial actors in the region; *c*) exhaust all feasible means of utilization and valorization of residue energy and materials of the *production system*⁵ including what has been historically referred to as waste. Furthermore, it should have *d*) a mechanism for assessing the suitability for implementation in a particular cement-producing facility considering applicability and desirability;

²End of pipe solutions are pollution-control approaches which aim to reduce the flow of pollutants into the environment *after* they are formed. These solutions are in contrast with pollution-prevention strategies which aim to reduce the generation of pollution at their source.

³Combustion of fuels during clinker manufacturing generates CO₂, but about twice as much CO₂ is formed by the chemical process of calcination itself. Due to this basic fact of chemistry, reducing CO₂ emissions of Portland cement is challenging.

⁴Producers and consumers as actors within an industrial system can develop synergistic linkages between themselves in order to achieve higher economic or environmental efficiency. These synergies can be in the form of material or energy exchanges, but can also shape in the form of knowledge sharing and collaboration. The field of Industrial Symbiosis (IS) which is strongly related to Industrial Ecology (IE) emphasizes the development of these synergies within an industrial system. The aim of IS is to promote the development of these synergies and study their contribution to the efficiency of industrial activities. (see Chertow, 2000; Lombardi and Laybourn, 2012)

and e) a method with a life-cycle based approach to quantify the improvement (or deterioration) of CO₂ footprint of cement products.

An approach which considers all of the above-mentioned elements might be referred to as an integrated approach toward identification and assessment of options for improving CO₂ performance of the cement production. Although several studies focus on individual aspects of improving CO₂ performance of cement, not many have approached it from an integrated view, combining a systematic identification and assessment of suitable improvement measures with life-cycle analysis of the production system. An integrated approach can provide valuable insights for the strategic planning of the production system.

Future-oriented assessment is not *new* to the cement industry. Although most studies have primarily focused on important but rather infinitesimal improvements in a very specific part of the cement production system, there are studies that have emphasized strategic possibilities for improvement (for example see Benhelal et al., 2013; CSI/ECRA, 2009; EIPPCB, 2013; Hasanbeigi et al., 2013; Morrow III et al., 2013; US EPA, 2010; Worrell et al., 2008). These studies are often comprehensive and informative, but seldom are based on a systematic methodology for identifying, structuring and assessing the possibilities for improvement in generic or in particular cases. Due to this, some possible solutions are underestimated or neglected. For instance, in these studies the possibilities for synergistic linkages between cement production and other industrial networks are typically not highlighted. Scholars in the fields of IE and IS have demonstrated examples of cases where material and energy synergies have benefited both cement production and the industrial region collectively (for example see Dong et al., 2013; Hashimoto et al., 2010; van Berkel et al., 2009). The insights of IE and IS can be used as a frame for searching, identifying or even proposing innovative ways that cement production can be improved (for example see Geng and Côté, 2002; Gibbs and Deutz, 2005; Reijnders, 2007; van Beers et al., 2007)

Similarly, life-cycle thinking and CO₂ footprinting using life-cycle based approaches are widely used in the cement industry (for example see Chen et al., 2010; Gäbel and Tillman, 2005; Huntzinger and Eatmon, 2009; Lu, 2010; Ortiz et al., 2009; Strazza et al., 2011; Valderrama et al., 2012; van den Heede and De Belie, 2012). Nevertheless these studies typically focus on assessing CO₂ footprint of products such as clinker or Portland cement and rarely try to assess the CO₂ footprint of the production system represented by its full portfolio of cement products. In addition, these studies are typically retrospective and do not assess the CO₂ footprint of future improved versions of a given production system. In cases that look into future assessment, the future scenarios are defined arbitrarily without providing methodological justifications about the feasibility and applicability of the selected scenarios in a particular setting.

⁵ *Production system* is defined as an industrial network of suppliers and consumers, which are connected in relation to producing (and consuming) a portfolio of products and services.

This research tries to reduce these gaps by developing a comprehensive assessment framework for *a)* systematic identification and categorization of potential improvement measures for the cement industry in general, based on the concepts of Cleaner Production, Industrial Ecology, and Industrial Symbiosis; *b)* selecting the feasible and applicable potential improvement measures and constructing future-oriented scenarios for a specific cement production system; and *c)* quantifying the CO₂ footprint of the proposed scenarios by using a life-cycle based approach.

In addition, by trying to take the *perspective of a cement producer* into account and looking at industrial development from such a standpoint, hopefully the academic approach of this research can add insights for strategic planning of cement production systems.

1.1 Aim and Research Questions

The overall aim of this research is to *strengthen the ways that CO₂ footprint improvement measures of cement production can be identified and assessed considering the perspective of a cement producer*. It is approached using the following research questions in relation to a particular cement production system:

- RQ₁: How can different options that can potentially improve the CO₂ footprint of cement production be identified and classified?
- RQ₂: How can the suitability of potential improvement options for a particular cement production system be assessed?
- RQ₃: How can the CO₂ footprint of different versions of a cement production system be quantified?
- RQ₄: How can a comprehensive assessment framework be developed which allows the construction of feasible and applicable future scenarios for a particular cement production system and the estimation of the CO₂ footprint of each scenario?

These research questions are formulated in relation to each other. RQ₁ and RQ₂ both aim to assess possible improvement options for a cement production system. RQ₁ has a general scope without limiting the search to any particular cement production system. RQ₂, however, considers a particular case and tries to assess the suitability of the options identified by RQ₁.

Any particular cement production system is subject to change. The task is to develop a method that allows the estimation of the CO₂ footprint of different versions of a given cement production system. The variations can occur due to the dynamics of industrial systems, that is, these systems are typically subject to change over time. RQ₃ is formulated in relation to this task.

RQ₄ is an integrative question. It combines RQ₁₋₃ in order to form a comprehensive framework for constructing suitable versions of a cement production system and quantifying the potential CO₂ improvements that can be achieved by implementing them. This assessment framework is applied to a case, which is a cement production system producing various cement products and consisting of a few geographically separate but interrelated production units.

1.2 Scope

In short, in this study *a comprehensive assessment framework is developed and applied to a cement production system*. This framework *identifies* and *categorizes* measures for improving CO₂ footprint of cement production systems in general; *identifies* suitable future improved scenarios for the given cement production system, considering its past and existing performance; and *quantifies* the performance of this production system under the improved conditions.

The approach for addressing RQ₁ and RQ₂ is to develop a framework for Multi-Criteria Assessment (MCA) which is based on literature search and qualitative methods (Article II). RQ₃ is addressed by creating a quantitative model based on Life Cycle Assessment (LCA) (Article I). RQ₄ has an integrative approach combining the methods developed in relation to RQ₁₋₃ (Article III). In order to make the study more accessible to cement producers and aiming for better communication, the point of departure of this study is the existing state of affairs in the cement industry. It uses concepts from CP, IE, IS, and LCA in order to develop an assessment approach which can be understood and used by cement producers.

The environmental performance of products or systems is represented by their *CO₂ footprint*. It is assessed by an Attributional LCA (ALCA) approach expressed in Global Warming Potential (*GWP100*) (IPCC, 2007a). ALCA allows the analysis of the main sources of CO₂ emissions within the cement production system. Alternative approaches such as Consequential LCA (CLCA) require sophisticated modeling and knowledge of the market dynamics which is beyond the scope of this research.

The system boundaries of the production system in the LCA models is defined as “cradle to gate”. This means that extraction, production and upgrading of raw materials, production and delivery of energy carriers, manufacturing of cement, and transport activities are included, while the “use phase” and “end of life phase” of cement are excluded. The main rationale for this choice is the diversity of cement applications in concrete structures and relatively limited information about the fate of concrete in the long term. This is a common choice for LCA studies of cement (Boesch and Hellweg, 2010; Chen et al., 2010; Huntzinger et al., 2009; Josa et al., 2004), although there are studies that have focused on the *end of life* of concrete (Kapur et al., 2008).

This study is prognostic and future-oriented in the sense that it seeks to identify and assess possible ways that the studied cement production system can be improved. In relation to possible changes, the study focuses mainly on technological changes and by the use of MCA evaluates which potential improvements are more appropriate for implementation. The guiding principles for searching for potential improvements is the concept of Life-Cycle Resource Efficiency (this concept is introduced in Section 3.2). In short, it is defined as strategies which can reduce the material and energy intensity of cement products when their life cycle is considered. Every measure which can potentially improve resource efficiency of cement production is considered as interesting enough to be included.

Another focus of this study is on *which of the identified changes are more appropriate for implementation* in contrast to analyzing *why things are as they are today*. The role of this approach is to help the relevant practitioners and decision makers reach a shared perception of *possible and suitable ways that things can improve*, and to get a sound estimate of *the performance implications of those changes*.⁶

In Chapter 4 some of these issues are further clarified.

⁶It may be argued that increased knowledge about the production system and its communication and learning outcomes can increase the capacity of organizations for eco-innovation and long term cultural change. On the other hand, one should be aware that the validity of such arguments depends on the positions that one takes regarding the meaning, necessity, and relevance of rationality and rational behavior.

Chapter 2

Cement Production

In this chapter the basics of cement production are introduced and a few of the characteristics which make cement production special are highlighted.

Cement-like materials have been known to many societies for thousands of years. Materials with properties similar to modern cement however only started to be used about 200 years ago. Today cement is used in virtually all corners of the world, typically in the form of mortar and concrete. In the last century, global cement production has been on the rise, though with various growth rates. This rising trend has not only continued but has clearly grown faster in recent decades (U.S. Geological Survey, 2005)

In 2012 about 3.7 billion tonnes of cement was produced worldwide and this figure is projected to reach 4.8 billion tonnes by 2017. In 2012, the largest producer of cement in the world was China with about 58%. Europe-27 and India each produced about 7%, while USA, Brazil, Iran, Vietnam, Russia, Turkey, and Japan each had about 2% of global cement production (U.S. Geological Survey, 2013). In 2012, the global concrete and cement market was about \$450 billion (RnR Market Research, 2013).

2.1 How Is Cement Produced?

Cement can be produced with different compositions and properties. Portland cement¹ is the most well-known type of hydraulic cements¹ consisting of about 95% of a material called clinker. Clinker is produced by heating a mixture of limestone² and clay to 1400 to 1600 °C in the cement kiln. The high

¹American Concrete Institute (ACI) defines hydraulic cement as “a binding material that sets and hardens by chemical reaction with water and is capable of doing so underwater” and Portland cement as “a hydraulic cement produced by pulverizing Portland-cement clinker and usually with addition of calcium sulfate to control setting” (ACI, 2013)

temperature of the kiln decomposes the calcium carbonate and CaO and CO_2 is produced. After the clinker is produced and cooled down, it is ground and blended with gypsum and ordinary Portland cement (OPC) is produced.

Alternative materials often referred to as supplementary cementitious materials (SCM) can partially replace clinker. These materials are ground and mixed with clinker at the required proportions in order to produce different types of cement. Granulated blast-furnace slag (GBFS) which is a residue from crude iron production is one of the most commonly used supplementary cementitious materials and ground GBFS (GGBFS) can partially substitute for clinker in blended cements. Alternatively, it can replace Portland cement when concrete is made.

Figure 2.1 shows clinker, Portland cement, and a blended cement production path in which clinker is substituted by supplementary cementitious materials such as GGBFS.

Figure 2.1: The production of Portland cement and blended cements in which supplementary cementitious materials such as Ground granulated blast-furnace slag (GGBFS) partially replaces clinker (from Article I).

Standards such as ASTM standards in the United States (ASTM, 2013) and EN 197-1 in Europe (2011) define the specifications of different cement types. According to EN 197-1, there are five main types of cement (CEM I to V). These cement types are primarily characterized by the share of clinker and supplementary cementitious materials which are used in their composition. CEM I with highest clinker content is the same as Portland cement.

2.2 Special Characteristics of Cement Production

Each tonne of clinker requires about 1.5 tonnes of raw materials. But in the foreseeable future, it is very unlikely that Portland cement production faces raw

²Limestone is largely composed of calcium carbonate ($CaCO_3$) in different crystal forms.

material scarcity issues. The main raw material required for the production of Portland cement is limestone, which in general is geologically abundant (U.S. Geological Survey, 2013).

However, if raw material scarcity is not the main challenge for the cement industry, high energy intensity and large CO₂ emissions are. Cement production can take on a diverse range of waste-derived or alternative materials and fuels, which are often cheaper than virgin counterparts. Thermal treatment in the kiln can degrade many hazardous compounds. Metaphorically speaking, cement production can act as a *scavenger* of industrial systems (Geng and Côté, 2002) and this quality creates unique opportunities for it to engage in symbiotic relationships with other industries (Reijnders, 2007).

In contrast to many other industries that generate large amounts of different types of wastes, cement production creates a relatively small amount of solid wastes per tonne of input raw material which is mainly in the form of cement kiln bypass dust. Most of the wastes are non-solid, in the form of low grade heat and gaseous emissions. CO₂ footprint of Portland cement production is dominated by emissions from combustion of fuels and the calcination process during clinker manufacturing. Emissions due to calcination (decarbonation of raw materials) is typically more than 50% of total CO₂ emissions in connection with Portland cement production (Huntzinger et al., 2009). It is important to note that this process is an integral part of clinker formation and is often considered unavoidable by the cement sector.

Roughly said, all types of cement have a similar function in construction materials. Therefore, for the Life Cycle Analysis of a cement production system as a whole, it is reasonable to create a virtual cement product (portfolio cement) representing all types of cement products. This is the approach that is used in this study for assessing the CO₂ footprint of the selected cement production system (Cluster West).

Chapter 3

Theoretical Framework

In this chapter the main theories and concepts that are used in this research are introduced.

This chapter begins by discussing the ideal form of industrial production and how it is theoretically defined in this thesis. Then the concept of Life-Cycle Resource Efficiency is introduced which forms a theoretical foundation for identifying and classifying the ways in which industrial systems can be improved. However, identification and classification of options need to be accompanied by assessment of their performance. This is explained briefly in relation to the choices to be made and challenges of assessing the performance of industrial systems. Finally, it is argued that IS can contribute to the expansion of the scope and diversity of improvement options in cement industry, but these improvement options need to be assessed in each particular case.

3.1 Ideals of Industrial Production

An often neglected point in the mission of *improving* industrial systems, is the assumption that *better* forms of industrial production exist. Forms which are supposedly closer to an ideal, that is, a *good industry* contributing to a *good industrial society*. It may be rather easy to establish a consensus about the idea that *better* industrial systems are a *possibility*, but the consensus often evaporates when one attempts to translate ideas about good industrial systems into actual norms and policies. There are many relatively popular concepts such as *sustainability* or *resilience* (for example see Ashford and Hall, 2011; Bhamra et al., 2011) which try to envision characteristics of *good* industrial systems (or societies). These are versatile concepts but their interpretations are often accompanied by socio-political connotations which make their uncritical usage vague, unconstructive, or even naïve. The existence

of large arrays of competing interpretations and expectations surrounding them, makes a tailored and clarified redefinition of these concepts difficult in the sense that it demands extensive skill, knowledge, and authority. Therefore, less encompassing concepts are used in this study, which may be bounded with lower ambitions, but hopefully are more tangible and transparent. This means that in this thesis complex and fuzzy conceptions of the ideal industrial system tend to be avoided.

One way to define an ideal industrial ecosystem is in relation to the amount of external inputs (energy and material) that they need and the amount of waste that they release into the environment. This approach is based on the analogies between industrial and biological ecosystems, which characterizes the field of Industrial Ecology. Ayres and Ayres (2002) have formulated three different types of ecosystem. Type I is the most linear and most reliant on external resources and sinks, implying that it assumes that it can utilize unlimited resources and can emit unlimited amounts of waste into the environment. Type II which benefits from the rather circular material flows (quasi-cyclic) uses limited external resources and emits limited waste. Finally the type III ecosystem benefits from truly cyclic material flow and therefore only needs external energy input and does not generate any waste.

As demonstrated in the above framework, arguably a necessary, but not sufficient¹, characteristic of a good industrial ecosystem is its ability to preserve and promote roundput, that is cyclical and cascading flows in contrast to throughput or linear flows. In this thesis the term *better* narrowly and loosely refers to an industrial production system which is closer to the above-mentioned ideals (a type II system which moves toward a type III system). This demonstrates the relevance of Industrial Ecology and its sister field, Cleaner Production, to the theoretical approach of this thesis.

3.2 Identification of Potential Improvements

The concepts of Cleaner Production and Industrial Ecology are close to each other and have overlapping principles and values (Ayres and Ayres, 2002, p. 41). Both emphasize the importance of *preventive* rather than *end of pipe* solutions. CP puts particular emphasis on actions upstream and from the perspective of a single company, while IE also emphasizes the actions that can be taken downstream and broadens the scope to incorporate cooperation between different companies (Baas, 2005, p. 26). Both schools prefer the preventive approaches which consider all the material and energy flows related to the life cycle of the products, rather than giving priority to specific parts of the life cycle or specific environmental media. Therefore, when assessing the environmental footprint of production systems, both concepts appreciate the

¹Arguably ideal industrial systems are often very profitable, but here the focus is on the environmental aspects. In general, in order to sufficiently define an ideal industrial production system, at the least one needs to incorporate ethics (values) into consideration.

value of expanded system boundaries (Ayres and Ayres, 2002, p. 39).

The resulting improvement strategies can be sorted into two groups: *efficiency improvement* and *substitution*. Efficiency improvement means reducing the material and energy throughput of the production system while maintaining its production volume. Substitution strategies refer to replacing hazardous or scarce materials or sources of energy with less hazardous and more abundant options. Both of these strategies can be operationalized on different levels: focusing on a single product, a process or an activity, a production system, a sector, a region, or an industrial ecosystem (Ayres and Ayres, 2002, p. 39).

In this research these strategies are referred to as Life-Cycle Resource Efficiency (LCRE) (or simply resource efficiency), which is considered the basis for developing a framework for identifying the potential improvement options for cement production. The focus is on cement production systems, but they are represented by their cement products or, to be more precise, their portfolio of cement products. This approach allows the cement manufacturers to identify and categorize a wide array of technological and strategic opportunities for potential improvements (see Ness et al., 2007).

3.2.1 Industrial Symbiosis and Cement Production

Industrial activities can be defined in a very broad sense as *the total activities performed by human societies* (Graedel and Allenby, 2003), while the emphasize is on *all forms of production and consumption in a modern industrial society*. In this study, this broad view of industry is only relevant to the extent that it can be linked to the resource efficiency of cement production systems. A production system is a conceptual construct and can cover a wide geographical area, spanning from local activities to global trading networks. While the pre-industrial form of economic arrangement was primarily based on locally based production and consumption, industrialization and modernization, accompanied by increasing globalization of trade and commerce, have often been in favor of large-scale production systems with supply and demand chains longer and increasingly international.

A production system which is rooted in local or regional resources can benefit from the local or regional supply and demand network in many ways. For instance, by decreasing the transportation of raw materials and products, decreasing the distance between producers and consumer which can make the environmental and social side-effects more visible and recognizable, and by decreasing the dependency on non-renewable resources (Johansson et al., 2005; Mirata et al., 2005). If these local resources are renewable (regenerative), it virtually implies relatively small-scale plants due to limits of resources and shorter transportation distances. Therefore, it can be argued that an ideal post-industrial vision for an industrial ecosystem can be related to the idea of a *locally bounded system with all-recycling flows (roundput)* and customers which are located not far away (Ayres and Ayres, 1996, pg. 278–280).

A locally bounded cement production system may seem unrealistic. In-

dustrial cement production involves the transformation of vast amounts of raw materials in an almost unilateral flow from lithosphere to technosphere (converting limestone to concrete). This process is intrinsically in need of economies of scale and centralized production, often involving massive machinery. However, cement production systems can still benefit from this vision. Cement plants typically rely on nearby sources of raw materials (such as limestone quarries). When cement is used as ready-mix concrete, its market becomes relatively limited to nearby regions, because ready-mix needs to reach its customer shortly after it is produced. Waste-derived fuels often have lower heating value compared to fossil fuels, therefore they cannot be shipped over very long distances. Increasing the share of these fuels by the cement industry is another trend in the localization of cement production. In addition, localization of cement production systems can manifest itself in the form of establishment of synergistic links and exchanges of material and energy with nearby industrial actors. Therefore, the benefits of localized production systems become entangled with the vision which is promoted and studied in the field of Industrial Symbiosis (IS).

There are different definitions of IS (for example see Chertow, 2000; Lombardi and Laybourn, 2012). At the plant level, IS promotes exchanges of byproducts, residues, or utilities. This means that at this level, IS is often related to the *substitution* strategy. However, engagement of different industrial actors in these types of exchanges means that on the eco-industrial level less material and energy input is needed. This mean that on eco-industrial level, IS can be more related to the strategy of *efficiency improvement*. Through collaboration and exchanges, industrial actors seek to substitute part of the material and energy throughput of their corresponding production facility with the byproduct of other facilities. While it is indeed a substitution strategy often driven by direct economic incentives, it is not necessarily a substitution of inputs with better alternatives. Substitution of hazardous materials with non-hazardous or less hazardous materials, or the substitution of scarce or non-renewable materials with abundant or regenerative ones are particularly focused in connection with Life-Cycle Resource Efficiency (LCRE)(see 3.2). Resource efficiency needs a broader focus than only exchanging material, energy, or utility as prescribed by IS.

The concept of IS relates to this study in predominantly two ways. First is in relation to the ideal of a more localized production and consumption system. IS strategies often promote local and regional exchanges which may provide opportunities to improve the resource efficiency of cement production. The second way in which IS is related to this study is its impact on the CO₂ footprint of the cement production system. As noted above, it is not always obvious that substitution of wastes, by-products and residues of other production systems is necessarily a resource-efficient choice from a life-cycle perspective. It is therefore important to consider IS as a concept that can help looking for options for improving the resource efficiency of cement. However, the impacts of those options should be assessed from a life-cycle perspective.

3.3 Assessment of Potential Improvements

Here the theoretical approach which is used in this thesis for assessing potential improvement options for cement production is presented.

3.3.1 Life Cycle Assessment of the Cement Production System

Life Cycle Assessment (LCA) is a suite of theories, methods, and tools which allows holistic assessment of the environmental impacts of a product or a service across its life cycle (Baumann and Tillman, 2004). There are two main types of LCA studies: Attributional (ALCA) and Consequential (CLCA). In this study the ALCA approach is used and the term LCA refers to ALCA unless specified².

Typically, in an LCA study a functional unit is selected and the input and output inventory of materials, energy carriers, emissions, and wastes are normalized to that functional unit, which is referred to as the Life Cycle Inventory (LCI). This inventory is collected in relation to defined boundaries for the studied system.

Improving the efficiency of the product and the production system are not necessarily the same thing. A production system can have different products, so in order to assess the effect of a measure on the performance of the system, it is important to consider the portfolio of the products of that system. Thus it is important to maintain the distinction between efficiency improvements of a *certain product* and the *portfolio of products* of the production system.

Depending on how the functional unit of a LCA study is defined, the method can be used for assessing the environmental impacts of a selected product or a production system as a whole. If the relationship between *production of a product* and *production of all products and by-products of the production system*, that is, its product portfolio, are known, it would be easy to calculate

²CLCA estimates how the changes in the output of the studied system may create consequences which have environmental impacts that should be considered (Zamagni et al., 2012). In other words it focuses on how the environmental impacts may change as a consequence of actions and decisions made within the studied system.

ALCA analyses the material flows within the boundaries of a selected system in relation to the delivery of a given function and calculates the environmental impacts associated with those flows. Its aim is to describe the environmental impact of physical flows attributed to a given function in the existing system.

One of the main differences between ALCA and CLCA is in their approach to dealing with allocation problems. An allocation issue occurs when an industrial process has several outputs and only one of those outputs is used in the system that we are studying. The problem is to partition the environmental impacts of that process in such a way that a fair fraction of that load is inherited to the studied system. CLCA solves the problem by expanding the system in such a way that all of the outputs of the industrial process are included in the studied system. This is called the system expansion approach to deal with an allocation problem (Weidema, 2001). While system expansion can be performed in ALCA, it is often not performed as systematically as it is in CLCA. In ALCA, the partitioning of environmental burden of a process is typically performed based on its physical properties, such as mass, energy content, volume, etc., or its economic values.

the life cycle environmental impact of one from the other. This relationship is not always straightforward. For instance, in cases where a production system produces multiple products with different functions, it would not be easy to calculate the impact of the production system (represented by its product portfolio) from the impact of a single type of its products.

As explained in Section 2.2, different cement products can, despite different characteristics and applications, conceptually be considered to have comparable functions. For instance, for the sake of estimation of the total impact of a cement production system, it can be assumed that 1 tonne of CEM I has the same function as 1 tonne of CEM III. With this assumption, the link between a single product and the portfolio of products can be established.

This forms the basis of the approach that is used for quantifying the environmental impact of selected products as well as the cement production system as a whole.

3.3.2 Simplified and Comprehensive Assessment

Performing LCA studies requires a lot of resources (Wenzel et al., 1997). If not only a product, but a production system as a whole is the target of study, the difficulty of doing an LCA study grows. For instance, such study requires more complicated and structured execution in order to effectively collect and compile data from heterogeneous sources. Data as such can have various forms of stochastic or epistemic uncertainties (Clavreul et al., 2013) making it harder to deliver robust results. In addition, studying an existing production system may not always be enough. Sometimes, it is important to prospect different possibilities for improvements within the production system such as changes of processes or conversion technologies, raw materials and energy carriers, different arrangement and setups of organizations, etc. However, these dynamics in the production systems change the Life Cycle Inventory (LCI) and therefore demand an updated version of the LCA study, which was time consuming and difficult in the first place. The dilemma here is that in order to have a good analysis of the system, wider system perspective and more comprehensive methodologies are required, but this makes the model less flexible in relation to studying the dynamics of the systems being studied. The need for simplified LCA methods which maintain their relevance and accuracy is highlighted by many scholars (Bretz, 1998; Hochschorner and Finnveden, 2003; Mueller et al., 2004; Pesonen et al., 2000; Ross and Evans, 2002; Soriano, 2004; Sun et al., 2003). The LCA methodology can be simplified by delimiting the data used and/or focusing on a few key indicators, using readily available generic data rather than compiling case-specific data, delimiting environmental impact categories and focusing on one or a few, delimiting the scope of LCA study, and using qualitative LCA methods. The relevance of using key indicators in the field of environmental management has been highlighted by many scholars (for example see Svensson et al., 2006).

In addition, a standard and traditional LCA methodology emphasizes

material and energy flows; therefore it *may* be a limited tool for envisioning the suitability of options for implementation within a production system. As noted by UNIDO (2013), “improving industrial performance requires a profound understanding of the underlying technological, structural and demographic changes that influence the evolution of manufacturing.” Therefore, LCA studies which are powerful tools for quantification of different production setups can be complemented by frameworks with multiple perspectives. Multi-criteria assessment frameworks can be developed on the basis of a wide umbrella concept (such as resource efficiency as envisioned in CP or IE as noted before) and systematically identifying and assessing different possibilities for improvement within an industrial production system. They may include qualitative assessment of the feasibility and applicability of potential improvement options. Qualitative approaches allow easier incorporation of contextual information and intuitive knowledge, such as opinions of participants, domain experts, and stakeholders into the assessment. Such frameworks can show which possibilities for improvements are viewed as more suitable for development. This information can be used to construct future scenarios. A simplified LCA which is based on a few key performance indicators can be used to quantify the performance of the production system for each scenario.

Seen in this way, there are no contradictions between simplicity and comprehensiveness. A full LCA model can be used for better understanding of the production system and defining the most relevant key indicators, while a simplified version based on these indicators allows the assessment of different versions of the production system. A qualitative assessment framework can be used to assimilate broad range of potential improvement options and assess their suitability from a multi-criteria perspective. The combination of these approaches (LCA, simplified LCA, multi-criteria assessment) can still be relatively simple yet rather comprehensive.

Chapter 4

Methodology

In this chapter the overview of the methods used in this research is presented. The studied case is introduced and the reasons for choosing it are explained. Finally, the overall design of the research is presented.

4.1 Research Method

A combination of methods is used in this research. Table 4.1 summarizes the relation between the research questions, the type of assessments, and the appended articles.

Table 4.1: Overview of the research questions, methods used, and their relation to the articles.

Research Question	Assessment or theme	Method	Article
RQ ₁	Identifying potential improvement measures	Qualitative approach; Literature search based on Life-Cycle Resource Efficiency inspired by Cleaner Production, Industrial Ecology, and Industrial Symbiosis	Article II
RQ ₂	Suitability of measures	Qualitative approach; Individual interviews, focus group meeting	Article II
RQ ₃	CO ₂ footprint of products and the production system	Multi-Criteria Assessment; Quantitative approach; Attributional LCA, simplified LCA based on six KPIs;	Article I
RQ ₄	CO ₂ footprint of future improved scenarios	Mixed approaches; Comprehensive assessment;	Article III

For assessing the CO₂ footprint an Attributional Life Cycle Assessment (ALCA) as per the LCA standard (ISO-14040, 2006; ISO-14044, 2006) was performed. The scope of this LCA model was *cradle to gate* and the functional unit was producing 1 tonne of clinker, cement product, or a virtually defined *portfolio cement product*. It was assumed that these products have comparable functions. Production data regarding the material and energy consumption and also production figures for Cluster West in 2009 were collected. These data were organized into Input/Output matrices of Cluster West and were used to create the inventory in the LCA models. Based on the results of the LCA six Key Performance Indicators were defined and a sensitivity analysis on them was performed. A simplified LCA model was created based on these KPIs which could estimate the CO₂ footprint of Cluster West (its portfolio cement).

A Multi-Criteria Assessment (MCA) framework was developed in order to include aspects such as improvement potential, feasibility, and applicability for implementation. This framework was developed in two parts: generic and site-specific. According to this framework, applying the generic assessment should start with a literature review of the scientific sources as well as existing industrial, governmental, and non-governmental publications. The guideline for leading the exploratory literature review was a conceptual model of a cement production system.

Inspired by Cleaner Production, documents addressing preventive and improvement measures in the cement plant were considered. Inspired by Industrial Ecology possibilities to use renewable and alternative raw materials and energy sources were explored. On the output side, IE and IS promote the idea that there should ideally be no waste or leftover material or useful energy streams, therefore in addition to the main products, literature dealing with the utilization, recycling, or valorization of CO₂ emissions and residue heat from cement production was considered. Any idea or strategy which could potentially lead to significant improvements in the resource efficiency of the conceptual cement production was included. In addition to publications in the field of cement, the scientific literature on Industrial Ecology and Industrial Symbiosis was included. The literature search was exploratory and did not aim to cover the full literature on cement. It explored existing and emerging ways that cement was produced and resulted in classification of potential improvement measures.

In order to better understand how the studied case (known as Cluster West consisting of three cement production sites, see section 4.2) operates a site visit to all three production facilities was performed. During this site visit, unstructured interviews with production managers at the plants were conducted. Data sheets regarding production and consumption figures of Cluster West in 2009 and 1997 were analyzed along with internal documents about the history of Cluster West and published CEMEX sustainability reports. At a later stage of the project, a focus group meeting was held. The purpose of this meeting was to discuss the methodology and receive feedback on the development of the assessment framework and collect the perspectives of

the participants on the future possibilities of cement production. The ideas generated in this meeting were incorporated into the assessment framework.

Applicability of improvement measures was assessed by applying the second part of the MCA framework, that is, its site-specific part. A self-completion questionnaire along with a guideline for the qualitative assessment was sent to CEMEX representative. This qualitative assessment of suitable improvement options for Cluster West was completed by the Cluster West management and senior technical staff. The data in the completed questionnaire were clarified by follow-up telephone conversations.

By utilizing the results of the MCA several possible scenarios for the future development of Cluster West was defined. The value of KPIs for each of these scenarios were estimated. The simplified LCA model was used to estimate the CO₂ footprint of Cluster West for each scenario.

4.2 Description of the Studied Case

CEMEX S.A.B. de C.V. (CEMEX) is an international producer and provider of construction materials active in more than 50 countries. The operation of CEMEX in Germany involves a production system located in the west of Germany (North Rhine-Westphalia), consisting of three cement plants which in this research are referred to as CEMEX Cluster West or simply Cluster West. The cement plants constituting Cluster West are Kollenbach in Beckum; the Dortmund plant in Dortmund, and the Schwelgern plant in Duisburg. Together, they form a work alliance, in order to produce different intermediate and final products. They are not co-located, but are all located in the same region. The distance between Kollenbach and Schwelgern is about 100 km, while Dortmund is in the middle. An overview of Cluster West and the main types of material and energy which are consumed by it and also the materials exchanged within the plants are depicted in Figure 4.1. This includes the inbound flows: mainly raw materials, fuel, and electricity; the internal flows: clinker, granulated blast-furnace slag (GBFS or ground GBFS), and several intermediate products; and the outbound flows: finished cement products. In addition to different cement products, Cluster West also produces ready-mix concrete which is not included in this study.

Kollenbach owns a local lime marl quarry, which is estimated to have enough reserves for 30 years, assuming the 2009 production rate. The Kollenbach plant, which is an integrated cement plant, produces clinker, intermediate products and finished cements with high clinker content (such as CEM I or CEM II). Its kiln system has a rotary kiln with a four-stage cyclone pre-heater but no pre-calcliner and its feeding kiln can accept secondary fuels.

The Schwelgern plant is a grinding and blending station and does not have a kiln system, but is equipped with two cement mills. This plant is co-located with an iron and steel plant owned by Thyssen Krupp, which in addition to steel, produces blast-furnace slag (BFS) and upgrades it into granulated blast-

Figure 4.1: Overview of CEMEX Cluster West in 2009 (figure from Article I)

furnace slag (GBFS) for consumption in the CEMEX/Schwelgern plant where it is milled into GGBFS. GGBFS has cementitious properties similar to clinker and can partly substitute it in the finished cement products. For example, CEM III can contain between 36% to 95% GGBFS in its composition. Like the Schwelgern plant, the cement plant in Dortmund does not have a kiln system and is a grinding and blending station. In this plant, clinker and intermediate products from Kollenbach are milled and mixed with the GBFS from Schwelgern plants.

In 2009, these plants produced 1.8 million tonnes of finished cement products combined. Shares of different cement products were as follows: CEM I, 8%; CEM II, 3%; CEM III/A, 55%; and CEM III/B, 34%. In order to calculate the portfolio cement product of Cluster West all of the cement products are considered. However, three cement products are selected in order to compare their CO₂ footprint. The selected products have clearly different clinker content. CEM I has the highest clinker content, while CEM III/A and CEM III/B are blended cements with much lower clinker content. In addition to these products, clinker produced at the Kollenbach plant is included in the comparative LCA study and is treated as a finished product. Cluster West uses all of the produced clinker for internal production.

A short overview of the history of the developments in Cluster West can add more insights into its existing configuration. The Kollenbach plant started its operation in 1911. In 1953, the first cyclone pre-heater in the world was installed in this plant (CEMEX-DE, 2010). Kollenbach remained rather innovative in relation to many technological upgrades and was among the early

adopters of using alternative fuels. In the early 2000s the feeding system of the Kollenbach plant was modified to allow the combustion of waste-derived fuels such as animal meat and bone meal, shredded tires and fluffy material produced from various solid wastes. This development, along with the addition of the Schwelgern plant to Cluster West and increasing utilization of Supplementary Cementitious Materials (SCM) such as GBFS in cement products demonstrate a strong drive for more material and energy-efficient cement production in Cluster West. The diverse cement portfolio of Cluster West provided the opportunity to study both the essential parts of the Portland cement production (*linear system*) as well as blended cement products (*synergistic system*).

4.3 Why Cluster West?

CEMEX owns hundreds of cement production facilities across the globe. In the conception phase of the research project, the initial plan was to select a few cement plants operating under varying conditions and compare their production systems. However, later it was decided to select a sophisticated enough case, but perform a deeper analysis on its development (compare its recent past with the present, and study possible future improvements). Dialogues with CEMEX led to the selection of the Cluster West. All three plants within Cluster West were operated under the same management structure, that is, CEMEX Germany. This would facilitate site visits, data collection, interviews, and in general studying the plants. LCA studies require accessible and reliable data and Cluster West presented a case which could provide well-documented production data about its existing and past production setups. This meant that it was possible to get rather close to the study object.

One of the aims of this study is to investigate the relevance of IE and IS to the resource efficiency of the cement industry. This can be achieved by studying a case which works as a living example of such relevance and is not purely conjectural. In 2009 Cluster West was already involved in symbiotic relationships with local and regional industries and also was a rather efficient cement production unit in comparison to the average production in Europe and also with many other plants within CEMEX. For instance, the co-location of the Schwerlgern plant and collaboration between CEMEX and Thyssen Krupp was an existing example of Industrial Symbiosis. The formation of Cluster West as described and the collaboration between its production units was also an interesting example of intra-organizational Industrial Symbiosis, where the collective characteristics and capacities of these plants were used to improve the overall resource efficiency and competency of the production system. In addition, in 2009, Cluster West was producing several types of cement products ranging from traditional Portland cement (CEM I) to products such as CEM III/B with less than 30% clinker content. Studying these products was another approach for assessing the relevance of IE and IS to cement production.

Another aim of the study is to analyze the ways in which a cement

production system can improve its CO₂ footprint in the future by identifying and implementing suitable improvement options. Therefore, it is reasonable to study a production system which has demonstrated itself to be dynamic in the past and is capable of change in the near future. With regard to its history of innovation and capacity for development, Cluster West is indeed an interesting case (see 4.2).

Therefore, in addition to the facts on the ground and practicalities of the research project, Cluster West is indeed a suitable case for this study. It has a noteworthy history of innovations for producing cement in more resource-efficient ways and establishing Industrial Symbiosis links. This history provide reasons to assume that it is likely that this track of improvements can be continued in the future, therefore, studying the ways that this production system can improve its resource efficiency and CO₂ footprint will not be a mere exercise in wishful thinking.

4.4 Research Design and Process

The research was performed during the years 2010 to 2011. Its aim was to contribute to a better understanding of the CO₂ footprint of different ways of producing cement and different cement products.

The main idea of the research was to analyze a particular cement production system and based on this analysis develop a comprehensive framework which could allow us to identify suitable ways to improve a cement production system and quantify the achieved improvements (or deterioration).

An overview of the research process is depicted in Figure 4.2). As illustrated in this figure, six questions which were asked sequentially represent the logical flow of the research process¹.

The first question was related to identifying and classifying different ways that the CO₂ footprint of cement production may be improved (question 1 in Figure 4.2). A Multi-Criteria Assessment (MCA) framework was developed and used in order to answer this question (Article II). It provided a structure for systematic literature search and collection and classification of potential improvement options. The first part of this assessment focused on a generic search and did not limit the search to particular conditions of Cluster West or any other specific cement production system. The generic assessment also qualified the feasibility of the identified improvement options. This part of the research process is further described, explained and discussed in Article II.

However, not all these identified options were applicable for Cluster West and the question was how to prioritize the most appropriate options for implementation in Cluster West. Before answering this question, a better understanding of the existing (and possibly past) conditions of Cluster West was essential. Therefore, the second question was related to the CO₂ footprint

¹These questions should not be confused with the research questions of this thesis. They are formulated only for easier demonstration of the research process.

Figure 4.2: Overview of the research process.

of the present version of Cluster West as it was operating in 2009 (question 2 in Figure 4.2).

To answer this question, an LCA of the production system was required. However, in 2009, Cluster West produced many different cement products and CEMEX was interested in having a comparative LCA study of a few key cement products, namely, CEM I, CEM II/A and CEM III/B. A full-scale ALCA of these products was performed. These products, through their similarities and differences, allowed the identification of important influencing factors for the CO₂ footprint of the system. Consequently, six key performance indicators (KPIs) were defined. Based on these KPIs a simplified LCA model was created. It made it possible to estimate the CO₂ footprint of the whole production system of Cluster West in 2009. The results of the simplified LCA model for 2009 were compared against the full LCA. This part of the research process is further described, explained and discussed in Article I.

In order to address how Cluster West could be improved in the future, it was considered beneficial to get a better perspective on its industrial dynamics in the past. This could reveal the trends and trajectories and point to the direction toward which the production system had been moving.

Therefore, the next question focused on what the conditions of Cluster West were in the recent past and its CO₂ footprint, (question 3 in Figure 4.2) CEMEX suggested 1997, because after that year, major changes in Cluster West occurred. A time frame of about ten years was considered a good time frame because it could arguably tell something about the reasonable rates of

change that could be achieved in the next five to ten years by Cluster West. The CO₂ footprint of the Cluster West production system in 1997 was estimated. The estimation and result are presented in Article I.

The next step in the study focused on the future options of Cluster West. The identified options for improving cement production were assessed in terms of what would be appropriate for implementation in Cluster West (question 4 in Figure 4.2). The assessment framework developed in Article II was used for answering this question by assessing the applicability of different improvement options for Cluster West.

Based on the analysis of improvement options for Cluster West, the next step was to define future improved scenarios for Cluster West (question 5 in Figure 4.2). Scenarios needed to be justified and reflect on different paths to which Cluster West's development may be directed. The results of the multi-criteria assessment which highlighted the appropriate improvement measures in Cluster West was used as the basis for constructing scenarios. Seven different scenarios were defined reflecting incremental and radical improvement possibilities for Cluster West (Article II).

Finally, it was time to estimate how much CO₂ improvement could be achieved if these scenarios were materialized in Cluster West. Therefore, it was needed to quantify the CO₂ footprint of the Cluster West production system in the future under varying scenarios (question 6 in Figure 4.2). This was done by utilizing the simplified LCA method based on six KPIs (Article III).

Chapter 5

Results

In this chapter the results of this research are presented. It includes the results of the LCA and simplified LCA, MCA, and their integration in the form of a comprehensive assessment.

It is not straightforward to separate *methodology* from *result* in a research project in which developing an assessment methodology is part of its aim. Therefore, the results presented in this chapter may overlap with the content of the Chapter 4).

5.1 LCA of Cluster West in 2009 and 1997

In this study, an ALCA method is used to quantify the CO₂ footprint of three different cement products (CEM I, CEM III/A and CEM III/B) produced in Cluster West in 2009.

The results of the LCA study show that the CO₂ footprint of the clinker produced in Cluster West is rather good when compared to the European average. However the CO₂ footprint of the average cement product of Cluster West, that is, the portfolio product, is much better (Figure 5.1). This is due to the fact that portfolio cement of Cluster West includes a large share of blended cements such as CEM III/A and CEM III/B which contain clinker substitutes such as GBFS. Furthermore, comparing the results for 1997 and 2009 reveals that although the CO₂ footprint of clinker production has been improved, the main improvement is visible if the portfolio production of the Cluster West is considered.

The LCA model is used to define six Key Performance Indicators (KPI) and a simplified LCA model to characterize the CO₂ footprint of Cluster West's production system (Table 5.1 and Figure 5.2).

For Cluster West in 2009, the corresponding relation between each KPI and

Figure 5.1: LCA results comparing CO₂ footprint of clinker and portfolio cement produced in Cluster West in 1997 and 2009 (from Article I).

the CO₂-eq of the system are calculated.

Table 5.1: Key Performance Indicators for cement production

Parameter	Description	Unit/Formula
KPI ₁	Clinker substitution rate	%
KPI ₂	CO ₂ emission due to calcination	Kg CO ₂ -eq/tonne clinker
KPI ₃	Specific heat consumption	MJ/tonne clinker
KPI ₄	Share of renewable fuels	% thermal energy
KPI ₅	Specific electricity consumption	kWh/tonne cement
KPI ₆	Share of renewable electricity	% electricity

Therefore, if we assume that in the near future (or in the recent past) the underlying conditions of Cluster West remained approximately the same, we can estimate the CO₂ footprint of different versions of Cluster West by changing the KPIs correspondingly. The simplified LCA model is used to estimate the CO₂ footprint of Cluster West under varying conditions, for instance, its configuration at present (2009), the past (1997), or future under different scenarios (Article III).

For 2009, the results of the simplified LCA model are compared with the ALCA of different products to check the validity of the model. Using

Figure 5.2: The Key Performance Indicators (KPI) used in the simplified LCA model of Cluster West (adapted from Article I).

a few indicators to estimate the performance of a production system not only simplifies the communication of the results and their possible usage by different stakeholders, but also allows easy estimation of different setups of the production system without having to chase many parameters. For example the full-scale LCA model of clinker is based on at least 50 parameters, but the simplified LCA model is based on only six parameters (KPIs).

5.2 Assessing Potential Improvement Options for Cluster West

For systematic identification, classification, and assessment of technologies and measures that can potentially improve the CO₂ footprint of cement production a MCA framework is developed (Article II). Rather than focusing on developing new technologies, this framework aims to organize and prioritize the existing body of technological and managerial knowledge in relation to improving cement production (Figure 5.3).

The framework is developed in two parts: *generic assessment* and *site-specific assessment*. The generic assessment is used for identifying improvement options for the cement industry in general, without referring to any particular production system. It starts with an explorative literature review and compilation of many improvement options. Inspired by CP, IE, and IS, all

Parts	Steps	Results
Generic study	Collection	Gross list
	Classification	Categorization scheme
	Improvement assessment	CO ₂ emission reduction potential
	Feasibility assessment	Degree of inter-connectedness
		Technological maturity
Site-specific study	Applicability assessment	Technical applicability
		Organizational applicability
		Implementation maturity
	Results and analysis	Best candidates
		Future candidates
		Industrial landscape

Figure 5.3: Multi-criteria assessment (MCA) framework (adapted from Article II).

measures which can contribute to the Resource Efficiency of the production system are included. The next step is to classify the gross list of ideas and create a categorization scheme, that is, a list of improvement options on a more abstract level. Four main groups of strategies are identified: *Production Efficiency*, *Input Substitution*, *Product Development*, and *External Synergies*. Each of these strategies is divided into a few improvement measures. Each improvement measure is assessed from two perspectives: its *feasibility* and *improvement potential*. The *feasibility* of a measure is characterized by two qualitative parameters: First is the *degree of interconnectedness* which reflects the number of independent organizations which need to collaborate in order to implement that measure, and *technological maturity* which qualifies the commercial availability of that measure. The *improvement potential* of a measure is assessed by a qualitative parameter called *CO₂ footprint reduction potential*. For each of these parameters, a 3-point qualitative scale and descriptive criteria are defined. The generic assessment can be used to map the *state of the art* of CO₂ improvement options in the cement industry (see Figure 5.4).

The site-specific assessment aims to provide a simple method to assess the *applicability* of the improvement options for a particular cement production system. This part of the assessment is participatory, in the sense that the

Figure 5.4: Overview of the generic assessment of potential improvement options for the cement industry. For more information about the designation of the codes, please refer to Table 5.2 (from Article II).

decision makers and experts at a particular plant are the most eligible persons for assessing what is most applicable for their production system.

The applicability is characterized by three qualitative parameters: *technical applicability*, which assesses whether the measure fits with the existing technologies or infrastructures, *organizational applicability*, which assesses whether the measure fits the goals and priorities of the organizations, and *implementation maturity* which assesses the existing level of knowledge about this measure in the organization.

The framework avoids weighing and scoring, and suffices to provide multi-criteria assessment and produce summary tables and various diagrams (similar to Figure 5.4) which can be analyzed and interpreted by decision makers and experts in the field for learning about their production system and enhancing their decision making.

The application of this framework for Cluster West highlighted the *Best Candidates* for improvement in Cluster West. Examples of such strategies are *increasing the clinker substitution rate* (PPC) which refers to producing cement products with higher share of supplementary cementitious materials; *improving the properties of blended cement products* (PPB), which enables the blended

cements to better compete with Portland cement; *using more alternative fuels* (IEF) and *alternative materials for clinker production* (IFM), and *producing electricity from the waste heat* from the cement kiln system (ERE) which improves the energy efficiency of the production system.

The qualitative MCA framework (Article II), combined with the quantitative simplified LCA model (Article I) are used to define future-oriented scenarios for Cluster West and to quantify the impact of each scenario (Article III).

5.3 CO₂ Footprint of the Cluster West in Future

By considering the results of the MCA which highlighted the suitable potential improvements for Cluster West, seven different scenarios are defined. These scenarios are defined by explaining the type of changes that they encompass. These changes are expressed both qualitatively and quantitatively. The description of each scenario is quantified into the equivalent amount of change in one or a few key performance indicators (KPIs) (see Table 5.2).

Improvement measures (Part II) ↓										Key performance indicators (Part I) →									
Production Efficiency	EEE	Electrical efficiency																	
	EEH	Thermal efficiency																	
	ERH	Pre-heating / drying																	
	ERE	Co-generation																	
	ERR	Recycle / reuse																	
	ERP	Pollution prevention and control																	
	IFC	Low temperature clinker production																	
	IFM	Alternative raw materials for clinker																	
	IEF	Alternative fuels																	
	IER	Renewable energy																	
Product Development	PPC	Clinker substitution																	
	PPB	Improve blended cements																	
	PNC	Clinkerless / no-calcline cement																	
	SEC	Carbon capture and storage																	
	SEB	Biological production																	
External Synergies	SEH	Synergistic heating																	
	SIP	Integration with power plant																	
	SIW	Integration with waste treatment																	
	SIC	Synergies among co-located firms																	
	Efficient plant																		
Case 1	Alternative raw materials																		
Case 2	Renewable fuels																		
Case 3	Clinker substitution																		
Case 4	Increased production																		
Case 5	More synergies																		
Case 6	More and new synergies																		
Case 7	More and new synergies																		

These scenarios reflect different conceptions of the future of the Cluster West. They can represent implementation of a set of improvement measures, or different ways in which the production capacity of Cluster West is utilized. For instance, it is possible to assume that in the future, the total cement production output of Cluster West remains the same, while less clinker is produced. It is also possible to assume that the production of clinker remains the same, but due to the implementation of strategies such as clinker substitution, the total cement production of Cluster West is increased.

With regards to implementing improvement measures, a few of the scenarios consist of rather incremental changes, based on the assumption that developments of Cluster West in the future are comparable to its developments from the recent past (1997).

Alternatively, a few scenarios are defined based on more radical changes in the production system. All of these scenarios are based on the measures which are identified as both feasible and applicable to Cluster West. In each scenario, the CO₂ footprint of both unit and total production of Cluster West (per 1 tonne, or per total production) are estimated.

Achieving radical improvements in Cluster West calls for more synergistic ways of production, that is, further implementation of Industrial Symbiosis initiatives (see Case 6 and 7 in Table 5.2, more information in Article III).

The CO₂ footprint of the Cluster West portfolio cement in 1997 was 703 kg CO₂-eq/tonne cement, in 2009 it was 385 kg CO₂-eq/tonne cement, and by using more Industrial Symbiosis approaches (such as in Case 6 and 7) in future it has potential to reach figures as low as 225 to 316 kg CO₂-eq/tonne cement.

One of the main outcomes of this research is the issue of the benchmarking of cement production. Benchmarks represent production systems, and if they fail to capture many of the existing or possible initiatives, they may become counterproductive. Traditionally, the benchmark has been based on clinker. It is true that improving the performance of clinker production is important and can be achieved by strategies such as using more renewable fuels and producing clinker at lower temperatures. However, this does not capture the fact that typically calcification emissions are integral to clinker production and to some extent unavoidable. A better approach is to switch benchmarking of the performance of cement production from *clinker* to *portfolio cement*¹. This will be a better indicator of the collective measures which are taken by a cement producer to reduce the CO₂ footprint of its production. This point is highlighted in this research and has become more eloquently supported in recent years (for example see Olivier et al., 2012)

¹It may be possible to use the same kind of argumentation in promoting the idea of benchmarking a cement production system based on its delivered functions, such as *concrete constructions*, including their life span and the end of life treatments. It should be noted though, that due to its scope, this study cannot provide an empirical basis for supporting this idea.

5.4 Comprehensive Assessment of Cement Production

Another way to characterize this research is to identify its main approaches and areas of focus.

The main focus of this study is on the cement production system, however, two other focal areas exist in this research: product focus, and industry focus. Product focus is used in performing the comparative ALCA on selected products in the selected production system. This forms a basis for calculating the six key performance indicators and constructing a simplified LCA model which allows the quantification of the production system as a whole. The other focus area is the cement industry. The generic part of the MCA can be used for systematic assessment of possibilities for improving cement production in general. The developed framework has provided a thorough basis for literature search. If the literature search in this part is performed thoroughly enough, results of the generic assessment can reflect the state of the art of potential improvement measures in the cement industry. In the MCA framework this is labeled as the *industrial landscape* (Figure 5.3 and Figure 5.4).

At least two approaches co-exist in this research. One is a quantitative assessment of environmental performance of the Cluster West production system using LCA and simplified LCA based on six key performance indicators. The other is a qualitative MCA framework for systematic identification and assessment of possible ways of improving the CO₂ footprint of the production system. The combination of these approaches allows the estimation of the CO₂ performance of the selected cement production considering its industrial dynamics in the past, present, and, through the formulation of empirically sound scenarios, the future.

The overall results of this research can be summarized as developing and applying a comprehensive assessment framework for assessing potential improvements of the cement production system. This comprehensive framework can be summarized as follows:

1. Select a cement production system and perform an LCA study on its existing system.
2. Create a simplified LCA model of the production system (Calculate the relationship between a few key performance indicators (KPI) and the CO₂ footprint of the production system, represented by its portfolio product).
3. Develop and perform a qualitative MCA in order to identify, classify, and assess various CO₂ improvement measures and prioritize the most suitable ones.
4. Based on the results of the MCA, develop several alternative versions of the production system in the future, considering cases with both incremental and radical changes.

5. By utilizing the simplified LCA model, estimate the CO₂ footprint of the cases.
6. Analyze the results and place the production system in the wider context of the industry.

This approach can be used for enhanced decision making by cement producers as well as other stakeholders who are interested in having a future-oriented vision of improvements based on the existing (and past) conditions of their production systems.

5.5 Industrial Symbiosis and the Cement Industry

In relation to the challenge of reducing the CO₂ footprint of the cement industry, a key question can be raised: to what extent can cement plants rely only on in-house improvement measures? In other words, how important are initiatives and concepts such as Industrial Ecology and particularly Industrial Symbiosis which promote active effort to establish synergistic links with other industries?

On a generic level, cement production is still dominated by Portland cement and although the share of blended cements is increasing, it is still relatively low (WBCSD/CSI, 2009). On a cement producer level, much of the efforts have been focused on site-oriented measures² which focus on the internal processes of the cement plant. These strategies are important for reducing CO₂ emissions of cement (IEA/WBCSD, 2009; Morrow III et al., 2013), but they have limited potential. The main reason for this limitation is the CO₂ emissions due to the calcification process, which accounts for more than 50% of clinker CO₂ emissions.

Therefore, parallel to site-oriented approaches, achieving radical reduction in CO₂ footprint of cement involves strategies to use more renewable fuels and electricity, invest in Carbon Capture and Storage³ technologies, or reduce the clinker content of the portfolio of cement products, that is, produce more blended cements using clinker substitutes such as GBFS or fly ash. These strategies often require that the cement producer involve other industrial actors which traditionally have not belonged to their supply chain. This demonstrates the importance of the perspectives of Industrial Symbiosis for the cement industry.

However, it is important to consider the potential limitations and challenges that Industrial Symbiosis strategies may face. Clinker substitutes such as

²A few examples of *site-oriented* or *inside the fence* measures are: adding pre-calciner to the kiln system, replacing the coolers and grinders with higher efficiency alternatives, or producing electricity from the low grade heat from the kiln.

³Carbon capture and storage is the process of capturing carbon dioxide from point sources such as fossil-fuel power, cement, or iron and steel plants and storing it in a safe place, typically an underground geological formation, so that it is not released into the atmosphere.

GBFS and fly ash are relatively limited resources and at best can replace about a third of the produced clinker (CSI/ECRA, 2009) and therefore their availability will influence the potential for increasing blended cements. Another factor is the influence of developments within the energy sector which can change the amount and quality of fly ash which is available for blended cement production. One such example is the increasing use of natural gas in coal-fired power plants.

Cement producers through the ownership of limestone quarries and their permits often have long-term and secure access to raw materials for clinker which may decrease their incentives for seeking clinker substitutes such as GBFS which often can only be secured for shorter periods. In addition, new standards are needed to increase the acceptance rate of blended cements and its market (IEA/WBCSD, 2009).

Chapter 6

Discussion

In this chapter the approach and results of the research are reflected upon. It starts with a discussion about the relationship between the results and the aim and research questions. It follows by critical reflections about its approach.

6.1 Reflections on the Aim and Research Questions

In this section the ways that this research has addressed its aim and research questions are discussed. Each research question is reiterated and is answered correspondingly.

RQ₁: How can different options that can potentially improve CO₂ footprint of cement production be identified and classified?

The generic part of the MCA framework developed in this research as explained in Section 5.2 (Article II) can be used to identify a wide array of potential improvement measures. This approach is based on the concepts of Cleaner Production, Industrial Ecology, and Industrial Symbiosis and aims to increase the Life-Cycle Resource Efficiency of the products or production system. If a literature search based on this framework is executed carefully and thoroughly, the *state of the art* of existing or emerging improvement measures in the cement industry will be identified and classified.

RQ₂: How can the suitability of potential improvement options for a particular cement production system be assessed?

In this research a particular cement production system, that is, Cluster West, was selected as the case of study. The site-specific part of the MCA framework developed in this research as explained in Section 5.2 (Article II) can be used to assess the feasibility and applicability assessment of different improvement measures and to highlight the most suitable candidates for implementation.

RQ₃: How can the CO₂ footprint of different versions of a cement production system be quantified?

In order to learn about the performance of the existing system a full LCA of the production system is required. All production output of the plant should be considered which can be estimated by its portfolio cement product. By calculating the value of the six key performance indicators (Table 5.1 and Figure 5.2) and performing sensitivity analysis on them it is possible to find out the relation between each KPI and the CO₂ footprint of the system. These KPIs represent a simplified LCA model of the cement production system. Therefore, by assuming that the underlying conditions of the production system remain relatively similar, by changing the value of KPIs corresponding to different setups of the production system, the CO₂ footprint of different versions of the cement production system can be quantified.

RQ₄: How can a comprehensive assessment framework be developed which allows the construction of feasible and applicable future scenarios for a particular cement production system and the estimation the CO₂ footprint of each scenario?

By integrating the above-mentioned approaches. MCA can identify the most suitable potential improvement options for the cement production system. Incremental or radical future scenarios can be developed based on the result of this assessment. Translate the defined scenarios into corresponding changes in each of the six key performance indicators and estimate the CO₂ footprint of the production system under each scenario. (Article II)

6.2 Critical Reflections on this Research

This research has been a learning opportunity, therefore, if it were to be repeated today, based on the experienced gained, it might be done differently, but not entirely so. The outline of the approach and the main elements and questions might remain rather similar, but more sophistication, care, and caution may be demonstrated in the way that the research is conceptualized, theorized, and performed. In this section this research will be reviewed *reflexively* (Alvesson and Skoldberg, 2000) in order to see in what *main* ways it could have been done differently, or possibly better.

This research focuses on a single type of environmental impact: greenhouse gas emissions, mainly in the form of CO₂ emissions. While it is true that other impact categories and other types of emissions could have been included in this study, due to special characteristics of cement production, there are good reasons for focusing on CO₂ footprint. CO₂ emissions due to calcination are integral to clinker production, and hence need particular attention. Arguably, the CO₂ footprint, at least in the case of cement is an expressive indicator, even if admittedly not encompassing the resource efficiency of the cement production. In addition, most of the other forms of emissions can be effectively reduced by various pollution control measures.

A more comprehensive approach would have included other environmental impacts of cement production in the assessment framework.

The LCA scope of this study has been *cradle to gate*. This means that the *use* and *end of life* phases of cement are not included. As mentioned before, the main reason for this choice was due to the fact that this study takes the perspective of cement producers and focuses on the areas that they can influence more directly. Applications of cement can be very diverse and it would have been challenging to try to find a good common basis for analysis and comparison. Nevertheless, this study could have been more exhaustive if the full life cycle of cement had been considered.

The empirical data used for this research is from the year 2009. Now we are in 2014 and regardless of the many justified reasons for such a duration between then and today which is in part unavoidable in the academic state of the affairs, it is reasonable to ask *whether the results of this research are still relevant*. This study was completed near the end of 2011, and obviously, Cluster West has been subject to change since then. These changes are not empirically reflected in this study. It would be interesting to set up a follow-up research in order to see to what extent the changes that were foreseen or estimated in 2011 have materialized in this production system. However, regardless of the possible changes in Cluster West, the assessment approach developed in this research is still relevant from a methodological perspective.

While attributional LCA (ALCA) is a powerful tool for identifying the environmental hot spots of a production system, it is not effective in including the consequences of changes in the studied system on the other sectors of the industry. A complementary approach is the consequential LCA (CLCA) which by considering market conditions methodologically incorporates the environmental consequence of the changes as the result of changes in the production system. CLCA is a more versatile approach for taking the rebound effects into consideration (Earles and Halog, 2011). Assessment of potential for improvement can improve if both the ALCA and CLCA approaches are utilized.

Uncertainty analysis is an important part of any assessment, especially when it comes to quantitative assessments such as LCA. Uncertainties can arise due to two broad reasons: the inherent and uncontrollable variability of parameters and factors (aleatoric uncertainty), and lack of knowledge about parts of the system (epistemic uncertainty). *Uncertainty blind* data collection and analysis can create results which look robust and informative, but are unreliable or misleading at their core. The site-specific production data collected from Cluster West provide a reliable empirical basis for the LCA study. While a simple uncertainty assessment is performed on the LCA results, this study could have benefited from a more systematic approach towards uncertainty assessment.

This research focuses on cement production. But what about other industries? Is it possible to use similar approaches for assessment of improvement options in other industries? On a general level, it is possible to have both

LCA and MCA approaches in studying developments of industrial systems. However, each industrial system has its own particularities that should be taken into consideration. Hence, the approach of this research may not be readily applicable to other types of industrial production, however, it may be possible to identify similarities and learn from its methodological approach.

It is often assumed that willingness and opportunity are sufficient factors for industries to turn their traditionally acquired expertise into *disrupting innovations*. However, another crucial factor is the ability or capacity of people and organizations to change (Ashford and Hall, 2011, chapter 7). In this study, the capacity of the cement producing organization for accepting and implementing a certain improvement measure is reflected in the *applicability assessment* of the MCA framework via a parameter called *implementation maturity* (see Figure 5.3). However, this issue could have been addressed by more in-depth qualitative research and by incorporating concepts from organization and innovation theories.

Finally, it is fair to raise the question of the perspective and the audience. *From which standpoint has this study been performed? Who is going to read and use its results?* Both of the scientific communities in the field of environmental systems analysis and environmental management may find the empirical and methodological results of this research useful. However, this study focuses on cement producers and tries to use concepts and tools such as IE, IS, CP, LCRE, and LCA in order to identify potential improvement options from the perspective of the cement industry. This is manifested in this study by the fact that it has been sponsored by CEMEX, and there are reasons to believe that similar approaches are of interest to other cement actors as well. From a *participatory* perspective, this study could have included a few of the other *possibly interested actors* in order to steer it in the direction of their needs, hence, increase the likelihood that its message is heard and its approach is used by the people who need it the most. For instance, those hypothetical actors (if they were asked) might have requested other types (such as economic risk or policy implications assessment) or other forms of assessment (such as developing a simplified tool instead of a framework).

But even then, the focus of study would have been on cement producers. Another way that this study could have been framed is to take a social or industrial perspective in a wider sense (policy perspective), in contrast to focusing on the cement industry (corporate perspective). In such an approach, the immediate questions would have been different. Instead of asking *in what ways cement industry can decrease its CO₂ footprint?*, the most resource-efficient ways to utilize the available alternative or renewable resources would have been studied. One example is the use of alternative fuels in the cement industry. Many of these fuels are refuse-derived fuels (RDF) which are produced from organic wastes or residues. If economic or environmental pressures push cement producers to use more of such fuels, from a wider societal perspective it may not be the most efficient way to deal with them. Waste-hungry industries such as incineration plants (or possibly cement plants running on

RDF fuels) may contribute to the formation of lock-ins, which make it harder to follow alternative pathways. Lock-ins can occur by material, technical, cultural, and institutional rationales. As noted by Corvellec et al. (2013) “the story of incineration as a successful way to treat waste has locked-in public support around the notion that incineration is the most efficient, profitable, and environmentally sustainable way to process waste.”

Chapter 7

Conclusions

This research was an attempt to create a comprehensive assessment framework for identifying and assessing potential improvement options of cement production systems.

It was based on studying a cement production system with three plants in Germany, referred to as Cluster West. The *cradle to gate* Attributional Life Cycle Assessment (ALCA) was performed in order to analyze the CO₂ footprint of several products of Cluster West. The results of this LCA study were used as the basis to define six key performance indicators (KPI). These KPIs could approximate the CO₂ footprint of the cement production system and were used as to construct a simplified LCA model. This model was used to quantify the CO₂ footprint of different versions of the cement production system. The reason that this simplified LCA model was created was to allow the estimation of CO₂ footprint of different versions of this production system in a simple way.

In order to identify potential improvement options a framework for Multi-Criteria Assessment (MCA) was developed. This framework provided guidelines for performing an exploratory literature search in order to identify and classify potential improvement measures for the cement industry. This part of the framework was based on the concepts of Cleaner Production, Industrial Ecology, and Industrial Symbiosis, which promote resource efficiency on different system levels. In addition, the MCA framework was developed and applied on the selected case in order to assess the feasibility and applicability evaluation of different options. It was applied both on a generic level, reflecting the future landscape of the industry, and on a production organization level reflecting the most applicable possibilities for change. Based on this assessment a few appropriate future-oriented scenarios for the studied cement production system were constructed, and the simplified LCA model was used to quantify the CO₂ footprint of the production systems for each scenario.

By integrating Life Cycle Assessment (LCA) and Multi-Criteria Assessment (MCA) approaches, this study provided a comprehensive assessment method for identifying suitable industrial developments and quantifying the

CO₂ footprint improvements that might be achieved by their implementation.

Cement producers can gain significant improvements in reducing their CO₂ footprint by following the strategies which focus on improvements within their organization. However, due to the fact that more than 50% of CO₂ emissions of clinker are emitted during calcination, it is not easy to reach radical improvements by only in-house improvements. As manifested by Cluster West, while it is possible to improve the CO₂ footprint of clinker by using more alternative fuels and more efficient production facilities, the larger improvements can be achieved on the portfolio level. Compared to Portland cement, very low CO₂ footprints can be achieved if clinker is replaced with low carbon alternatives, such as Granulated Blast Furnace Slag (GBFS) which are the by-products of other industrial production. Benchmarking a cement production system by its portfolio product is therefore a more reasonable approach, compared to focusing on the performance of its clinker production.

This study showed that Industrial Ecology and Industrial Symbiosis which promote *over the fence* initiatives for material and energy exchanges and collaboration with non-traditional partners, are relevant to the cement industry. However, the contingent nature of these strategies should always be noted, because the mere exercise of such activities may not lead to a more resource-efficient production system. Therefore, in search of potential improvements, it is important to keep the search horizon as wide as possible, while, however, assessing the potential improvements in each particular case. The comprehensive framework developed in this research was an attempt in this direction.

Chapter 8

The Way Forward

This research can be continued in few different ways. By using CLCA, the consequences of changes in the cement production system can be included in the quantification of the potential gains. In addition, uncertainty-aware modeling approaches can be used to increase our understanding about knowledge gaps, risks, and the properties of the cement production system.

The MCA framework can be extended to assess other aspects of perceived improvement measures. For instance, aspects such as other environmental impacts (in addition to CO₂ emissions), institutional conditions, amount and availability of alternative materials, and competition for using and securing alternative materials can be added.

Strategists on the individual organization, industry or sector, or policy makers representing the wider society, are often interested in identifying the possibilities for improvement, either by improving existing practices or by developing new technologies. The often asked questions are *what are the plausible ways that technological developments in an area can be shaped in the future? To what extent are they beneficial, desirable, relevant, or acceptable? What are the driving forces and barriers? What are the threats, opportunities and risks involved in relation to the sociotechnical landscapes?*

On a more general level, the extension of this research can be seen in the light of this recurring theme.

Bibliography

- ACI (2013). entries for “hydraulic cement”, “Portland cement”.
- Alvesson, M. and K. Skoldberg (2000, May). *Reflexive Methodology: New Vistas for Qualitative Research* (1 ed.). SAGE Publications Ltd.
- Ashford, N. A. and R. P. Hall (2011). *Technology, globalization, and sustainable development: transforming the industrial state*. New Haven, Conn.; London: Yale University Press.
- ASTM (2013). *ASTM Volume 04.01, September 2013, ASTM C150 / C150M - 12, Standard Specification for Portland Cement*,. Subcommittee C01.10 on Hydraulic Cements for General Concrete Construction.
- Ayres, R. U. and L. Ayres (1996). *Industrial ecology: towards closing the materials cycle*. E. Elgar.
- Ayres, R. U. and L. Ayres (2002). *A handbook of industrial ecology*. Cheltenham, UK; Northampton, MA: Edward Elgar Pub.
- Baas, L. W. (2005). *Cleaner production and industrial ecology: Dynamic aspects of the introduction and dissemination of new concepts in industrial practice*. Eburon Uitgeverij BV.
- Bansal, P. and B. Mcknight (2009). Looking forward, pushing back and peering sideways: analyzing the sustainability of industrial symbiosis. *Journal of Supply Chain Management* 45(4), 26–37.
- Baumann, H. and A.-M. Tillman (2004, March). *The hitch hiker’s guide to LCA*. Student Literature.
- Benhelal, E., G. Zahedi, E. Shamsaei, and A. Bahadori (2013, January). Global strategies and potentials to curb CO₂ emissions in cement industry. *Journal of Cleaner Production*, 142–161.
- Bhamra, R., S. Dani, and K. Burnard (2011). Resilience: the concept, a literature review and future directions. *International Journal of Production Research ahead-of-p*(ahead-of-p), 1–19.

- Blomqvist, L., T. Nordhaus, and M. Shellenberger (2012). Planetary boundaries: A review of the evidence.
- Boesch, M. E. and S. Hellweg (2010, December). Identifying improvement potentials in cement production with life cycle assessment. *Environmental Science & Technology* 44(23), 9143–9149.
- Bretz, R. (1998). SETAC LCA workgroup: Data availability and data quality. *The International Journal of Life Cycle Assessment* 3(3), 121–123.
- CEMEX-DE (2010). Consolidated environmental statement (beckum and rudersdorf plants) 2010. Environmental statement, CEMEX WestZement GmbH, CEMEX OstZement GmbH.
- Chen, C., G. Habert, Y. Bouzidi, A. Jullien, and A. Ventura (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.
- Chertow, M. (2000). Industrial symbiosis: Literature and taxonomy. *Annual Review of Energy and the Environment* 25, 313–337.
- Clavreul, J., D. Guyonnet, D. Tonini, and T. H. Christensen (2013). Stochastic and epistemic uncertainty propagation in LCA. *The International Journal of Life Cycle Assessment*, 1–11.
- Corvellec, H., M. J. Zapata Campos, and P. Zapata (2013, July). Infrastructures, lock-in, and sustainable urban development: the case of waste incineration in the göteborg metropolitan area. *Journal of Cleaner Production* 50, 32–39.
- CP/RAC (2008). Manual of pollution prevention in the cement industry. Technical report, Regional Activity Centre for Cleaner Production (CP/RAC).
- CSI/ECRA (2009). Development of state of the art—techniques in cement manufacturing: Trying to look ahead. Technical report.
- Dong, H., S. Ohnishi, T. Fujita, Y. Geng, M. Fujii, and L. Dong (2013). Achieving carbon emission reduction through industrial & urban symbiosis: A case of kawasaki. *Energy*.
- Earles, J. M. and A. Halog (2011, June). Consequential life cycle assessment: a review. *The International Journal of Life Cycle Assessment* 16(5), 445–453.
- EIPPCB (2013, April). Cement, lime and magnesium oxide manufacturing industries.
- Gäbel, K. and A.-M. Tillman (2005). Simulating operational alternatives for future cement production. *Journal of Cleaner Production* 13(13-14), 1246–1257.

- Geng, Y. and R. Côté (2002). Scavengers and decomposers in an eco-industrial park. *International Journal of Sustainable Development and World Ecology* 9(4), 333–340. cited By (since 1996)24.
- Gibbs, D. and P. Deutz (2005). Implementing industrial ecology? planning for eco-industrial parks in the USA. *Geoforum* 36(4), 452–464. cited By (since 1996)51.
- Graedel, T. E. and B. R. Allenby (2003). *Industrial ecology*. Prentice Hall.
- Hasanbeigi, A., W. Morrow, E. Masanet, J. Sathaye, and T. Xu (2013, June). Energy efficiency improvement and CO₂ emission reduction opportunities in the cement industry in china. *Energy Policy* 57, 287–297.
- Hashimoto, S., T. Fujita, Y. Geng, and E. Nagasawa (2010). Realizing CO₂ emission reduction through industrial symbiosis: A cement production case study for kawasaki. *Resources, Conservation and Recycling* 54(10), 704–710.
- Hochschorner, E. and G. Finnveden (2003). Evaluation of two simplified life cycle assessment methods. *International Journal of Life Cycle Assessment* 8(3), 119–128.
- Huntzinger, D., J. Gierke, S. Kawatra, T. Eisele, and L. Sutter (2009). Carbon dioxide sequestration in cement kiln dust through mineral carbonation. *Environmental Science and Technology* 43(6), 1986–1992.
- Huntzinger, D. N. and T. D. Eatmon (2009, May). A life-cycle assessment of portland cement manufacturing: comparing the traditional process with alternative technologies. *Journal of Cleaner Production* 17(7), 668–675.
- IEA/WBCSD (2009). Cement technology roadmap. Technical report, Geneva.
- IPCC (2007a). Climate change: synthesis report. Technical report, IPCC Secretariat, 7 bis Avenue de la Paix C. P. 2300 Geneva 2 CH- 1211 Switzerland,.
- IPCC (2007b). Climate change: Synthesis report, summary for policy makers.
- ISO-14040 (2006). Environmental management – life cycle assessment – principles and framework. *International Standard Organisation, Geneva, Switzerland*.
- ISO-14044 (2006). Environmental management – life cycle assessment – requirements and guidelines. *International Standard Organisation, Geneva, Switzerland*.
- Johansson, A., P. Kisch, and M. Mirata (2005, August). Distributed economies – a new engine for innovation. *Journal of Cleaner Production* 13(10–11), 971–979.

- Josa, A., A. Aguado, A. Heino, E. Byars, and A. Cardim (2004, August). Comparative analysis of available life cycle inventories of cement in the EU. *Cement and Concrete Research* 34(8), 1313–1320.
- Kapur, A., G. Keoleian, A. Kendall, and S. E. Kesler (2008). Dynamic modeling of in-use cement stocks in the united states. *Journal of Industrial Ecology* 12(4), 539–556.
- Lombardi, D. R. and P. Laybourn (2012). Redefining industrial symbiosis. *Journal of Industrial Ecology* 16(1), 28–37.
- Lu, H. (2010). Evaluation of life-cycle assessment studies of chinese cement production: Challenges and opportunities.
- Merriam-Webster (2014). Optimization.
- Mirata, M., H. Nilsson, and J. Kuisma (2005, August). Production systems aligned with distributed economies: Examples from energy and biomass sectors. *Journal of Cleaner Production* 13(10–11), 981–991.
- Morrow III, W. R., A. Hasanbeigi, J. Sathaye, and T. Xu (2013). Assessment of energy efficiency improvement and CO₂ emission reduction potentials in india's cement and iron & steel industries. *Journal of Cleaner Production* 65, 131–141.
- Mueller, K., M. Lampérth, and F. Kimura (2004). Parameterised inventories for life cycle assessment: Systematically relating design parameters to the life cycle inventory. *International Journal of Life Cycle Assessment* 9(4), 227–235.
- Ness, B., E. Urbel-Piirsalu, S. Anderberg, and L. Olsson (2007). Categorising tools for sustainability assessment. *Ecological Economics* 60(3), 498–508.
- Olivier, J. G., J. A. Peters, and G. Janssens-Maenhout (2012). *Trends in global CO₂ emissions 2012 report*. PBL Netherlands Environmental Assessment Agency.
- Ortiz, O., F. Castells, and G. Sonnemann (2009). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials* 23(1), 28–39.
- Pesonen, H. L., T. Ekvall, G. Fleischer, G. Huppes, C. Jahn, Z. S. Klos, G. Rebitzer, G. W. Sonnemann, A. Tintinelli, and B. P. Weidema (2000). Framework for scenario development in LCA. *The International Journal of Life Cycle Assessment* 5(1), 21–30.
- Reijnders, L. (2007). The cement industry as a scavenger in industrial ecology and the management of hazardous substances. *Journal of Industrial Ecology* 11(3), 15–25.

- RnR Market Research (2013). Global concrete and cement market – key trends and opportunities to 2017. Technical report, Timetric.
- Rockström, J., W. Steffen, K. Noone, s. Persson, F. S. Chapin III, E. Lambin, T. M. Lenton, M. Scheffer, C. Folke, and H. Schellnhuber (2009). Planetary boundaries: exploring the safe operating space for humanity. *Ecology and society* 14(2), 32.
- Ross, S. and D. Evans (2002). Excluding site-specific data from the LCA inventory: How this affects life cycle impact assessment. *International Journal of Life Cycle Assessment* 7(3), 141–150.
- Soriano, V. J. (2004). A simplified assessment methodology to environmentally-sound product design.
- Strazza, C., A. Del Borghi, M. Gallo, and M. Del Borghi (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.
- Sun, M., C. J. Rydh, and H. Kaebernick (2003). Material grouping for simplified product life cycle assessment. *The Journal of Sustainable Product Design* 3(1), 45–58.
- Svensson, N., L. Roth, M. Eklund, and A. Mårtensson (2006). Environmental relevance and use of energy indicators in environmental management and research. *Journal of Cleaner Production* 14(2), 134–145.
- UNEP (1994). *Government strategies and policies for cleaner production*. United Nations Environment Program.
- UNIDO (2013). The future of manufacturing.
- US EPA (2010). Available and emerging technologies for reducing greenhouse gas emissions from the portland cement industry.
- U.S. Geological Survey (2005). Historical statistics for mineral commodities in the united states, data series 2005-140.
- U.S. Geological Survey (2013). Cement. In *Mineral Commodity Summaries 2013*, pp. 38–39. U.S. Geological Survey.
- Valderrama, C., R. Granados, J. Cortina, C. Gasol, M. Guillem, and A. Josa (2012). Implementation of best available techniques in cement manufacturing: A life-cycle assessment study. *Journal of Cleaner Production* 25, 60–67.
- van Beers, D. d., G. Corder, A. Bossilkov, and R. van Berkel (2007). Industrial symbiosis in the australian minerals industry: The cases of kwinana and gladstone. *Journal of Industrial Ecology* 11(1), 55–72. cited By (since 1996)51.

- van Berkel, R. (2000). Cleaner production for process industries. *Plenary Lecture. Perth WA7 Chemeca*.
- van Berkel, R., T. Fujita, S. Hashimoto, and M. Fujii (2009, March). Quantitative assessment of urban and industrial symbiosis in kawasaki, japan. *Environmental Science & Technology* 43(5), 1271–1281.
- van den Heede, P. and N. De Belie (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.
- van Oss, H. and A. Padovani (2002). Cement manufacture and the environment - part i: Chemistry and technology. *Journal of Industrial Ecology* 6(1), 89–106.
- van Oss, H. and A. Padovani (2003). Cement manufacture and the environment, part II: environmental challenges and opportunities. *Journal of Industrial Ecology* 7(1), 93–126.
- WBCSD/CSI (2009). *World Business Council for Sustainable Development - The Cement Sustainability Initiative: Cement Industry Energy and CO₂ Performance, Getting the Numbers Right*.
- WBCSD/CSI (2012). 10 years of progress and moving on into the next decade. Technical report, CSI.
- Weidema, B. (2001). Avoiding co-product allocation in life-cycle assessment. *Journal of Industrial Ecology* 4(3), 11–33.
- Wenzel, H., M. Hauschild, and L. Alting (1997). Environmental assessment of industrial products-volume 1-tools and case studies. *Institute for Product Development, Technical University of Denmark, Chapman & Hall*.
- Worrell, E., C. Galitsky, and L. Price (2008). Energy efficiency improvement and cost saving opportunities for cement making. an ENERGY STAR guide for energy and plant managers.
- Wright, L. A., S. Kemp, and I. Williams (2011, February). ‘Carbon footprinting’: towards a universally accepted definition. *Carbon Management* 2(1), 61–72.
- Zamagni, A., J. Guinée, R. Heijungs, P. Masoni, and A. Raggi (2012). Lights and shadows in consequential LCA. *The International Journal of Life Cycle Assessment*, 1–15.