ROOZBEH FEIZ

**SYSTEMS
ANALYSIS
FOR
ECO-INDUSTRIAL
DEVELOPMENT**

APPLIED ON
CEMENT AND BIOGAS
PRODUCTION SYSTEMS

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“Systems Analysis for Eco-Industrial Development
Applied on Cement and Biogas Production Systems”

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To arrive where you are, to get from where you are not,
You must go by a way wherein there is no ecstasy.
In order to arrive at what you do not know
You must go by a way which is the way of ignorance.
In order to possess what you do not possess
You must go by the way of dispossession.
In order to arrive at what you are not
You must go through the way in which you are not.
And what you do not know is the only thing you know
And what you own is what you do not own
And where you are is where you are not.

—Thomas Stearns Eliot (1888–1965), *East Coker*

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Abstract

Our industrial systems are not sustainable—a major challenge which demands several types of responses. Eco-industrial development can be seen as such a response, with the goal to establish industrial systems that are both ecological and economical. Industrial Ecology is another closely related response. It is based on the idea that natural systems can be used to understand how to design sustainable industrial systems, for example, by shifting from linear industrial processes to cyclic systems, where waste streams can be avoided or minimized through utilization as raw materials for other processes. In this thesis, the possible contributions of industrial ecology/symbiosis to eco-industrial development are investigated through the use of systems analysis approaches. Two systems analysis methods are used: life-cycle assessment and multi-criteria analysis. These methods are applied on two types of industrial systems: cement and biogas.

Cement is among the most used materials in the world with extensive resource consumption and environmental impact, manifested for example by the high levels of CO₂ emissions. Multi-criteria analysis was used to identify, classify, and assess different measures to improve the climate performance of cement production, while life-cycle assessment was employed to quantify the CO₂ emissions. Combined, multi-criteria analysis and life-cycle assessment were used for an integrated assessment of different eco-industrial development paths. Most of the feasible and resource-efficient improvement measures were related to utilization of secondary resources, for example minimizing the clinker content of the cement by replacing it with byproducts from steel and iron manufacturing, or using refuse-derived fuels. Effective utilization of these secondary raw materials and fuels can be achieved through industrial symbiosis.

Biogas is viewed as part of a larger transition toward a biobased economy where resources—bio-materials and bio-energy—are used in a cascading, circular, and renewable manner. Multi-criteria analysis was used to assess the feasibility and resource efficiency of using different types of biomass as feedstock for biogas and biofertilizer

production. In addition to aspects such as renewable energy and nutrient recycling, cost efficiency, institutional conditions, environmental performance, the potential per unit, and the overall potential were considered. In another study, life-cycle assessment was used to analyze the environmental performance of biogas production from source-sorted food waste using a dry digestion process. The study showed that the performance of this dry process is better than or comparable with most of the existing wet biogas processes in Sweden. The critical sources of uncertainty and their impact on the overall performance of the system were analyzed. Factors influencing methane production, as well as processes related to soil after the digestate is applied as biofertilizer on land, have the greatest influence on the performance of these systems.

For both cement and biogas systems industrial symbiosis involving collaboration and better utilization of local/regional secondary resources, can result in resource-efficient eco-industrial development. Life-cycle assessment and multi-criteria approaches can serve as two complementary methods for investigating the feasibility, potential, and resource efficiency of different development paths. These approaches can provide input into decision-making processes and lead to more informed decisions.

Sammanfattning

SYSTEMANALYS FÖR EKOINDUSTRIELL UTVECKLING—TILLÄMPAD PÅ CEMENT OCH BIOGAS PRODUKTION

Våra industriella system är inte hållbara—en stor utmaning som kräver olika typer av åtgärder. Ekoindustriell utveckling kan betraktas som en sådan åtgärd, eller respons, med avsikten att etablera industriella system som både är sunda ekonomiskt och ekologiskt. Industriell ekologi är en annan och närbesläktad respons, baserad på idén att naturliga system kan användas som förebilder, för att förstå hur hållbara industriella system kan designas. Det kan till exempel handla om ett skifte från linjära industriella processer till cykliska, där avfallsströmmar kan undvikas eller minimeras genom att de omvandlas till råvaror för andra processer. I den här avhandlingen undersöks om och hur industriell ekologi/symbios kan bidra till fortsatt ekoindustriell utveckling, genom användning av systemanalysmetoder. Två typer av industriella system står i fokus: cement- och biogasproduktion. Vidare används två typer av miljösystemanalytiska metoder: livscykelanalys och multikriterieanalys.

Cement är ett av världens mest använda material och är förknippat med omfattande resursanvändning och stor miljöpåverkan, exempelvis i form av höga utsläpp av koldioxid. Multikriterieanalys användes för att identifiera, klassificera och bedöma ett flertal förbättringsåtgärder som kan ge bättre klimatprestanda. Livscykelanalys användes för att kvantifiera utsläppen av koldioxid. Kombinerade användes multikriterieanalys och livscykelanalys för en form av integrerad bedömning av olika ekoindustriella utvecklingsvägar för cementindustrin. De flesta förbättringsåtgärderna som bedömdes vara genomförbara och resurseffektiva var kopplade till användning av sekundära resurser, exempelvis i form av att mängden cementklinker minimerades och ersattes av restprodukter från järn- och stålindustrin samt att avfall användes som bränsle. Effektiv användning av den här typen av sekundära material kan realiseras genom industriell symbios.

Biogas ses som en del i en större omställning i riktning mot en biobaserad ekonomi, där biomaterial och bioenergi används i

kaskadsystem—förnyelsebart och cirkulärt. Multikriterieanalys tillämpades för att utvärdera genomförbarhet och resurseffektivitet för olika substrat till biogas- och biogödselproduktion. Aspekter avseende förnyelsebar energi och näringscirkulering beaktades, även kostnadseffektivitet, sociala och institutionella förutsättningar, miljöprestanda, potentialen per enhet samt potentialen totalt. I en annan studie användes livscykelanalys för att studera miljöprestandan för biogasproduktion baserad på utsorterat matavfall i en torr rötningsprocess. Studien visade att den torra processen hade bättre eller likvärdig prestanda jämfört med många av de våta processer som används för motsvarande ändamål i Sverige. Kritiska källor till osäkerheter och deras påverkan på den totala prestandan för systemet analyserades. Störst betydelse hade de faktorer som påverkar metanproduktionen samt processer i jorden/marken efter att digestatet lagts ut som biogödsel.

Både för cement och biogassystem kan industriell symbios, som involverar samverkan mellan lokala/regionala aktörer och användning av sekundära resurser, leda till resurseffektiv ekoindustriell utveckling. Livscykelanalys och multikriterieanalys kan användas som två kompletterade metodologiska approacher för att undersöka genomförbarhet, potential och resurseffektivitet för olika utvecklingsvägar. Dessa metoder kan bidra till beslutsfattandet och stödja mer välgrundade beslut.

Appended Papers

THIS THESIS is based on the following appended papers (*Table 1*). Full text of these papers can be found in the Appendix (Articles).

Paper	Title
Paper I	Improving the CO ₂ Performance of Cement, Part I—Utilizing Life-Cycle Assessment and Key Performance Indicators to Assess Development within the Cement Industry. <i>Journal of Cleaner Production</i> (Feiz et al., 2015a).
Paper II	Improving the CO ₂ Performance of Cement, Part II—Framework for Assessing CO ₂ Improvement Measures in the Cement Industry. <i>Journal of Cleaner Production</i> (Feiz et al., 2015b).
Paper III	Improving the CO ₂ Performance of Cement, Part III—The Relevance of Industrial Symbiosis and How to Measure its Impact. <i>Journal of Cleaner Production</i> (Ammenberg et al., 2015).
Paper IV	Assessment of Feedstocks for Biogas Production, Part I—A Multi-Criteria Approach. <i>Journal of Resources, Conservation & Recycling</i> [submitted] (Feiz and Ammenberg, 2016).
Paper V	Assessment of feedstocks for biogas production, Part II—Results for Strategic Decision-Making. <i>Journal of Resources, Conservation & Recycling</i> [submitted] (Ammenberg and Feiz, 2016).
Paper VI	Life-Cycle Assessment and Uncertainty Analysis of Producing Biogas from Food Waste—A Case Study of the First Dry-Process Biogas Plant in Sweden [manuscript] (Feiz et al., 2016).

Table 1: List of papers appended to this thesis

PAPERS I–III were developed from earlier versions presented at the Greening of Industry Network (GIN) conference, October 2012, in Linköping, Sweden.

My Contribution to the Papers

PAPERS I–III were written in close relationship to each other, and I was actively involved in all stages of their development. I played a major role in establishing the integrative methodology which encompasses these three papers. Jonas Ammenberg actively participated in the writing process of all of these articles, while Mats Eklund provided comments. I also benefited from the advisory inputs of Leenard Baas and Richard Marshall.

- Paper I: Along with Anton Helgstrand, I had a major contribution in data collection, life-cycle assessment (LCA) modeling, analysis and writing of this paper. I developed the simplified LCA model based on a few key performance indicators.
- Paper II: I had a major contribution in all parts of this paper, including data collection, analysis, development and application of the multi-criteria assessment framework, and writing.
- Paper III: While Jonas Ammenberg is the leading author of this paper, I made major contributions to it, specifically in relation to developing the scenarios, applying both the quantitative and qualitative methods developed in Papers I & II to them, and performing the synthetic analysis based on the results.

PAPERS IV & V are closely related to each other and I played an important role in all parts of their development. Jonas Ammenberg participated in the writing of both papers, while Mats Eklund provided feedback on several occasions.

- Paper IV: I had a major contribution in this article regarding development of a multi-criteria framework for assessing the potential, feasibility, and resource efficiency of using different feedstock for biogas production.
- Paper V: While Jonas Ammenberg is the leading author of this article, I made major contributions to it, specifically in relation to literature search, participation in stakeholder meetings and workshops, and data collection regarding several of the studied key areas, as well as the synthetic analysis based on the results.
- Paper VI: I performed all the work related to this article, while Niclas Svensson and Mats Eklund contributed with feedback and reviews.

Other Related Publications

- Feiz, R., 2011. Improving Climate Performance of Cement Production—Developing an Assessment Framework and Applying it to a CE-MEX Cement Production Cluster in Germany (Master’s 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 (Report). Linköping University, Sweden.
- Feiz, R., 2014. Industrial Ecology and Development of Production Systems—Analysis of the CO₂ Footprint of Cement (Licentiate Thesis). Linköping University, Linköping.
- Ammenberg, J., Feiz, R., Bohn, I., 2016. Systematic Assessment of Feedstocks for an Expanded Biogas Production—A Multi-Criteria Approach (Report). Biogas Research Center, Linköping University, Sweden.

Note on the Layout

The visual layout of this book is based on the work of Edward Tufte (Tufte, 1990, 2001) and corresponding L^AT_EX document class (Godby, 2015). In this style, pages have a wide margin on the right side. This margin is used for presenting the captions of tables and figures. In addition, all footnotes are shown as sidenotes—in the margin. The sidenotes are marked by Arabic numbers in the text, that is, like see-the-sidenote⁴.

In addition, there are a few endnotes, which are shown at the end of the essay, just before the reference list. The endnotes are designated by roman numbers, that is, like see-the-endnote^{iv}.

Chapter 1

Introduction

In this chapter the background of the research and its aims, research questions, and scope are presented. This is complemented by a short section about the research environment and its context.

OUR INDUSTRIAL SOCIETIES, with all their undeniable achievements, appear to be unsustainable. Issues such as climate change, resource depletion, and pollution are linked to different social and economic dynamics and have created very complex challenges (Rockström et al., 2009; Steffen et al., 2015; cf. Blomqvist et al., 2012; also see Meadows et al., 1972, 2004; cf. Turner, 2008). It is important for us to transform our societies in order to put an end to their expanding undesirable social and ecological impacts, and change their development toward sustainable, lively, and equitable forms of collective living (Sachs, 2009). One of the main fronts of such transformation relates to industrial activities—mainly in the form of production of goods and services—and reducing their associated environmental impacts.

In response to these challenges, several efforts and approaches have emerged in the last decades (Kates et al., 2001; Komiyama and Takeuchi, 2006). Examples of such efforts are the introduction of policies and the development of strategies on different levels. Some are top-down, focusing on major institutional changes—for example, through industrial policies (European Commission, 2014) or national strategies—while others are bottom-up, focusing on the activities of industrial actors and industry-led initiatives—for example, industrial standards and environmental management systems (UNIDO, 2011), or green supply chain management (Srivastava, 2007).¹ Despite their diversity and differences, these examples of initiatives promote ecological and economical industrial development; an aim which can

¹ Most of these efforts can be viewed in the light of schools of thought such as *ecological modernization* (Hajer, 1996; Mol and Spaargaren, 2000), which argue that it is possible to transform industrial activities into more ecological and economical ones, without requiring the abandonment of the core institutions of modern society. The underlying assumption of ecological modernization is that “decoupling” of economic development and ecological damage is possible (Fischer-Kowalski and Swilling, 2011; von Weizsäcker et al., 2014). While ecological modernization and similar schools are contested (Mol et al., 2014), the scope of this thesis falls within their general framework.

be collectively called *eco-industrial development* (Cohen-Rosenthal and McGalliard, 1998). The main idea of eco-industrial development is that industries can improve economically, and at the same time, reduce their environmental impacts (Cohen-Rosenthal, 2003; Fang et al., 2007; Gibbs et al., 2005). Eco-industrial development can focus on addressing local, regional, or global environmental issues, but, in practice, it often prioritizes local (or regional) development, and explores the potential for feasible improvements within a particular geography and by specific actors (Cohen-Rosenthal, 2003; Geng et al., 2014; Gibbs et al., 2005).ⁱ

Eco-industrial development can be pursued through several strategies, which according to the OECD (2010) can be categorized as: (i) *pollution control*, that is, implementing end-of-pipe solutions; (ii) *cleaner production*, through modifying the production processes and products by process optimization, improving efficiency, and substituting toxic and non-renewable materials with non-toxic and renewable ones; (iii) *eco-efficiency*, which requires a systematic approach to environmental management, for example by adopting environmental management systems, setting strategies, and implementing monitoring mechanisms; (iv) *life-cycle thinking*, which means to extend the environmental responsibility by adopting green supply chain management and corporate social responsibility; (v) *closed-loop production*, which requires a restructuring of the production methods, with the aim of reducing the use of primary resources; and (vi) *industrial ecology (IE)*, which calls for the integration of different production systems, new partnerships, and participation in eco-industrial parks. These strategies have some overlapping areas, and each can be effective in certain applications and contexts. Nevertheless, the industrial ecology strategy (Ayres and Ayres, 1996; Graedel and Allenby, 1995) has a particular strength because it is based on the principle that increasing resource efficiency and reducing the environmental impacts should be integrated with all the material and energy flows through the life-cycle of industrial activities, considering different economic sectors, and from both the short and long-term perspectives (ADB and IGES, 2008).² In other words, industrial ecology emphasizes a *broad systems approach* with large temporal and spatial boundaries in order to minimize the risk of sub-optimization or missing out on an important impact upstream, downstream, or sidestream of the industrial activities.

The vision of industrial ecology, relates to the practical aim of eco-industrial development: both envision industrial systems with

² Resource efficiency refers to decreasing the required energy and materials—and other resources—while delivering the same industrial output. Increasing the resource efficiency of industrial systems is stressed at the highest level of European growth strategies (European Commission, 2015).

good ecological and economic performance. Since industrial ecology promotes a wider systems perspective, it can influence approaches to eco-industrial development in at least two instrumental ways related to the “identification” of development opportunities and “assessing” their performance. First, it expands the system from a geographical and organizational perspective, an approach that can be valuable for *identifying* new ways of organizing industrial activities. This means that one looks at an industrial production plant in relation to its surrounding geographical and organizational environment—as opposed to the ordinary view which considers the production plant in isolation from its environment, and largely focuses on its traditional suppliers and customers. This approach opens up new possibilities for interaction between the production plant and its local or regional neighbors. These interactions may involve synergistic collaborations with new actors to share knowledge, resources, and infrastructures, in order to enhance the resource efficiency and economic performance. This aspect of industrial ecology is called *industrial symbiosis (IS)* (Chertow, 2000; Ehrenfeld and Chertow, 2002).³

³ Industrial symbiosis is further elaborated on in Chapter 3.

The second way that increasing the scope of the industrial systems can influence the approaches to eco-industrial development is to *assess* the environmental impacts of industrial activities in their whole life-cycle. This means including the activities that are needed for extracting raw materials; conversion into usable materials and energy carriers; production, delivery, and use of goods and services; disposal of consumed products; and the processes required for waste management and end-of-life treatment. The broadened scope allows for more meaningful and comprehensive assessments. From this perspective, life-cycle approaches and tools such as life-cycle assessment (LCA) (Baumann and Tillman, 2004; ISO, 2006a) become an important part of industrial ecology in relation to eco-industrial development.⁴

⁴ Life-cycle approaches are further elaborated on in Chapter 3.

Therefore, industrial ecology, both in vision and approach, is closely related to eco-industrial development and can contribute to both identification of development possibilities and assessing their environmental impacts. Furthermore, it is important to consider the role that these analyses can play in providing support for decisions regarding implementation of different development paths and initiatives. Industrial ecology and related systems analysis approaches can better serve decision-making processes directed toward implementation, if practitioners and other relevant stakeholders are welcome to participate and provide their input (Baas and Boons, 2004). This participation can serve as both quality assurance and a reality check,

and allows the inclusion of conceptual, empirical, and anecdotal information in the analyses (Spangenberg, 2011).

This thesis uses industrial ecology and systems analysis approaches for identifying opportunities for eco-industrial development and assessing their environmental performance and implementability, with the aim of producing relevant input for decision-making processes. Two types of industrial systems, cement and biogas, are analyzed.

1.1 Cement Production

CEMENT PRODUCTION, is the first industrial system studied in this thesis. Cement is among the most used materials in the world; in fact, several billion tonnes of cement are produced globally each year. Production of cement is energy and material intensive (van Oss and Padovani, 2002, 2003), and therefore has significant environmental impacts. Considerable amounts of CO₂, SO₂, NO₂, and other pollutants are caused by cement production. While all of these are important and receive lots of attention, CO₂ emissions are particularly critical: about 5 % of global anthropogenic CO₂ emissions are attributed to cement production (EIPPCB, 2013; WBCSD, 2009, 2015). Thus, reducing CO₂ emissions is among the most important challenges of the cement industry, and the industry plans to significantly reduce its CO₂ emissions in the following decade. Many major cement producers, as part of their carbon reduction strategy, have emphasized the need for *identifying* the available and emerging technologies, *evaluating* their potential for reducing CO₂ emissions, and ensuring their timely implementation (WBCSD, 2015). Therefore, cement is an interesting industry to study from the industrial ecology, industrial symbiosis, and systems analysis perspectives, because it epitomizes the scale of the challenges which mature and established industries are faced with.

The potential linkages of cement production with other industrial activities within industrial clusters have been highlighted in several studies (Nisbet, 1995; van Beers et al., 2007; van Berkel et al., 2009; Vigon, 2002). But most of these studies have not viewed the industrial development from the perspective of cement producers; instead, they have been interested in the study of the character or the emergence of industrial symbiosis in a given industrial area (Baas, 1998; Chertow and Miyata, 2011; Dong et al., 2014; Hashimoto et al., 2010; Jacobsen, 2006; Notarnicola et al., 2016; van Beers et al., 2007; van Berkel et al., 2009). Several studies have identified strategies for improving

the CO₂ footprint of cement.⁵ These strategies are typically based on detailed technical knowledge about cement production. However, the studies often lack a systematic methodology for identifying and structuring the development potentials (for a few examples, see Benhelal et al., 2013; CSI/ECRA, 2009; EIPPCB, 2013; Hasanbeigi et al., 2013, 2012; Hendriks et al., 1998; Morrow III et al., 2013; US EPA, 2010; Worrell et al., 2008). Therefore, they tend to classify and structure their findings in such a way that strategies that involve internal improvement within the cement production plant are mixed with strategies that demand inter-organizational collaborations and industrial symbiosis.

Several studies have quantified the CO₂ footprint of cement production systems, either by modeling specific technological innovation, or by comparing several future alternatives (Chen et al., 2010, 2015; Gäbel and Tillman, 2005; García-Gusano et al., 2014; Huntzinger and Eatmon, 2009; Li et al., 2014; 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 the CO₂ footprint of cement products produced at a single cement plant, and rarely link their studies to the range of feasible and applicable improvement measures, including a systematic view on industrial symbiosis initiatives. In addition, they are either retrospective or they define future scenarios arbitrarily without providing sufficient methodological justifications about the feasibility and applicability of the selected scenarios in any particular setting. In general, not many studies have tried to integrate the two aspects of eco-industrial development and systems analysis of cement: (i) identifying, classifying, and assessing CO₂ improvement measures, including inter-organizational collaborations and industrial symbiosis, and considering feasibility, which can be used for defining effective and implementable development scenarios, and (ii) quantifying the CO₂ reductions that can be gained by the pursuit of those scenarios.

1.2 Biogas Solutions

BIOGAS SOLUTIONS represent the second type of industrial system that is studied in this thesis. Since biogas production is principally based on biological processes, biogas solutions can be viewed as part of a broader transition to a biobased economy. A biobased economy is an industrial economy which relies on biological processes, uses natural inputs and limited amounts of energy, and produces no

⁵ The CO₂ footprint, or *carbon footprint*, is a measure of the total amount of CO₂ and other greenhouse gas 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).

waste, since discards of one process are inputs to another (EBA, 2014; European Commission, 2011a). This is in contrast with a fossil-based economy, in which non-renewable resources are commonly used in energy-intensive and wasteful production systems.⁶

The term *biogas solutions*—instead of *biogas production systems*—is used in this thesis in order to highlight that biogas can be viewed as an innovation process within an emerging industrial paradigm in which it can play several different roles (Lybæk et al., 2013; Olsson and Falldé, 2015).⁷ It occurs in relation to *waste treatment*, *renewable energy* for industry, *biofuel* for transportation, and organic *farming*. For example, in Sweden, anaerobic digestion is commonly used for the treatment of sludge from waste water treatment plants. In the last decade, treatment of municipal food waste in biogas plants has become increasingly popular (Swedish Waste Management Association, 2015). The digestate—the residual product of biogas production—from these plants is used as biofertilizer and in organic farming (*ibid.*), which contributes to better nutrient recycling. Upgrading biogas to vehicle fuel is relatively common (Persson et al., 2006), and in several municipalities, biogas is used to fuel city buses (Falldé and Eklund, 2015). Biogas can be produced in stand-alone production plants relying on the supply of feedstock from the market, or it can be produced in integration with other industrial systems (SGC, 2008), relying on their previously used materials, purifying their wastewater, and contributing to their overall efficiency. Therefore, the term *solution* better fits the multiplicity of possibilities in which biogas technologies can be applied to, and it better reflects their potential for connecting different sectors, infrastructures, production systems, or policy areas (Hjalmarsson, 2015; Olsson and Falldé, 2015).

Biogas can be produced from many different types of biomass and in different scales, but it is typically linked to small-scale production units—compared to fossil-based large-scale production systems. Since biogas production relies on biomass, these production units are mainly bounded by the regional capacities—and markets—for supplying suitable and affordable feedstock. Therefore, although biogas production can benefit from the *economies of scale*, increasing the scale is often associated with several problems related to resource availability and logistics (Gold and Seuring, 2011; cf. Wrigley, 1962). As a result, many biogas producers are faced with high costs and business uncertainties which serve as barriers for further development.⁸ Responding to these challenges demands coordinated cooperation of actors to remove the existing barriers through technical and business

⁶ For more information about biogas production see Section 2.2.

⁷ According to the European Commission (2010), innovation process is defined as “changes that speed up and improve the way we conceive, develop, produce and access new products, industrial processes and services . . . and create more jobs, improve people’s lives and build greener and better societies.”

⁸ For a recent review of the potential of biogas production in Sweden see Martin (2015a). In this study, the main influencing factors in the expansion of biogas production in Sweden are identified as *feedstock availability*, *digestate management*, and *institutional conditions and support systems* (cf. Lantz et al., 2007).

innovations—and sometimes influencing policies—which allow biogas solutions to adapt to each unique situation (Ersson et al., 2015; Lantz et al., 2007).⁹

Biogas production is commonly linked to the production of renewable energy carriers. Biogas producing facilities typically receive feedstocks—such as industrial or municipal wastes—as input and deliver biogas as their main output. Digestate is often considered as the byproduct of biogas production. It contains essential nutrients for plants and can substitute for mineral fertilizers. As a result of this focus on the production of renewable energy carriers, sometimes the potential of biogas solutions for integration with other industries—for example a biogas plant which is installed within a large industrial cluster and relies on various waste streams—and their inherently *dual function* of producing renewable energy *and* recycling the essential nutrients are under-represented.¹⁰ Adopting a perspective such as industrial ecology, which emphasizes closing the material loops, will include aspects of both *biogas for renewable energy* and *biogas for nutrient recycling*.

Many studies focus on biogas process technologies and individual processes within the biogas plant—for example improving the anaerobic digestion within the reactor. There are, however, only few studies that are based on a wide systems perspective concerning life-cycle impacts as promoted by industrial ecology (for a few Swedish examples see Börjesson and Berglund, 2006, 2007; Börjesson et al., 2015; Tufvesson et al., 2013). The inherent connections between biogas solutions and other systems means that life-cycle-based and systematic approaches for identifying the risks and opportunities are important for the developments involving biogas technologies. Investigating the potentials of biogas solutions and the various roles that they can play in relation to eco-industrial development, and from a life-cycle perspective, is an area which is not fully explored.

SYSTEMS ANALYSIS APPROACHES should also take into account the uncertainties of biogas solutions. These solutions, like most emerging biobased systems, are complicated and there are many knowledge gaps and uncertainties about their potentials and performance. Uncertainties of biogas systems arise due to the large number of parameters, their dependency on specific local conditions, and the relative lack of knowledge about the ways that some of those parameters can change. For example, assessing the amount of feedstock—here, referring to biomass or organic materials—that can be used for biogas production,

⁹ Actors refer to all the stakeholders, individuals, groups, or coalitions within industry, civil society, or public institutions that are involved in—or influenced by—the processes and initiatives which support industrial, urban, or community developments. Actors can include policy-makers, entrepreneurs, experts, intermediaries, and end-users. This definition is adapted and expanded from the formulation of social actors by Sénécal (2012).

¹⁰ Still, there are several studies which view biogas as an integral part of other industrial systems. For example, see Andersson et al. (2014); Broberg Viklund and Lindkvist (2015); Ersson et al. (2015); Martin et al. (2014).

is subject to several assumptions about ecological considerations, technological development, and economic factors (Egnell and Börjesson, 2012; European Environmental Agency, 2013). Another example is related to uncertainties in the life-cycle environmental impacts of biogas solutions. Since many of these solutions are linked to agricultural production, LCAs—and other systems analysis approaches—are faced with uncertainties about system boundaries and assumptions about long-term impacts on the soil systems (Bouwman et al., 2002; Meyer-Aurich et al., 2012; Minnen, 2008). While assessment of uncertainties is a challenge of all LCAs (Hellweg and Canals, 2014), this challenge is more reflected in LCAs of biogas systems: most of these studies do not sufficiently emphasize identifying, representing, and propagating these uncertainties, and tend to report their results as either point-values or using simple error bars (for example, see Bernstad and la Cour Jansen, 2011; Carlsson et al., 2015; Chiew et al., 2015; Evangelisti et al., 2014; Hijazi et al., 2016; Inaba et al., 2010; Lantz and Börjesson, 2014).

The uncertainties of biogas systems add to the existing challenges of many biogas producers for profitability and growth. They also mean that decision-makers and actors who promote the transition toward a biobased economy, may not be able to identify and assess the proper roles which biogas solutions can play in such a transition, or to incorporate them into their decisions. Methodical approaches toward identification and management of uncertainties (Awudu and Zhang, 2012; Canals et al., 2011; Malça and Freire, 2010) can reduce some of these uncertainties, facilitate communication, and support decision-making.

Studying biogas solutions from the perspective of industrial ecology, and systematically investigating their potential, performance, and feasibility, is an area worthy of further elaboration.¹¹

¹¹ See several related studies such as Andersson et al. (2014); Fallde and Eklund (2015); Martin and Eklund (2011); Martin et al. (2014), which have viewed biogas solutions from the perspective of industrial ecology and industrial symbiosis.

1.3 Aim

THE AIM OF THIS THESIS is to *investigate the relevance of the industrial ecology, industrial symbiosis, and systems analysis approaches for the eco-industrial development of cement and biogas production systems, and to provide methodological insights for assessing the feasibility and performance of relevant eco-industrial development paths in order to facilitate strategic decision-making regarding their implementation*. The focus on *implementation* highlights the central role of the *actors* who can influence the implementation of eco-industrial development

initiatives. Similarly, *decision-making* refers to the decisions that these actors take, and *feasible* refers to the kind of initiatives that they find implementable. Furthermore, *strategic* refers to long-term goals of these actors in relation to eco-industrial development and how they can approach these goals. This aim is operationalized via two main research questions. The first question focuses on empirical aspects of the studied cases, which are from cement production and biogas solutions, while the second explores the methodological dimension of the aim.

Research Question 1 (RQ₁)

In what ways can industrial ecology, in combination with industrial symbiosis, contribute to eco-industrial development within cement and biogas production systems?

Box 1.1: Research Question 1

This research question is approached through two sub-questions related to the studied cases from cement and biogas production systems. Research Question 1_a (RQ_{1a}) asks about the relevance of industrial ecology and industrial symbiosis for the developments within the cement industry, while Research Question 1_b (RQ_{1b}) raises a similar question regarding biogas solutions. Answers to these questions provide a basis for discussing the common patterns—if there are any—that might be identified from these two seemingly different industrial systems and what might be concluded from their differences.

Research Question 2 (RQ₂)

How can systems analysis approaches be used for assessing the feasibility and resource efficiency of relevant eco-industrial development paths, and therefore support strategic decision-making for their implementation?

Box 1.2: Research Question 2

This research question is approached through three sub-questions. Research Question 2_a (RQ_{2a}) asks how systems analysis can be used

for identifying and assessing feasible and resource-efficient options for eco-industrial development, considering the perspectives of industrial ecology and industrial symbiosis. Research Question 2_b (RQ_{2b}) asks how systems analysis approaches can be used for quantifying the environmental performance of the identified options, as well as identifying and assessing critical factors and key uncertainties that can influence the performance. RQ_{2b} is related to RQ_{2a} in that the latter tries to assess and quantify the performance of the strategies which are identified by the former. Finally, Research Question 2_c (RQ_{2c}) asks if it is possible to integrate the two systems analysis approaches which are explored in RQ_{2a} and RQ_{2b}. Such integrated assessment approach would allow both the construction of feasible development scenarios for an industrial system and assessing its environmental footprint in each scenario.

1.4 Scope

THIS THESIS is based on studies of cement and biogas industrial systems. The studies on cement are based on an existing production system, which consists of three plants located in Germany (see Chapter 4). The data collected reflects the conditions in 2009 (and 1997). A multi-criteria framework was developed and used in order to identify potential improvement options and assess the feasibility of the identified options. Life-cycle assessment was used for quantifying the CO₂ footprint of cement production from a *cradle-to-gate* perspective. In addition, the CO₂ footprints of several cement products were compared with each other. The historical development of the production system was then analyzed by comparing its situation in 1997 with 2009. Finally, some feasible development paths were defined and the CO₂ footprint of the cement production system was quantified in each of these scenarios.

Two studies related to biogas production are included. The first study assessed the potential and suitability of using five types of feedstock for biogas and biofertilizer production, considering Swedish conditions. The studied feedstocks were ley crops, straw, blue mussels, household food waste, and stickleback fish (a type of non-edible fish). The materials used for this study were mainly gathered from the literature, but this information was complemented and reviewed by the Biogas Research Center (BRC) representatives from both academia and industry. The second study was based on an actual biogas plant in Sweden which treats household food waste as feedstock for

biogas production. The study used life-cycle assessment (LCA) in order to compare two treatment systems based on dry and wet digestion processes. Since this study did not include the distribution and use of biogas, its scope was *cradle-to-gate*; however, the digestate handling and use as biofertilizers were included.

THE SYSTEMS ANALYSIS APPROACHES used in the studies were aimed at facilitating strategic decision-making regarding the implementation of resource-efficient cement or biogas solutions. While some organizational aspects considering the feasibility of the identified development options were included in the multi-criteria assessment frameworks, generally, organizational aspects and management processes were not focused on. The goal of the studies was to provide usable information on the basis of which more informed decisions can be made, while the decision-making processes were not focused on.

1.5 Thesis Outline

THIS PH.D. THESIS consists of a cover essay and six appended papers. The cover essay consists of several chapters, which here are briefly introduced.

In the current chapter, the background, aims, and scope of this thesis are introduced. In addition, the research journey and my participation in different projects are presented chronologically. Chapter 2 (Technological Background) then provides a short technical introduction to cement and biogas production. Next, the theoretical frame of reference and key approaches of this thesis are presented in Chapter 3 (Theories and Approaches). In Chapter 4 (Methodology), an overview of the methodological approach of this thesis is presented. Following this, the results are presented in Chapters 5–7. The cement study is presented in Chapter 5 (Integrated Assessment of the CO₂ Footprint of Cement). Chapter 6 (Resource-Efficient Biogas Solutions) displays the results of two biogas-related studies: First the result of the study for assessing the resource efficiency and feasibility of using different feedstocks for biogas production is presented. This is followed by the results of the second study, in which key factors and the main uncertainties of producing biogas from source-sorted food waste were analyzed using life cycle assessment. Finally, a framework for integrated systems analysis based on multi-criteria and life-cycle approaches is suggested in Chapter 7 (Toward Integrated

Systems Analysis). The thesis concludes with Chapters 8 (Discussion) and 9 (Conclusions), where the main findings, approach, and implications are discussed and summarized.

1.6 *Research Journey*

RESEARCH EDUCATION IN LINKÖPING UNIVERSITY consists of two main elements: performing research and taking courses.¹² The largest share of the Ph.D. education time is allocated to research related activities, often in the form of involvement in externally funded projects. The content of this thesis and the appended articles are primarily the result of my participation in several research projects, which for enhanced readability are structured conceptually—that is the content is not always presented in the form or order that the research was performed. However, in this section these research projects, which ran through 2010–2011 and 2013–2016 and led to the completion of this thesis, are presented chronologically.

THE CEMENT RESEARCH (Papers I–III) is the result of a project funded by CEMEX, which is an international producer and provider of construction materials in more than 50 countries. The aim of the project was to contribute to a better understanding of the CO₂ footprint of cement production—involving different ways of producing cement and different cement products—and to systematically investigate different ways of improving the CO₂ footprint of cement production in the CEMEX production facilities. Initially, the proposal was to study several cement plants located in different countries and represent different production conditions. Eventually, however, a cement production cluster consisting of three plants in Germany was selected as the object of investigation. The reasons for this selection were the good availability of historical production data in these plants, and the fact that the conditions and the organization of these plants had changed so much in the last 10 years (1997 to 2009). Thus, they were considered as an interesting case for studying the impact of different improvement strategies, including some which could fit under the category of IS. In addition, these plants provided an opportunity for studying traditional Portland cement production as well as more synergistic alternatives. The report of this project was published in 2011 (Ammenberg et al., 2011). Later on, and based on this report and the empirical data gathered during the project, Papers I–III were developed and published. In these papers, the methodological approach

¹² In practice, it is common for Ph.D. candidates to take part in teaching or organizational activities as well.

regarding integrated systems analysis of the CO₂ footprint of the cement production system, as well as the relevance and potential of IS for the cement industry, were further developed both theoretically and empirically.

THE PROCESS of establishing a transdisciplinary center of excellence focusing on biogas, which began many years ago, came to fruition by the end of 2012. The vision of the BRC is to contribute to the implementation of resource-efficient biogas solutions in different sectors and applications. The BRC has a triad of funding: Linköping University, the Swedish Energy Agency, and a number of industrial and municipal partners and members, each contributing about one-third of its budget. The research areas are also a triad, focusing on the process, system, and societal levels. The research projects related to this thesis have been part of the system research area.

Since access to suitable feedstock is among the most important prerequisites for expanding biogas production in Sweden, one of the system projects focused on the assessment of feedstock for biogas production. The results of this project formed the basis for Papers IV & V. In these papers, a framework for multi-criteria assessment of different feedstock for biogas production was developed and applied. This framework was mainly used for qualitative or semi-quantitative assessment, but relied on both quantitative and qualitative data for input. The assessment included many aspects related to resource efficiency and feasibility for implementation. The assessed feedstocks were ley crops, straw, blue mussels, household food waste, and stickleback fish. Ley, straw, and blue mussels were assessed considering generic Swedish conditions, while household food waste and stickleback fish were assessed in connection to particular cases—that is, were case-specific. This project is still ongoing, and will continue to develop and apply multi-criteria frameworks for assessing different types of biogas solutions.

The second biogas project related to this thesis focused on quantitative assessment of the environmental (and economic) performance of biogas production systems. This project is represented by Paper VI, which focuses on the environmental performance of producing biogas from the source-sorted organic municipal food waste, using dry and wet anaerobic processes and quantification of the main uncertainties.

THE RESEARCH ENVIRONMENT in the Division of Environmental Technology and Management (ETM) at Linköping University has influenced the theoretical and methodological approach of this research.

Mainly, the connecting thread between all of these research projects is the *Mode 2* approach to scientific production (Gibbons et al., 1994), where stronger emphasis is placed on collaboration between researchers and actors belonging to the problem domain in order to ensure that the scientific output remains close to *implementation* and real-world issues. In this approach, scientific knowledge is co-produced by both researchers and non-academic stakeholders, who are welcome to play an active role in the design, orientation, and execution of the research. In addition, in our research environment, a broad systems view of industrial development and better utilization of local and regional resources through increased interconnectedness is generally promoted. These approaches are typically manifested in the form of theories which are related to IE and industrial symbiosis.¹³

¹³ Industrial ecology and industrial symbiosis are explained in greater detail in Chapter 3 (Theories and Approaches).

Chapter 2

Technological Background

In this chapter a short introduction to the basics of cement and biogas production is presented.

2.1 Basics of Cement Production

CEMENT-LIKE MATERIALS have been known to many societies for thousands of years (Blezard, 1998; Hill, 1996), but materials with properties similar to modern cement only started to be used about 200 years ago (Hewlett, 2003, p. 4). 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 accelerated in recent decades (U.S. Geological Survey, 2013a, 2016). In 2015 about 4.1 billion tonnes of cement were produced worldwide, which was in fact slightly lower than the previous year. The global cement production curve for the last 90 years can be approximated by an exponential function with an annual growth rate of about 5 % (see *Figure 2.1*).

The largest producer of cement in the world is China, with about 57 % of the global production.¹ Europe-27 and India each produce about 7 % of the global cement production, while the USA, Brazil, Iran, Vietnam, Russia, Turkey, and Japan produce about 2 % each (U.S. Geological Survey, 2013a, 2016). In 2012, the global concrete and cement market was about \$450 billion (RnR Market Research, 2013).

CEMENT CAN BE PRODUCED with different compositions and properties. Ordinary Portland cement (OPC) is the most well-known and used type of hydraulic cement, consisting of about 95 % of a material

¹ In order to grasp the scale of cement consumption in China, consider the fact that in just two years (2011 and 2012) it has consumed more cement than the United States has produced in the whole twentieth century (ICR, 2013; U.S. Geological Survey, 2013b, 2016)

Figure 2.1: Global cement production, historical trend 1926–2015. Data from U.S. Geological Survey (2013b, 2016)

called clinker.² The raw materials used for production of clinker are mainly calcium carbonate and siliceous materials such as Limestone or chalk, as well as shale or clay. Production of OPC, which in Europe is known as CEM I, consists of two main steps: production of clinker in the cement kiln, and grinding and blending it with gypsum and other materials to produce the cement product. First, a mixture of Limestone and clay is heated up to about 1400–1600 ° in the cement kiln. The high temperature of the kiln decomposes the calcium carbonate, and calcium oxide (CaO) and CO₂ are produced. Clinker is produced from the reaction of CaO with alumina, silica and other minerals. This process is known as calcination. After the clinker is produced and cooled down, it is ground and blended with gypsum in order to produce OPC.

ALTERNATIVE MATERIALS, often referred to as supplementary cementitious materials (SCMs), can partially replace clinker in order to produce other types of cement, which are generally referred to as Blended cements. The most commonly used SCMs are granulated blast-furnace slag (GBFS)—a residue from crude iron production—and coal fly ash, but there are many other materials, including industrial byproducts, that show similar properties (see *Figure 2.2*). These materials are ground and mixed with clinker in the required proportions. Standards such as ASTM in the United States (ASTM, 2013) and European Standard EN 197-1 (2011) define the specifications of different cement types.

According to EN 197-1, there are five main types of cement (CEM I–V). These types of cement are primarily characterized by

the share of clinker and SCMs in their composition. CEM I with highest clinker content is the same as Portland cement. An example of blended cement is CEM III, which can contain between 5–95 % of GBFS, or more specifically, ground granulated blast-furnace slag (GGBFS). GGBFS has cementitious properties similar to clinker and can, to a large extent, substitute for it in finished cement products.

Figure 2.3 shows how the addition of SCMs and the production of blended cements such as CEM III can reduce the use of clinker. In this case, clinker is substituted by GBFS.

EACH TONNE OF CLINKER requires about 1.5 tonnes of raw materials (Association and others, 1997; Locher, 2006). Historically, coal, and later fossil fuels, have been the main fuels for the production of clinker. The cement industry is both energy- and material-intensive (CEMBUREAU, 2013). The main raw material required for the production of Portland cement is limestone, which is geologically abundant. In the foreseeable future, it is very unlikely that Portland cement production faces raw material scarcity issues (U.S. Geological Survey, 2013a). However, if raw material scarcity is not the main challenge for the cement industry, high energy intensity and large CO₂ emissions are (CEMBUREAU, 2013). The CO₂ footprint of Portland cement production is dominated by emissions from the calcination process and combustion of fuels during clinker manufacturing (Worrell et al., 2001). The calcination process is responsible for about 60 % of the total CO₂ emissions (WBCSD, 2015; WSP et al., 2015). It is important to note that this process is an integral part of clinker formation and is often considered unavoidable by the cement sector; therefore, strategies to substitute the clinker are particularly important. The rest of the CO₂ emissions are due to

Figure 2.2: Approximation of the composition of different cementitious materials in a ternary diagram. Redrawn based on several sources, including Lothenbach et al. (2011); Peyronnard and Benzaazoua (2011), and Tariq and Yanful (2013).

Figure 2.3: A simplified illustration of producing Portland and blended cements in which a supplementary cementitious material (SCM) such as granulated blast-furnace slag (GBFS) partially replaces clinker (adapted from Paper I).

the combustion of fuels, and indirectly from the use of other energy carriers such as electricity.

CEMENT PRODUCTION can take in a diverse range of waste-derived or alternative materials and fuels, which are often cheaper than their 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).

2.2 *Basics of Biogas Production*

BIOGAS, WHICH MAINLY CONSISTS OF BIOMETHANE, is produced when organic materials are broken down by microorganisms through anaerobic digestion—that is, in the absence of oxygen.³ Anaerobic digestion is a naturally occurring process, and the microorganisms which produce biogas play an important role in the global carbon cycle: after living organisms die, their bodies decompose and are recycled back into the ecosystem (Prentice et al., 2001). The composition of raw biogas depends on the digested organic material, but it typically contains 50–70 % methane and 30–50 % carbon dioxide, and minor amounts of other gases such as water and hydrogen sulfide. From an energy perspective, methane is the main component of raw biogas.

Controlled and purposeful biogas production has a long history. Many human societies have used it as a source of energy for several millennia (He, 2010). Modern examples of biogas production include collection from landfill sites, anaerobic treatment of sewage sludge,

³ Sometimes, the syngas produced by thermal gasification is also considered to be biogas. But in this thesis, biogas refers solely to the gas produced through anaerobic digestion.

and co-digestion plants where various industrial or municipal organic wastes, as well as agricultural crops or residues, are used (Abbasi et al., 2012).

On a global scale and compared to other energy carriers, biogas production is small, but is growing at a considerable rate: it has seen a more than threefold increase between 2000 and 2011, from about 80 to 300 TWh (World Bioenergy Association, 2014). The rate of growth varies in different parts of the world. Biogas production has roughly increased by a factor of two in the USA, by a factor of four in the EU, and by a factor of seven in China (World Bioenergy Association, 2014). In most places, biogas is used for electricity or heat production. Switzerland and Sweden are exceptions, because about half of the produced biogas is upgraded and used as transportation fuel (IEA Bioenergy Task 37, 2014). Since the 1960s, biogas has been produced in municipal wastewater treatment plants in Sweden. Initially, the main purpose of biogas solutions was to reduce the volume of sludge, but gradually, and especially after the oil crisis of the 1970s, biogas started to be seen as a source of energy and a solution for reducing environmental impacts (Swedish Gas Association, 2011). According to Energy Gas Sweden (2015), 277 biogas plants were operating in Sweden in 2014, producing 1.8 TWh methane.⁴ 50 % of these plants were based on wastewater treatment, 22 % recovered methane from landfills, 13 % were farm-scale plants, 13 % were large-scale co-digestion plants, and 2 % were located within certain industries. The dominant part of the biogas production in Sweden comes from co-digestion and waste water treatment plants which produce 40 and 38 %, respectively, of the total biogas produced. In 2014, 57 % of the total produced biogas was upgraded, while 24 % was used for heat and 3 % for electricity production. Almost all of the digestate produced at co-digestion and farm-scale plants was used as biofertilizers, while this figure for biogas plants at wastewater treatment plants was only 30 %.

FOUR MICROBIAL ACTIVITIES are involved during the anaerobic digestion of organic materials (van Haandel and van der Lubbe, 2012). The first activity is hydrolysis, where special enzymes break down large molecules of carbohydrates, proteins and lipids. The second one is acidogenesis, or fermentation, where products of hydrolysis are fermented into fatty acid intermediaries. The third is acetogenesis, where intermediaries are converted to hydrogen, carbon dioxide, and acetate. Finally, the fourth activity is methanogenesis, where

⁴ The figure of 277 *biogas plants* includes the first thermal gasification plant in Sweden (Energy Gas Sweden, 2015).

Figure 2.4: A simplified illustration of producing biogas and biofertilizers from primary and secondary organic materials.

methanogenes produce methane from acetate, hydrogen, and carbon dioxide. Typically, the temperature of digesters is either in the range of 20–30 ° or higher than 40 °, which are referred to as mesophilic or thermophilic processes, correspondingly.

In theory, almost any type of organic material—biomass—can be used as input to biogas production. *Figure 2.4* shows an overview of a generic biogas production system. Organic materials which are fed into the biogas plant are generally referred to as *feedstock* or *substrate*. In *Table 2.1*, the theoretical amounts of biogas and biomethane that can be produced by anaerobic digestion of the main types of biodegradable organic materials—carbohydrates, fats, and proteins—are shown. Proper pre-treatment may increase—to a certain extent—the biodegradability of other materials such as lignocellulosic biomass.

Biomass	Biomethane (Nm ³ CH ₄ /tonne)	Composition of raw biogas (CH ₄ :CO ₂ ; % vol.)
Carbohydrates	415	50:50
Lipids (fats)	1014	70:30
Proteins	496	50:50

Table 2.1: Theoretical biogas yield from three main types of organic materials, based on the Buswell formula (Angelidaki and Sanders, 2004).

While there are many different designs for anaerobic digestion, an important distinction can be made between the wet and dry systems. In a dry process, substrates with higher dry matter content (DM) can be fed into the reactor: the dry matter content for the dry process is typically 20–35 %, while in the wet process it is 2–10 %

(Nordberg and Nordberg, 2007). Both systems may require proper pre-treatment in order to remove unwanted materials—such as plastic pieces or other non-degradable solids—from the input feedstocks. Therefore, the wet process is commonly used for situations where the available substrates have a relatively low dry matter content (high water content). Sometimes, additional water is added to the substrate in order to reduce the dry matter content to the acceptable range. The digestate produced in the wet process contains a higher amount of water compared to the digestate of the dry process. Historically, the wet process has been the most popular in Sweden, and most large-scale plants in Sweden are based on this type of system.

After the organic materials are anaerobically digested and biogas is produced, most of their nutrients end up in the leftovers, called *digestate*. Digestate can be used as biofertilizers in farms, through which valuable nutrients such as nitrogen or phosphorous are recycled back into the biomass production systems, which in turn can decrease the need for mineral fertilizers in these systems. Small-scale biogas production tends to be used for cooking, heating, or lighting, while large-scale biogas plants can use biogas for co-generation of heat and electricity, or production of vehicle fuel through the upgrading of the raw biogas so that its methane content reaches above 97 %.

BIOGAS SOLUTIONS ARE VERSATILE and can fit several purposes—they are multi-functional. Many types of organic materials with varying characteristics and qualities can be used as input for biogas production. In addition to biogas, which is a renewable energy carrier, anaerobic digestion leads to the production of digestate, which contains nutrients and stable organic materials suitable for agriculture. Biogas is commonly framed as a potential source of renewable energy which is expected to compete with other bioenergy/biofuels and to contribute significantly to the reduction of fossil fuels. Overemphasizing the renewable energy dimension of biogas solutions disfavors their inherent multi-functionality, for example in relation to their potential for nutrient recycling.

Chapter 3

Theories and Approaches

In this chapter the theoretical foundations and the main approaches of this thesis are introduced. This includes a short introduction to industrial ecology, resource efficiency, and industrial symbiosis. The approach to environmental systems analysis is discussed by focusing on the life-cycle approach, the multi-criteria approach, knowledge and uncertainty, and uncertainty management in systems analysis.

THE OVERARCHING theoretical umbrella of this thesis is industrial ecology (IE), both as a metaphor of a circular economy and as a methodological foundation for studying industrial activities from a broad systems perspective. IE provides a theoretical framing for eco-industrial development toward higher resource efficiency, as in industrial symbiosis (IS), and provides methodological approaches for assessing the performance and feasibility of eco-industrial development, as in life-cycle assessment (LCA) and multi-criteria analysis (MCA) (*Figure 3.1*).

While life-cycle approaches are commonly used within IE, multi-criteria approaches are less well-known. Nevertheless, in this thesis, both of them are regarded as systems analysis approaches related to IE. In the following sections, the theoretical and methodological concepts of this thesis are introduced.

3.1 *Industrial Ecology and Resource Efficiency*

RESOURCES refer to all supplies or stocks that are—or can be—inputs into an economy, typically referring to environmental or natural resources such as metals, minerals, fuels, fish, timber, water, soil, clean air, biomass, biodiversity, land and sea, and ecosystem services

Figure 3.1: Schematic overview of the relationship between the theoretical and empirical approach of this thesis.

(European Commission, 2011c).¹ Resource efficiency is defined as “a way to deliver more with less. It increases aggregate economic value through more productive use of resources over their life-cycle. It requires using those resources in a sustainable way, within the planet’s long-term boundaries. This includes minimizing impacts of one resource’s use on other resources, including the environment” (European Commission, 2011c). Resource efficiency covers *material resource efficiency*, *natural resource efficiency*, *energy efficiency*, and *waste generation and impact*, considering the life-cycle of products, services, or activities (Rademaekers et al., 2011). Simply put, resource efficiency means to be more economic—in a broad sense of the word—with the available resources and try to draw more value from them. The European Commission (2015) places resource efficiency (RE) under its broad strategy for Sustainable Development, and as part of the Europe 2020 strategy for “smart, sustainable, and inclusive growth” (European Commission, 2011b).

THE FIELD OF INDUSTRIAL ECOLOGY (IE) envisions industrial systems that are engaged in a network of symbiotic relationships where wastes or residues of one actor are “food” for others (Frosch and Gallopoulos, 1989). This means that the dependence of industrial systems on virgin materials from the earth’s crust can significantly diminish, and the economy can be made more circular.² IE promotes a broad systems perspective—systems with large boundaries, which means viewing the technological solutions in their full life-cycle, and as embedded sub-systems in the larger ecological and socio-technical

² For earlier examples of using an ecological metaphor for envisioning better industrial systems see Renner (1947); cf. Erkman (1997).

systems (Ayres and Ayres, 2002). Inherent in IE is the importance of broad systems perspectives in order to minimize the risk of sub-optimization and problem shifting. In addition, IE calls for a conceptual redefinition of waste; that is, a transition from viewing *waste as a disvalue*—pertaining to a negative economic value—to *waste as resource*—a potential source of value.ⁱⁱ This transformation of the view on “waste” and the emphasis on closing the loops does not deny the existence of waste—which is an inevitable part of most economic activities. Therefore, it is compatible with other strategies such as the waste hierarchy (European Commission, 2008) and material cascading.³

Ayres and Ayres (2002) have formulated three different types of industrial systems. Type I has a linear flow of energy carriers and materials, and therefore relies on the continuous supply of new energy carriers and materials as well as the availability of sinks for disposing the produced wastes. Type II has a quasi-circular flow of materials and energy carriers. It uses less external resources, produces less waste, and emits less emissions. Finally, the Type III system benefits from truly cyclic flows of materials and energy carriers. It only needs primary renewable energy as input and does not produce any material waste. According to this view, a necessary—but not sufficient—characteristic of a good industrial system is its ability to preserve and promote round-put, that is cyclical and cascading flows, in contrast to throughput, or linear flows. Therefore, from the theoretical standpoint of IE, industrial production systems can improve by getting closer to the above-mentioned ideals: for example becoming increasingly more like Type II and Type III systems.

THE CONCEPT OF IE can be operationalized for increasing the resource efficiency (RE) of industrial systems in two complementary ways. First is its descriptive (or positive) dimension, which allows it to be used as a framework for the disciplined study of material and energy flows within and without industrial systems. This aspect of IE is manifested in many systems analysis approaches such as LCA or material flow analysis (MFA)—although these approaches can also be used for normative analysis. These approaches can lead to an increased knowledge about the RE and other characteristics of the studied systems (Ayres and Ayres, 2002). Decision-makers—being designers, managers, or policy-makers—can use these *accounting* results in order to make more informed decisions regarding improving or maintaining the RE of their corresponding industrial systems (*ibid.*).

³ Sometimes, total waste prevention is too costly, or simply not possible. *The ALARA principle—As Low As Reasonably Achievable*—provides a vague but commonsensical approach toward waste prevention and waste minimization (Faure and Ruegg, 1994).

In addition, IE has a prescriptive (or normative) dimension which is based on its metaphoric view of good industrial systems (Ayres and Ayres, 2002). As a normative science, IE emphasizes norms such as connectedness, cooperation, and community. These norms go beyond the analysis of material and energy flows within a given system (Ehrenfeld, 2000) and promote certain types of industrial development, often referred to as IS. Industrial symbiosis represents a shift in the organization of industrial activities with the aim of improving economic and environmental performance through resource-efficient utilization of wastes, residues, and byproducts. Therefore, industrial symbiosis has direct relevance to improving the RE of industrial systems (Laybourn and Lombardi, 2012). However, systems analysis is needed to compare the local gains in resource efficiency with each other, and to ensure that these local gains are valid when wider systems perspectives and full life-cycles are considered.

3.2 *Industrial Symbiosis*

INDUSTRIAL SYMBIOSIS (IS) is, as mentioned before, closely linked to the normative ideals of industrial ecology. At its core, IS is about the cooperation of industrial actors in sharing their resources—energy, materials, byproducts, wastes, utilities, and knowledge—in order to gain both environmental and economic benefits (Chertow and Park, 2016).⁴ In comparison to industrial ecology, which is fairly abstract and general, industrial symbiosis places a particular emphasis on concrete synergies that can enhance the utilization of wastes, residues, or byproducts. While individual units—plants or organizations—can gain from industrial symbiosis, the general idea is to collectively improve the resource efficiency of the collaborating units. These units can be located near each other, for example, in an industrial area (eco-industrial park), but symbiotic relations can also occur between distant units. Typically, the efficient exchanges of utilities, byproducts, energy and materials often require short distances, if not direct proximity (Chertow, 2000). Nevertheless, exchanges of high-value materials, or other forms of symbiotic relationships, such as shared knowledge or infrastructure, can occur over much longer distances.

Industrial symbiosis can be studied from from at least three different perspectives (Zhang et al., 2014): characterization of the types of symbiotic relationships that have emerged or can potentially shape

⁴ The earliest and most famous example of industrial symbiosis is located in Kalundborg, Denmark (Branson, 2016; Chertow, 2007; Ehrenfeld and Chertow, 2002; Ehrenfeld and Gertler, 1997; Gertler and Ehrenfeld, 1996; Grann, 1997; Jacobsen, 2006).

among the actors (structure), assessing the economic or environmental impacts of the symbiotic network and the allocation of those impacts between the participating industries (benefits and costs), and studying the historical evolution and the conditions under which it has evolved or can potentially evolve into (process). Due to the complexity of assessing the benefits and costs of industrial symbiosis from a life-cycle perspective, it is common to focus on the direct environmental or economic impacts within the studied industrial system. This means, in many cases, that environmental gains from industrial symbiosis are taken for granted (Martin, 2015b). Few studies have suggested methods for assessing the benefits of industrial symbiosis (Eckelman and Chertow, 2013; Liu et al., 2011; Martin et al., 2013; Mattila et al., 2012; Sokka et al., 2011, 2008; van Berkel, 2010). This thesis provides an approach for assessing the CO₂ footprint of cement production—involving industrial symbiosis—from a life-cycle perspective (see Chapter 4).

IS can be viewed as a transformative concept which can be used for developing existing industrial clusters (brownfield development) or as a basis for constructing new industrial systems from scratch (greenfield development) (Lambert and Boons, 2002). The focus of this thesis is mainly on brownfield development, and primarily on the structural relevance of IS for industrial developments and the methods for investigating its potentials and impacts. The studied systems from cement production and biogas solutions are viewed in this light—that is, the nature and structure of symbiotic relations and their impacts. The CEMEX case represents a brownfield development, where changes within a cement production system from 1997 to 2009, as well as a few projected future scenarios, are investigated, and where the improvement gains are quantified. Biogas solutions can play different roles; but they can be seen as an extension of existing industrial production systems or as infrastructures related to waste management, transport, and agriculture.

3.3 Environmental Systems Analysis

RAPID AND WIDESPREAD social and technological changes of the last decades can cloud the bigger picture of industrial development and its impacts on the natural environment, especially, if these changes are

combined with diverse and uncertain aspects of socioeconomic systems which occur on different scales. For obvious reasons, decision-making by industrial stakeholders is primarily based on financially-oriented economic analysis. Focusing on this narrow economic perspective is necessary—economic actors need to sustain themselves. Nevertheless, from a societal perspective and considering a long-term view, this is not enough.⁵ Therefore, when considering important decisions regarding the sustainable trajectories of societies, it is important to include the physical and/or ecological aspects of the economy as well; aspects which can be effectively traced by following the flows and stocks of materials including water, energy, pollutants, etc.ⁱⁱⁱ Indeed, decision-makers, such as policy-makers and planners in public and private sectors, have an increasing tendency to integrate environmental considerations into their corresponding activities (European Commission, 2013; Lenschow, 2002; Runhaar, 2016).

Collectively, environmental systems analysis (ESA) refers to approaches, methods, frameworks, and tools that can be used in decision-making regarding the design and implementation of more resource-efficient industrial activities—considering a broad systems perspective.⁶ ESA is the systematic study of existing or hypothetical technological systems, and their relation to their surrounding industrial or ecological systems, in order to obtain structured knowledge about their potentials for growth or for addressing certain problems, feasibility, and performance, including aspects such as resource efficiency, environmental impacts, and risks.^{iv} This knowledge can be used by decision-makers, planners, and implementers to make better decisions, either by adopting preferred technological solutions or through changing the way that their corresponding industrial systems are managed or organized.

There are many different tools for ESA (Finnveden and Moberg, 2005; Neto et al., 2008; cf. Ness et al., 2007). Some of these tools such as environmental impact assessment (EIA), Eco-design, and multi-criteria analysis (MCA) are procedural, while others such as life-cycle assessment (LCA) or material flow analysis (MFA) are analytical. The aim of procedural tools is to improve the processes of decision-making, for example by incorporating the views of stakeholders. Analytical tools are used to model the system in order to provide technical information which can be used for better decisions (Wrisberg et al., 2012). Decision processes—and the procedural tools that support them—do not typically lead to “discoveries”, but strive for the “creation” of balanced decisions. However, analytical approaches

⁵ Textbooks within the field of ecological economics provide several accounts of the inherent limitations of classic economic views (Daly and Farley, 2010; cf. Sagoff, 2012).

⁶ It should be noted that environmental systems analysis can include issues that are not directly linked to environmental performance—such as technological maturity or profitability. Therefore, depending on the key focus, sometimes the notion of the *environment* becomes implicit in systems analysis. In this thesis, the terms *systems analysis* and *environmental systems analysis* are used interchangeably.

may directly lead to “discoveries” (Wrisberg et al., 2012): for example finding out that the most environmental impacts of a product are from a certain stage of its life-cycle. Therefore, analytical tools such as life-cycle assessment can be used as part of the procedural tools, such as multi-criteria analysis. It is important to note that the distinction between these two approaches is not always clear, as most of these tools can be used for mixed purposes. In this thesis, the life-cycle and multi-criteria approaches are viewed, developed, and applied in complementary ways and are explained in the following sections.

3.3.1 Life-Cycle Approach

WHEN RESOURCE EFFICIENCY, performance, or certain environmental impacts of an industrial activity—a product, a service, or a function—are to be investigated, it is important to include the set of all the activities that are collectively needed for it to happen. These activities include the provision of raw materials, their treatment and conversion into usable products or services, transportation, distribution, consumption, reuse, recycling, disposal and end-of-life treatment. A *life-cycle approach* includes a more holistic investigation of the impacts of an industrial activity over its full life-cycle.⁷ Using such an approach means that the analysis goes beyond the manufacturing plants—where the products are made—or the cities and buildings—where the products are used—and includes environmental, social, and economic impacts of industrial activities in their whole life-cycle, preferably from *cradle-to-grave*.⁸ The characterizing feature of these approaches is their consideration of the full life-cycle (cradle-to-grave) of industrial activities, irrespective of the type of impact categories that are included. This means a life-cycle study can only focus on a single impact category, such as global warming potential.

The most widely used life-cycle-based method for systems analysis is LCA (ISO, 2006a,b), which is a quantitative framework for analyzing the environmental and economic performance of the studied system.⁹

Once the goal and scope of an LCA are defined, three main analytical steps are required: (i) identifying the relevant processes for the delivery of the functional unit, considering its life-cycle; (ii) determining the environmental pressures such as use of resources and various emissions; and (iii) calculating the environmental impacts of those processes. According to ISO 14040 (ISO, 2006a,b), the first two steps are called *inventory analysis* while the third step is referred to as

⁷ In practice, life-cycle approaches are not always *holistic*, and are not always about environmental impacts. It is common that only one or few of the many known environmental (or economic or social) impacts are considered, and sometimes part of the life-cycle is excluded—for example considering only the greenhouse gas emissions which contribute to climate change, and excluding emissions related to eutrophication, acidification, or impact on biodiversity loss. Nevertheless, life-cycle approaches, in principle, favor more holistic analysis of impacts, which means including several impact categories through the full life-cycle.

⁸ Parallels exist between life stages of an individual organism and that of an industrial activity: design (conception), production (birth), use (maturity), and disposal (death). It is important to view these parallels as metaphors, and not analogies. This is also true for other concepts that use biological parallels—industrial ecology, industrial metabolism, and industrial symbiosis (Ayres, 2001; Ehrenfeld, 2003).

⁹ While the standard LCA has a clear reference to environmental assessment, similar life-cycle-based analytical tools such as life-cycle costing (LCC) can be used for economic assessment of industrial activities.

impact assessment. LCA is based on a set of linear equations which can be presented in the condensed matrix form of $I_{LC} = CS(I-A)^{-1}\gamma$ (Hertwich, 2005). Here, I_{LC} is the life-cycle impact vector containing several impact categories, S is the table of emission factors for each unit process, C is the table of characterization factors for each impact category, γ is the functional unit or final demand vector, A is the process matrix, I is the identity matrix, $I-A$ is a matrix which contains inventory information about life-cycle activities such as production, use, and disposal, and $S(I-A)^{-1}$ is the inventory analysis. In short, life-cycle impacts are calculated by multiplying the impact matrix with the inventory matrix and then normalizing the result to the functional unit.

LCA is a quantitative approach, but in general, life-cycle approaches can be applied in other ways as well, such as qualitative or simplified studies (Jensen et al., 1997). As mentioned before, LCA is mainly an analytical tool, but it can also be used in relation to decision-making.

3.3.2 Multi-Criteria Approach

A MULTI-CRITERIA APPROACH to systems analysis refers to any formal approach that explicitly accounts for multiple areas, or criteria/attributes, when assessing different alternatives (cf. with definitions from Communities and Local Government, 2009; Mendoza and Martins, 2006). In this approach, it is acknowledged that the problem is multi-dimensional and no single solution may exist that can optimize all the identified criteria. This means the multi-criteria approach is bound to seeking compromises between different key aspects of the problem (Wrisberg et al., 2012).¹⁰

Decision-making regarding the implementation of feasible, applicable, and resource-efficient technological solutions involves many different aspects. Sometimes the aspects are not clear themselves and can only be identified and defined through dialog among researchers and practitioners. When faced with such open-ended and multi-faceted questions, which are sometimes referred to as *wicked problems*, the utilized approach to systems analysis has to be flexible, allow incorporation of subjective knowledge of the practitioners and experts, and be able to deal with both quantitative and qualitative information.¹¹ In these situations methodologies based on the multi-criteria approach, such as MCA, are appropriate (Dixit and McGray, 2013). Wang et al. (2009), in their review of multi-criteria

¹⁰ It is quite possible that a single solution exists which satisfies all criteria, however, the multi-criteria approach does not necessarily require it. If such a single solution does not exist—or is difficult to find—the multi-criteria approach is inherently suitable for seeking compromises between different criteria.

¹¹ *Wicked problems* are a class of problems where there might be disagreements in their definition because different stakeholders may *frame* them differently, the search for their solutions is open-ended and inconclusive, and they are faced with a changing set of constraints and conditions. Consequently, these problems defy *final solutions*, regardless of how complicated the utilized analytical tools are (Churchman, 1967; Rittel and Webber, 1973).

decision analysis methods, noted that these approaches have become increasingly popular in decision-making regarding sustainable energy solutions because of the multi-dimensionality of the sustainability goal and the complexity of socioeconomic and bio-physical systems.

BEYOND PRACTICAL EXPEDIENCY in dealing with the wicked problems, there are more fundamental reasons, at epistemological level, for adopting a multi-criteria approach. There are many evidences that the very fabric of what we perceive as reality is not based on a unified and homogeneous kernel, but is formed by complementary parts which are distinct and cannot be reduced to each other. In other words, the kernel of reality itself is composed of complementary parts and complementarity is a *fundamental organizing principle of nature itself* (Barab, 2010).^v

In relation to the systems analysis of feasibility—or closely related aspects such as suitability or applicability—of a certain technological solutions—many complementary aspects can be identified and studied, without any methodological need to reconcile them and flatten them out into a single-dimensional indicator. A narrower perspective that focuses on the short-term profitability of an industrial actor, such as a biogas producer, should be viewed as complementary to a wider perspective that considers societal impacts and long-term sustainability. The climate performance of a given technological solution—typically linked to CO₂ emissions—complements its potential impacts on nutrients recovery or other environmental impacts. Technical and physical aspects such as availability of mature technological solutions and appropriate infrastructure, complement the governance and institutional aspects which define the rules of the game for industrial actors and other related stakeholders. A multi-criteria approach, through the acknowledgment of these inherent complementarities, allows us to inclusively and systematically analyze different aspects of the problems simultaneously. In this way, diverging aspects, impacts, and dimensions of various phenomena can—or ought to—be included in the analysis.¹²

Acknowledgment of these complementary aspects does not necessarily stop us (or decision-makers) from merging these aspects through quantitative approaches involving weighting and sorting, a practice which is common among many MCA studies in the literature. The results from a multi-criteria assessment can be weighted, compared and combined in order to analytically produce a decision.

¹² Moving away from a single-dimensional view toward systems analysis can also lead to over-fragmentation and inclusion of too many (seemingly) distinct aspects or criteria in the analysis. The multi-criteria approach of this thesis seeks to be as comprehensive as deemed necessary by researchers and the involved actors, but to include only a few aggregated key aspects in order to maintain the simplicity. Attempts are made to distinguish important and/or incommensurable aspects and define them as distinct key areas (see Chapter 4).

However, this may require comparing or combining incommensurable aspects. Therefore, the weighting and scoring is generally avoided in the multi-criteria approach of this thesis, and is treated as an open possibility for further analysis. Nevertheless, the identified areas and indicators are largely aggregated as a deliberate strategy of keeping their number low. This allows the equivalent of “weighting and scoring” by discussion, and without quantitative calculations.

3.3.3 *Knowledge and Uncertainty*

ATTAINING PERFECT KNOWLEDGE about complex subjects of an investigation—such as industrial production systems and their impacts—is not possible. Our knowledge about complex environments is imperfect, and it typically accompanies some degree of *irreducible* uncertainty. Predictable laws of physics allow us to exclude unrealistic options, but we cannot obtain an absolutely detailed representation or prediction of any particular phenomenon (Peat, 2002). Therefore, in our decisions we rely on models of the world: approximations which for any of our particular purposes are *good enough*.

Two commonly identified types of uncertainties are aleatory and epistemic uncertainties (Apostolakis, 1990; Helton et al., 2004). Aleatory uncertainty refers to things that are not knowable in principle, due to randomness and chaoticness that is inherent in their behavior.¹³ Aleatory uncertainty!aleatory is also known as variability, stochastic, irreducible, or type A uncertainty. Epistemic uncertainty, in contrast, refers to the things that are knowable in principle, but for some practical reasons we do not have sufficient knowledge about them (yet). Epistemic uncertainty is also known as state of knowledge, subjective, reducible, or type B uncertainty. Mapping out uncertainty and all its variations in a complete and consistent manner is an open philosophical challenge (Elkan, 1994).

The ubiquitous and different types of uncertainty do not bring a need for a large number of methods to manage uncertainty, or to make decisions under uncertain conditions. We make decisions under uncertainty all the time, and surprisingly, when faced with a complex environment, we often adopt simple approaches.¹⁴ Complex situations often call for simple rules for decision-making. This is because the collection and processing of a huge amount of relevant information for a complex decision—as suggested by rational decision-making—is costly and can exceed our cognitive capacities. Recognition of this inefficient decision-process was the main reason

¹³ In the philosophy of probability, a distinction is made between predictable and unpredictable variations (Deming, 1975; Keynes, 1921). Predictable variations, originate from *common causes* and are measurable forms of uncertainty where historical, quantifiable variations can be used for prediction, while unpredictable variations arise from *special causes* which are unusual, not seen before, and non-quantifiable. Predictable variations can incline toward being objective or subjective, as in frequency or Bayesian probabilities.

¹⁴ According to Herbert Simon, “human beings, viewed as behaving systems, are quite simple. The apparent complexity of our behavior over time is largely a reflection of the complexity of the environment in which we find ourselves” (Simon, 1969, p. 110).

that theories such as *decision-making under uncertainty*, concepts such as *bounded rationality*, and approaches such as *heuristics* and *satisficing* were developed (Gigerenzer, 2008; Kochenderfer et al., 2015; Simon, 1956, 1969).¹⁵ In addition, it is not always true that more information yields better decisions: sometimes ignoring is not only cheaper, but also helps us to make better decisions (Gigerenzer, 2010).

In environmental modeling, statistical approaches are often used for the representation of uncertainty (Chatfield, 2006). But according to Haldane (2012), when the sample space is small, the performance of simpler, heuristic strategies is better. This is because parameters are more sensitive when the number of samples is small. Therefore, the risk of inaccurate overfitting of the historical data increases.¹⁶ Simple models, especially when the samples are infrequent, are less prone to such errors.

THE TYPICAL PURPOSE OF ESA is to provide usable input into decision-making processes, that is, to support decision-making. In the light of theoretical understanding of decision-making under uncertainty, it is important to adopt approaches that capture the most important aspects of uncertainty, while avoiding unnecessary complications—which can be as undesirable as oversimplification. Furthermore, the value of common sense, intuition, and subjective judgment (in addition to other sources of knowledge) in approaches to systems analysis and uncertainty management should not be underestimated (Wierzbicki, 1997). Similarly, qualitative or semi-quantitative approaches such as MCA can complement quantitative and more structured approaches such as LCA. In either of these approaches, the subjective sources of knowledge and expert opinions become particularly important when available information is infrequent (sparse), heterogeneous, or somewhat contradictory.

In ESA, there is no standardized way to define and manage uncertainty and validate its consequent impacts on the results. This is true even in LCA, which is among the most standardized and established environmental systems analysis methods (Björklund, 2002; Finnveden et al., 2009; Groen et al., 2014; Heijungs and Huijbregts, 2004). Typically, inventory data, choices, and relations are identified as the main sources of uncertainty, which are sometimes referred to as parameter, scenario and model uncertainty, respectively (Finnveden et al., 2009; Heijungs and Huijbregts, 2004; Huijbregts and v Zelm, 2012; Huijbregts, 1998a,b; Lloyd and Ries, 2007). Parameter uncertainty arises from errors, missing data, or imprecision in the

¹⁵ According to Gigerenzer (2010), a heuristic is “a mental process that ignores part of the available information and does not optimize, meaning that it does not involve the computation of a maximum or minimum.” Heuristic approaches toward the generation of satisfaction, as opposed to optimizing approaches are called satisficing.

¹⁶ The principle of parsimony, or Occam’s Razor, demands to use procedures and models which contain only what is necessary for the modeling, and nothing more. Overfitting occurs when excessively structured models or procedures are used in violation of the parsimony (Hawkins, 2004; cf. Jaynes, 1990).

Forms of uncertainty Why does it arise?	Sources and types of uncertainty Where does it arise in the input of the study? What can go wrong?	Approaches to uncertainty How to deal with it?
Aleatory (stochastic)	Inventory Data <ul style="list-style-type: none">• Variability (variability of a parameter is ignored, while it can vary depending on the conditions)• Miss-specified (incorrect description of data which implies different time, scale, or technology)• Erroneous (an error in unit conversion)• Incomplete (missing emissions for some processes)• Rounding-off (rounding down 0.149 to 0.1 which is more than 30% wrong)	Scientific approach Do more research, gather more information (better data and models) Aims to remove or reduce the uncertainty
	Choices (e.g. assumptions, scenarios) <ul style="list-style-type: none">• Inconsistency in relation to goals and scope (use average technology for some unit processes, while using best available technologies for others)• Inconsistency across alternatives (different allocation methods for different unit processes)	Social approach discuss with stakeholders (consensus, recommendations, policy) Aims to remove or reduce the uncertainty
Epistemic (Lack of knowledge)	Relations (e.g. models) <ul style="list-style-type: none">• Wrong (linear modelling of a non non-linear phenomenon)• Incomplete (effect of a factor is neglected)• Inaccurate implementations (bad choice of algorithm in software)	Statistical approach Aims to incorporate the uncertainty
<ul style="list-style-type: none">• Parameter variation and scenario analysis (best/worse case comparison)• Classical statistical theory based on probability distributions, tests of hypothesis, etc.• Monte Carlo simulations and other sampling approaches• Analytical methods, based on first-order error propagation• Less conventional methods, such as non-parametric statistics, Bayesian analysis, and fuzzy set theory• Qualitative uncertainty methods, for instance, based on data quality indicators.		

input data. Scenario uncertainty is the result of the choices—often normative—that we make while constructing the system, but can also arise from the variation in the characteristics of scenarios. Model uncertainty depends on the way that we mathematically define and structure the relationships between different parts of the system (Lloyd and Ries, 2007). To the extent that “scenario definitions and choices” or “modeling assumptions” can be represented by parameters, part of the scenario or model uncertainties can be viewed as parameter uncertainty. Variability is often due to inherent characteristics of parameters, but can also be related to spatial or temporal differences.

Finnveden et al. (2009) identify three different strategies to deal with uncertainty in LCA, but their categorization appears to be

Figure 3.2: Forms, sources, types, and the main approaches toward uncertainty. The categorization and the provided examples are mainly based on Finnveden et al. (2009), however, their original structure is visualized and slightly altered.

relevant to other systems analysis approaches as well, such as multi-criteria analysis. The first is the scientific approach, which emphasizes the importance of further research and information gathering with the aim of reducing the uncertainty. The second is the social approach, which seeks the same goal via participatory consensus building among a wider circle of stakeholders or through formal recommendations and standards. The third is the statistical approach, which, unlike the other two approaches, does not aim to reduce the uncertainty, but focuses on its incorporation in the process of the systems analysis. *Figure 3.2* summarizes different forms and sources of uncertainty in LCA—and other systems analysis approaches—as well as a few examples of their manifestations in practice.

Most of these approaches, albeit to a different degree, are adopted in the approach of this thesis toward managing the uncertainty. Regarding the sources and types of uncertainties, the focus has been on uncertainties in the inventory data and choices. Both life-cycle and multi-criteria studies rely on the scientific approach to uncertainty management, by referring to the existing literature and trying to gather information which reflect the state of the art of the knowledge. The social approach is used by adopting a participatory approach to the research and incorporating stakeholders' and experts' views in the setting up and execution of the research. Finally, the life-cycle study of biogas solutions rely on the statistical approach and on methods from probability and possibility theories for uncertainty management. The statistical approach is further explained in the following section.

3.3.4 *Sparse Data and Uncertainty Propagation*

Stochastic sampling methods such as Monte Carlo simulation (Burmaster and Anderson, 1994; Helton et al., 2006; Metropolis and Ulam, 1949) are powerful ways for propagating quantified uncertainty of the input to the output of the models. Monte Carlo simulation requires that a form of probabilistic interpretation is assigned to each input parameter, that a large number of sample input vectors are randomly generated, and that results are deterministically calculated and collected in an output vector which is the aggregated form of the propagated uncertainties of all the input parameters. If the variability of the input parameter is known and parameterized, it can be represented by a probability distribution which can be used as the basis for stochastic sampling. However, in LCA data collection we are often faced with parameters whose behavior cannot be readily described by common

probability distributions. In addition, data collection involves experts’ opinions and data from heterogeneous sources which are subjective, or have to be operationalized subjectively. Possible values of parameters are not always determined by their objective variability, but they can also vary due to our lack of knowledge, translated into epistemic uncertainties. During data collection, it is important to be able to deal with epistemic uncertainties as well. If there is high epistemic uncertainty—for example, due to the lack of enough relevant and meaningful information about geographical, temporal, technological, or contextual variabilities—representing the uncertainties by any particular probability distribution becomes arbitrary. In these situations, possibility distributions provide a more suitable basis for representing uncertainties, and for stochastic sampling (*Figure 3.3*).

Figure 3.3: Suitability of possibility distributions when epistemic uncertainty is high or variabilities are due to unknown patterns of randomness

In this thesis, the uncertainty of those input parameters whose behavior is prone to high epistemic uncertainty is defined by fuzzy or possibility theory (Dubois and Prade, 2012; Zadeh, 1978). Once the possibility domains of the input parameters are defined, they can be used for generating random samples for Monte Carlo simulation. Since uncertainty propagation in LCA using probability distributions and Monte Carlo simulation is rather well-known, here the focus is more on dealing with the uncertainty management during the data collection (inventory) phase of LCA using possibility distributions.

DATA COLLECTION AND LIFE-CYCLE INVENTORY is an important part of LCA. Data collection is always faced with the challenge of uncertainty, and compiled data can be heterogeneous or inconsistent. Data quality issues can arise because the LCA practitioner has to rely on different sources of information: experts' opinions, which can be inconclusive or contradictory, and literature, with varying degrees of reliability, relate to different contexts and places, are derived from different assumptions and methods, and are framed by different normative choices. Even when data is collected in relation to the core parts of the studied system, we are not immune to uncertainty. This can be due to several reasons, for example if the duration in which the plant has been operating under stable configuration is short, or if the type of data which has been historically monitored is not long or large enough to produce a realistic picture of the variabilities of the parameters. In addition, sometimes the purpose of the study demands consideration of more variabilities than are actually present in the production data, for example considering future developments. In these situations, the LCA researcher has to make assumptions about future developments, which at best can only be educated—but uncertain—estimates. If we have sufficient amounts of data in relation to a certain parameter, methods based on classical statistical theory can be used to produce a good estimate of its variabilities, for example by mapping the parameters into a random variable which follows a certain probability distribution. This is often referred to as physical or frequency-based approach to probability which can yield rather objective understanding about the variability of a given parameter. However, as far as LCA data collection is concerned, in many cases and for many parameters, the available and relevant data is not that extensive. Hence we are faced with limited or sparse data. Regardless of how objective probabilities of the parameters are, as long as we do not know them, their uncertainty will appear to us as epistemic. Quite commonly, the LCA practitioner is faced with a few values that do not provide a meaningful basis for frequency-based estimation of the underlying probability distribution. Thus, the practitioner who is willing to perform uncertainty propagation using sample-based approaches such as Monte Carlo simulation is forced to either: (i) skip the parameter from the sampling group by simply fixing it to an arbitrary single value which they find most reasonable—for example, pick the mean value of the available data; (ii) define an arbitrary minimum-maximum interval based on the available data; or (iii) arbitrarily choose a probability distribution

to characterize the uncertainty. Arguably none of these solutions is the most effective way of utilizing the heterogeneous, subjective, and sparse data at hand.

An alternative approach, which is based on the *Bayesian* (subjectivist) theory of probability, is to view the available data as evidence which represents subjective knowledge about different degrees of belief about the possible values of a parameter. This subjective knowledge can be of an *expert* from which the LCA practitioner gathers information about the likely values of a parameter, or it can be the interpretation of the LCA practitioner themselves after they have gathered several values from the literature, and have formed their opinion about the likely values of that parameter. In situations where subjective knowledge is an important and undeniable ingredient of the information, this approach is more suitable for interpreting the limited data (Apostolakis, 1990) (see *Figure 3.3*). The subjective knowledge can be presented by a triangular distribution, which is simply a minimum-maximum interval with the addition of a mode which represents the most likely value. After the parameter is described by a triangular distribution, it can be fed into the next stages of an uncertainty propagation method, such as Monte Carlo simulation. Without abandoning the stochastic uncertainty propagation methods—in this case Monte Carlo simulation—in this thesis, fuzzy theory (Zadeh, 1978) and possibility distribution functions are used as an effective and practical way of collecting and representing the subjective knowledge in a more effective and still practical way. Possibility distributions are less structured compared to probability distributions, while they specify more structure than simple intervals (Helton et al., 2010). Therefore, they are more suitable when epistemic uncertainty (subjective) is mixed with the variability (objective) uncertainties, and highly structured representation of uncertainty through utilization of a known probability distribution is not possible. Possibility distribution represents both the upper and lower bounds of all possible probability distributions which might represent the variability of the parameter. A whole family of probability distribution can be defined within the upper and lower bounds defined by the possibility distribution (Clavreul et al., 2013). The possibility distribution acts as a net that ensures most of the epistemic uncertainty in relation to the parameter value is captured.

A simple and versatile way to define possibility is a trapezoidal possibility distribution. This distribution is defined by a minimum, a lower mode (or left mode), an upper mode (or right mode), and a

Figure 3.4: A possibility distribution characterized by a trapezoidal shape, defined by four parameters: a minimum (min), a lower mode (lm), an upper mode (um), and a maximum (max)

maximum value, as illustrated in *Figure 3.4*. The values smaller than the minimum and larger than the maximum represent the unlikely values. Here, we are confident that they are unlikely to occur, and therefore their possibility is set to 0. Values between the lower and upper modes are most likely to occur. In this case, we are confident that they are likely to occur, and therefore their possibility is set to 1 and they form the core interval. Values larger than the minimum and lower the maximum are likely. In this instance, we are partially confident about their occurrence, so their possibility value is set to a number between 0 and 1, in proportion to their distance from the core interval. These values form the support interval. It is important to note that this designation of values between 0 to 1 is based on known information (Helton et al., 2010), which is a subjective matter and reflects the state of our knowledge, including whatever epistemic uncertainty we think we have. In a way, this possibility function can be seen as the representative of both the aleatory and epistemic uncertainties associated with a parameter.

Chapter 4

Methodology

In this chapter the main methods which are used (and developed) in this thesis are presented. This includes an overview of the research design of the thesis and how it relates to the methods used in each article. In addition, the methods of each study are presented in three sections, each related to a group of closely related articles: reducing CO₂ emissions from cement production (Papers I–III), assessing feedstock for biogas production (Papers IV & V), and producing biogas from food waste (Paper VI).

THE METHODS USED in this research are based on two approaches to ESA (Section 3.3). In order to investigate the environmental performance of the studied systems—cases from cement production and biogas solutions—and identify critical factors that can influence their performance, life-cycle assessment (ISO, 2006a,b) was used. To explore and assess the potential and feasibility of different options for developing the studied industrial systems, the multi-criteria approach was employed.

4.1 *Research Design*

IN THE STUDY OF THE CEMENT production system (Papers I–III), both LCA and MCA were used in a complementary and integrated manner. This level of methodological integration was made possible by several circumstances.¹ First is the fact that the study object represented a mature and well-defined industrial production system. The environmental impact of cement production is dominated by its huge CO₂ footprint, which was one of the reasons that the study, since its inception, was focused on finding effective and feasible ways

¹ The issue of integrated systems analysis is further discussed in Chapter 7.

for reducing it from a theoretical perspective of industrial ecology. Furthermore, the focus was on a particular production system, where a good level of detailed knowledge about the material flows existed and was made available to us.² The direct material flows were mainly either minerals or combustible waste-derived fuels, and their amounts and characteristics were provided by the cement plants in detail. Moreover, the production system in 2009 was compared with the one (that existed) in 1997 in order to provide a basis for further improvements in the future. In-depth assessment of uncertainties was not part of the project setup, as the uncertainties were considered to be reasonably low or unproblematic in connection with the systems analysis of the CO₂ emissions of cement production. Therefore, quantitative uncertainty analysis was not included in the assessments in a systematic manner. Nonetheless, a simple uncertainty assessment was conducted, as uncertainty intervals in the final results—based on commercial LCA databases.

SEVERAL FACTORS, such as focusing on a single environmental impact category, studying a specific and mature cement production system, and avoiding systematic uncertainty analysis, allowed us to develop and test an *integrated systems analysis approach* in this research. In Paper I, LCA was used to model the production system, quantify the impacts of the activities that contributed to its CO₂ footprint, and define a simplified LCA model based on a few key performance indicators (KPI) which could approximate the overall CO₂ footprint of the production system under varying development scenarios—including innovations and IS initiatives. In Paper II, MCA was used to systematically identify, classify, and assess different measures that could be implemented in the studied cement production system. Each measure was assessed from several perspectives covering its *potential impact on the CO₂ performance* and *feasibility* for implementation. Feasibility was considered from two perspectives: generic feasibility—for the cement industry in general, which was simply referred to as *feasibility*, and site-specific feasibility, which was referred to as *applicability*. As a result, a strategic map of the identified improvement measures was created which could highlight the “best candidates”, that is, those that could be directly implemented, as well as “future candidates”, or those that could be implemented in the future, if some of the obstacles were removed. Finally, both of the systems analysis approaches were integrated in Paper III. LCA standards place insufficient emphasis on scenario development. Therefore, instead of relying on the LCA

² The project setup was the main influencing factor in focusing on reducing the CO₂ emissions, as well as selection of the studied cement production plants.

framework, the result of MCA was used to define implementable future scenarios. The CO₂ performance of the production system, under the assumptions of these scenarios, was quantified by using the simplified LCA based on the key performance indicators.

BIOGAS SOLUTIONS, and biogas-related systems have several characteristics which pose difficulties for an the integrated systems analysis. What makes biogas solutions special is the diversity of industrial and societal contexts which can shape their organization and purpose. For example, the type of feedstock that is used for biogas production can fundamentally alter the characteristics and performance of a biogas solution—a farm-based biogas plant using manure and straw is different from a large-scale plant using agricultural crops, and both are different from a co-digestion plant which is set up around digesting organic wastes. Furthermore, commercial biogas solutions are relatively new and rapidly evolving in relation to the feedstocks that are used, the institutional conditions in which they operate, and the way that their byproducts, such as bio-fertilizers, are valued and utilized. Biogas Research Center (BRC) has been set up to cover these different aspects of biogas solutions. Within the BRC, system studies of biogas solutions are split into several subtopics, covering issues such as assessing the suitability of using different biomass as feedstock for biogas production as well as quantifying the effect of utilizing biogas solutions in various industrial or urban systems. The biogas studies in this thesis (Papers IV–VI) focus on two types of questions regarding biogas solutions, and use the multi-criteria and life-cycle approaches to investigate them. A multi-criteria framework is developed and used for assessing the *potential*, *feasibility*, and *resource efficiency* of using existing or new feedstocks for biogas production. Compared to the multi-criteria approach of the cement study, a much broader and more detailed MCA framework was developed for assessing feedstocks for biogas production (Paper IV). This framework can be used to assess the feedstocks from ten different key areas, including *biomass and biomethane potential*, *nutrient recycling potential*, *institutional conditions*, *technical feasibility*, *physical and geographical accessibility*, *profitability*, *energy and environmental performance*. This framework was used to assess several feedstocks, which were chosen to represent different industrial contexts and sectors. In Paper V the results of assessing feedstocks such as ley crops, straw, blue mussels, and household food waste are presented. Both the development of the framework and the selection of feedstocks to be assessed were the

result of a participatory process, including researchers, experts and representatives of different collaborating organizations.

In a parallel research project, the environmental performance of treating source-sorted municipal organic waste (food waste) through biogas production was studied, using the LCA methodology. The focus was on dry anaerobic digestion system (which is new in Sweden), but it was compared with the wet anaerobic digestion of food waste. The studied dry-process system was based on a real biogas plant, while the wet system was based on existing literature of Swedish biogas production. Several environmental impact categories—global warming potential, eutrophication potential, and cumulative energy demand—were included in the study. The biogas plant which used the dry digestion process is relatively new and represents the first of its kind in Sweden. For comparability, the wet process alternative was based as much as possible on similar assumptions, and only the parts of the two systems which were different were altered. For example, the food waste collection system and transportation distances were assumed to be the same for both scenarios, but the electricity demand for pretreatment was altered accordingly. In order to gain better insight into critical factors and uncertainties that influence the environmental performance of these systems, a systematic approach to uncertainty propagation and assessment was used. The uncertainty management in this LCA study was a combination of using fuzzy intervals during data collection, as well as performing a Monte Carlo simulation for uncertainty propagation.

In comparison with the cement study, both of the systems analysis approaches used in the biogas-related research were more extensive and developed. They covered more areas of investigation, considered several environmental impact categories, and had further methodological elaboration, including in-depth uncertainty analysis. In contrast to the cement studies, these two studies were not characterized by an *integrated* approach to systems analysis—that is, combining MCA and LCA. This was because the aims of these projects were different, and thus did not demand the integration of MCA and LCA. Nevertheless, from a methodological perspective, these two discrete approaches demonstrate the contours of possible integrated systems analysis approaches in studying emerging and complicated biobased industrial systems such as the studied biogas solutions. In Chapter 7, this methodological possibility is further discussed. An overview of the methods used in the appended papers is listed in *Table 4.1*.

Article	Topic	Systems Analysis	Method
Paper I	Cement	CO ₂ footprint of the selected products; simplified LCA model based on a few KPIs	LCA, six KPIs (quantitative)
Paper II	Cement	Identifying and assessing feasible and applicable measures for improving CO ₂ footprint of cement	MCA (qualitative/ semi-quantitative)
Paper III	Cement	CO ₂ footprint of innovations, including industrial symbiosis	Integrated assessment using MCA and LCA: future scenarios defined by MCA; performance estimated by the simplified LCA based on six KPIs (quantitative & qualitative)
Paper IV	Biogas	Developing a framework for assessing the potential, feasibility, and resource efficiency of feedstocks for biogas production	MCA (extended and broad) (qualitative)
Paper V	Biogas	Assessing the potential, feasibility, and resource efficiency of using ley crops, straw, blue mussels, and household food waste for biogas production	MCA: generic and case-specific assessments (qualitative/semi-quantitative)
Paper VI	Biogas	Environmental performance, critical factors, and uncertainties of producing biogas from food waste	LCA: uncertainty propagation (quantitative)

In the following sections more specific presentations of the methodological aspects of different parts of this research are presented.

Table 4.1: Overview of the methods used in the different articles

4.2 Improving the CO₂ Footprint of Cement (Papers I–III)

A COMBINATION OF METHODS, including attributional LCA and MCA, was used in order to identify the feasible CO₂ improvement measures in a cement production system, known as CEMEX Cluster West, and to quantify the potential improvements. Cluster West represented several innovations, including synergistic material and energy exchanges with a nearby iron and steel plant as well as intra-organizational synergies with other cement plants within the cluster. In order to quantify the feasible improvement potentials, MCA was used to identify and develop scenarios. The CO₂ performance of cement production in this cluster in 2009 was quantified through a LCA. Then, the CO₂ improvement potentials under these development scenarios were quantified using the result of the LCA in 2009 and several KPIs. In the following subsections, CEMEX Cluster West is introduced, and the methodological choices related to the assessments are explained.

4.2.1 *The Studied Case*

CEMEX CLUSTER WEST consisted of three cement plants located in the German state of North Rhine-Westphalia and in the cities of Beckum-Kollenbach, Dortmund, and Duisburg (Schwelgern plant).³ Together, they formed a work alliance to produce different intermediate and final cement products. The distance between Kollenbach and Schwelgern is about 100 km, while Dortmund is located in the middle of the two. An overview of Cluster West and its major flows of energy and materials is shown in *Figure 4.1*. This includes the inbound flows, mainly of raw materials, fuel, and electricity; the internal flows of clinker, granulated blast-furnace slag (GBFS) and ground granulated blast-furnace slag (GGBFS), and several intermediate products; and the outbound flows of finished cement products.

³ These plants belonged to CEMEX-Germany, and the provided information refers to the status of Cluster West at the time of the study (data from 1997 and 2009).

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

CEMEX owned a local lime marl quarry at Kollenbach, with estimated reserves of 30 years at the 2009 production level. The Kollenbach plant, which was an integrated cement plant, produced clinker, intermediate products and finished cements with high clinker content (such as CEM I or CEM II). Its kiln system had a rotary kiln with a four-stage cyclone pre-heater, but no pre-calciner and its feeding system could receive secondary fuels.

The Schwelgern plant was a grinding and blending station and did not have a kiln system, but was equipped with two cement mills. This plant was co-located with an iron and steel plant owned by Thyssen Krupp, which in addition to steel, produced blast-furnace slag (BFS) and upgraded it into GBFS for consumption in the CEMEX/Schwelgern plant where it was milled into GGBFS. Like the Schwelgern plant, the cement plant in Dortmund did not have a kiln system and was a grinding and blending station. In this plant, clinker and intermediate products from Kollenbach were milled and mixed with the GBFS from the Schwelgern plant.

In 2009, these plants produced 1.8 million tonnes of finished cement products. 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 were considered. However, three cement products were selected in order to compare their CO₂ footprints. 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 was included in the comparative LCA and was treated as a finished product. Cluster West used 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 the increasing utilization of supplementary cementitious materials (SCMs) such as GBFS in cement products, demonstrates 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 (more linear system) and blended cement products (more synergistic system).

4.2.2 *Identifying Suitable Improvement Measures*

IN ORDER TO IDENTIFY and assess suitable improvement measures in Cluster West, an MCA framework was developed. The framework was developed mainly based on common sense, the literature, and dialog with CEMEX representatives. The purpose was to keep it short and simple, but make it a guide for structuring existing knowledge and creating a strategic overview of the most important aspects for decision-making—both from the theoretical perspective of industrial ecology, and the practical perspective of CEMEX. It was decided that this framework should be able to:

- identify different CO₂ improvement measures—a gross list of ideas;
- classify the identified measures into a few categories—a categorization scheme;
- qualitatively assess the potential of the measures for improving the CO₂ footprint of cement production—a generic assessment of the CO₂ emission reduction potentials;
- assess the feasibility of the identified measures in general;
- assess the applicability of the identified measures considering the specific conditions of Cluster West;
- provide overviews which could be used for strategic decision-making.

The framework consisted of two parts: a generic part that referred to those aspects relevant for cement production in general, and a site-specific part that referred to those aspects which were relevant to Cluster West—or any other cases. For each important criteria regarding feasibility of the improvement measures (or key questions regarding potential, generic feasibility, and site-specific feasibility or applicability), a few qualitative indicators were defined with three-step scales of *low*, *medium*, or *high*. In order to make the assessment more consistent, each of these indicators was better supported by clear, descriptive text for each of the scales to simplify the judgment concerning when it should be assessed as low, medium, or high. A conceptual cement plant was used to systematically search for and classify the measures (*Figure 4.2*). Inspired by cleaner production, industrial ecology, and industrial symbiosis, documents addressing

Figure 4.2: Conceptual model of cement production and the main categories of improving measures (figure adapted from Paper II)

preventive and improvement measures in cement production were 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 on the cement industry, the scientific literature on industrial ecology and industrial symbiosis was included. On the input side, this involved the search for possible ways of using renewable and alternative raw materials and energy sources. On the output side, IE and IS promoted the idea that there should ideally be no waste, leftover material or useful energy streams; therefore, in addition to the main products, literature dealing with the utilization, recycling, and valorization of CO₂ emissions and residue heat from cement production was considered. The literature search was exploratory and did not aim to cover the full extent of the literature related to cement. It explored existing and emerging ways that cement was produced and resulted in the classification of potential improvement measures.

We visited all three production facilities and during these visits, production managers at the plants were interviewed. 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 study and its methodology, receive feedback on the development of the assessment framework, and collect the perspectives of the participants on the future possibilities of cement production. The feedback and ideas from this meeting were incorporated into the MCA framework (its development and application).

A self-completion questionnaire, along with a guideline for the qualitative assessment, was sent to CEMEX representatives. This qualitative assessment of suitable improvement options for Cluster West was completed by managers and senior technical staff. The data in the completed questionnaire was clarified by follow-up telephone conversations.

4.2.3 *Comparing Cement Products*

ONE OF THE AIMS of the study was to compare selected cement products of Cluster West, namely clinker, CEM I—ordinary Portland cement (OPC), and two types of blended cements known as CEM III/A and CEM III/B. For this purpose an attributional LCA study

was performed. The scope of this LCA model was *cradle-to-gate*, and the functional unit was producing one tonne of cement. It was assumed that these products have comparable functions. This is a fair assumption, because these cement types are rigorously standardized and are used for a diverse range of applications, despite some technical and economic differences (CEMBUREAU, 2012). Production data regarding the material and energy consumption as well as production figures for Cluster West in 2009 were collected. This data was organized into input/output matrices of Cluster West and was used to create the inventory in the LCA models.

Based on the results of this LCA, several KPIs were defined and a sensitivity analysis of them was performed. The test results showed that these KPIs, to a very large extent, represented the CO₂ footprint of the cement products produced in Cluster West. Therefore, they could be used for approximation of the LCA; that is, a simplified LCA model.

4.2.4 Comparing Cement Production Systems

ANOTHER AIM of the study was to assess the performance of the production system in its present condition (2009) in comparison to its state in the recent past (1997) and several feasible alternatives in the near future.

In order to model the production system (and not a cement product), it was assumed that the production system produced a virtual cement product referred to as *portfolio cement*. This virtual product represented the average production of all three cement plants within Cluster West. In addition, the same LCA which was used for studying the CO₂ footprint of the products was used, but in a simplified form constructed from the few KPIs which were previously identified (see 4.2.3). This simplified model was used for estimating the CO₂ footprint of the cluster under different configurations—to the extent that those configurations could be quantitatively represented by altering the values of the KPIs. It was assumed that some of the underlying conditions which governed the cluster in 2009, were reasonably similar in its recent past (1997), or would remain rather similar in its near future.

Data regarding the conditions of the cluster in 1997 was collected and translated into a new set values for the KPIs. The simplified LCA model was used for approximating the CO₂ footprint of the cluster at that point in time. The same approach could be used to model

the CO₂ performance of future scenarios, however it was not known which development trajectory was the most suitable for implementation in the cluster. Before quantifying the future CO₂ footprint of cement production in Cluster West, it was decided to first systematically identify and assess the most suitable improvement measures.

4.2.5 *Assessing Future Production Systems*

BASED ON THE RESULT of the MCA, several suitable scenarios for the future development of the cluster were defined. The value of KPIs for each of these scenarios was estimated. The values of these KPIs were discussed with CEMEX representatives in order to ensure that they were reasonable representations of each envisioned scenario. The simplified LCA model, based on the KPIs, was used to estimate the CO₂ footprint of the cluster for each future scenario.

The combination of approaches based on LCA and MCA allowed identification of effective and feasible measures for improving the CO₂ footprint of cement production in the cluster. Furthermore, it allowed quantification of the impact of changes, including IS, on the CO₂ footprint of the overall production system.

4.3 *Assessing Feedstock for Biogas Production (Papers IV & V)*

4.3.1 *Framework for Multi-Criteria Assessment of Feedstocks*

A MULTI-CRITERIA ASSESSMENT FRAMEWORK was developed in order to assess the potential, feasibility and resource efficiency of using different feedstocks for biogas production (Paper IV). In comparison to the cement study (section 4.2), a similar albeit more extensive, approach to MCA was adopted. The underlying logic and flow of this multi-criteria approach was simple and based on pragmatism, common sense, intuition, and participation, with a normative approach due to the vision of BRC, which seeks the “implementation of resource-efficient biogas solutions”. The development and application of the multi-criteria framework consisted of the following steps, which were performed iteratively (see *Figure 4.3*):

- (i) Framing of the assessment, which included identification of the main aims and perspectives, as well as selecting the feedstocks that should be assessed. In this step the participating experts and practitioners were also determined.

- (ii) Defining the key areas (key questions) relevant to the aim and main perspectives, and developing qualitative and semi-quantitative indicators (and sub-indicators) for each key area in such a way that the most important information about each key area and the uncertainty of the assessment could be represented. For each indicator, qualitative scales with clear definitions were defined.
- (iii) Compiling relevant information which was needed for answering each key question and assessing its indicators.
- (iv) Performing the assessment, which means using the framework for multi-criteria assessment of a few selected feedstock categories.
- (v) Creating overview tables and graphs and drawing conclusions from the results.

This approach resembles a *double funnel* with two narrow ends, but which is wide in the middle. It begins with a strategic question, which is approached by a handful of key questions related to different key areas. These key areas are in turn presented by several indicators (and sub-indicators if required). Extensive information is gathered—either through a search of the literature and document study, or by directly referring to domain-experts—in order to assess the identified indicators, which in turn can be used to answer the key questions and ultimately provide insight into the original strategic question.

The developed framework can be used for generic as well as site- or case-specific assessments. In addition, it can be used as a guide for systematic and in-depth review of the existing body of knowledge about the feedstock (in-depth study), or as a framework for a quick (screening) study, relying mainly on the already present knowledge and opinions of participating experts.

INTERACTION WITH STAKEHOLDERS played an important role in the development of the framework. The involved stakeholders included professionals representing biogas-producing companies, companies which distribute and valorize digestate as biofertilizers, farmers who are actual or potential producers of feedstock as well as users of biofertilizers, and researchers with specialties in microbiology, agriculture, and biogas process optimization. Through these continuous interactions, the “key areas” which were considered relevant and important for assessing the potential, feasibility, and resource efficiency of different feedstocks for biogas production were identified and defined. The interactions with stakeholders were complemented by literature

Figure 4.3: Main steps of developing and applying the multi-criteria framework for assessing feedstocks for biogas production. The circular view is used to highlight the iterative process.

studies and conceptual thinking about resource efficiency, covering aspects such as minimizing the life-cycle energy and material consumption, preserving the nutrients, identifying competing and alternative applications, and minimizing the costs. This approach allowed us to increase our domain knowledge and improve the effectiveness of the discussions with other participants of the research.

Each key area was extensively studied and analyzed in order to identify the set of indicators that could sufficiently cover that key area.⁴ An attempt was made to minimize the number of indicators for each key area in order to keep the framework relatively simple and to facilitate decision-making. As a result, most of the key areas were characterized by one or two indicators.

In order to bring more clarity and consistency to the assessment, structured or semi-structured scales for each indicator were defined using easy and understandable quantitative ranges, or verbal descriptions of different qualitative values of each indicator. During the assessment, one could pick values for each indicator out of the well-defined five-step scales. These values were consistently defined for each indicator between *very poor*, *poor*, *satisfactory*, *good*, and *very good*.⁵ In addition, three-step scales were used in order to show the uncertainty regarding the assigned value(s) to each indicator, where “*” refers to high uncertainty (not certain), “**” refers to some uncertainties, and “***” refers to low uncertainty (rather certain).

⁴ Sufficient is a subjective term, and here means “good enough” according to the judgment of the project participants, researchers, and other reviewers.

⁵ Defining these scales in an understandable, well-defined, and consistent manner was a major challenge.

One or more indicators were defined in relation to each key question (or key area). For some key areas and questions—such as biomethane yield—the choice of indicators was rather straight forward, because similar quantitative parameters were already used and there were existing values for them. In a way, these areas were more bounded and easier to define. Other key areas and questions—such as environmental and energy performance—are more complex, which made them more difficult to be characterized through simple indicators and scales. Our main strategies for dealing with these more complex areas were to (i) treat them as distinct but interpenetrating, semi-permeable, and porous concepts which naturally overlap and blend with other areas; (ii) utilize a combination of qualitative and quantitative scales which allowed the incorporation of subjective knowledge of the experts and higher levels of aggregation and abstraction; and finally, if required, (iii) use more than one indicator for their assessment.

An important challenge was to formulate indicators and scales that could cover the most essential aspects of each key question, without including too many aspects which could lead to overcomplicated scales and difficulties to carry out the assessment. Nevertheless, since the indicators did not always cover all relevant aspects for a key area, it was important to not only assess the feedstocks against the scales, but also to look at the compiled inventory of information and write down important conclusions that were not well covered by the indicators. Since the assessment welcomed the intuitive and subjective judgments of the experts—both as participants and assessors—differing or conflicting results might be achieved. Therefore, providing sufficient supporting evidence for the assessments of each key question, and each indicator could increase the transparency and decrease the variabilities due to subjective judgments of different assessors. In addition, once many feedstocks were assessed individually, all assessments could be reviewed by a group of experts to identify inconsistencies and improve the coherence of the assessments. Finally, since the main purpose of this multi-criteria assessment was to facilitate overview and decision-making, certain levels of synthesis and simplification were acceptable and indeed inevitable.

4.3.2 *The Studied Feedstocks*

THE FEEDSTOCKS WERE SELECTED considering the interests of the participants and their respective organizations, and with the aim

of including both a *well-known* feedstock—to test the method and create a familiar reference—as well as several “new” ones. Another aim was to include feedstocks which could be studied from a *generic* perspective across Sweden, but also include *case-specific* assessments, for example considering a particular biogas plant. Therefore, the feedstocks were selected to both *test* the developed assessment method and respect the *business interests* of the participating organizations.

The assessed feedstocks were ley crops, straw, blue mussels, household food waste, and stickleback fish. Ley crops are agricultural products and were suggested by the federation of Swedish farmers, or LRF, to be studied from a generic Swedish perspective.⁶ Ley crops refer to a group of plant species, typically consisting of legumes—for example, red and white clover, and lucerne/alfalfa—and grasses—for example, timothy, tall fescue and English rye grass (Engström, 2004)—and is commonly used as fodder.

Straw is the byproduct (residue) of grain and oilseed cultivation and was suggested by the agricultural cooperative Lantmännen, a major producer of food, bio-energy, and agricultural products in the Scandinavian countries. Straw was also studied from a generic perspective.

Farmed blue mussels—*Mytilus edulis*—was considered as a new feedstock with relatively limited research regarding their use for biogas production. Mussels—along with stickleback fish—were also selected in order to test the assessment framework on the aquatic feedstocks. Blue mussels naturally and abundantly grow in the Baltic Sea region, but our focus was placed on the potential and feasibility of using cultured mussels for biogas production.

The source-sorted organic fraction of municipal solid waste—food waste from households—was suggested by a municipal energy and waste management company, NSR, which is also a biogas producer from food waste. Food waste was assessed from a case-specific perspective, considering the conditions of this particular company located in the southwest of Sweden.

Stickleback fish were suggested by a coastal municipality—Västervik—which has been engaged in several projects related to resource-efficient use of aquatic resources in order to reduce eutrophication, produce biogas, improve the local economy, and promote organic agriculture. The assessment of stickleback fish was performed in a screening manner, via several extended interviews with experts from the studied municipality. The purpose was to use the MCA framework as a way to guide interviews and facilitate gathering and organizing the

⁶ In this thesis “ley crops” are assessed as a single feedstock, referred to as “ley”.

knowledge and expertise of the corresponding experts. The results of the stickleback fish assessment are included in Paper IV, while the results of the assessment of other feedstocks are presented in Paper V.

4.4 *Biogas Production from Source-Sorted Food Waste*
 (Paper VI)

THE GOAL of this study was to investigate the environmental performance of treating source-sorted food waste using dry anaerobic digestion processes, under typical Swedish conditions and in comparison with existing systems which use wet processes, and to quantify the main uncertainties that exist within these systems.

This study was based on a biogas production plant located in Mörrum, Sweden (“VMAB plant”) referred to as the “reference case”. This plant uses a dry process to digest source-sorted food waste. It produces biogas from source-sorted food waste collected from several municipalities including Karlshamn, Olofström and Sölvesborg. These municipalities jointly own the biogas plant and its related waste management facilities. This plant has been operational since 2013, and is currently the largest Scandinavian co-digestion plant which uses a dry digestion process for digesting food waste.

Parameter	Remarks
Starting year	2013
Location	Mörrum, Sweden
Owners	Municipalities of Karlshamn, Olofström and Sölvesborg
Feedstocks used	Source-sorted (separated) food waste
Process type	Dry process, continuous, thermophilic (two digesters)
Capacity (tonnes/year)	20000
Food waste treated in this study (tonnes/year)	10000

Table 4.2: The VMAB biogas plant in Sweden

The food waste—and other organic wastes—are collected using compacting trucks and transported to the VMAB plant. There, it undergoes pretreatment, which involves shredding the waste and the removal of plastics and lighter parts by passing the shredded parts through an air-blown tunnel. The digesters currently operate under thermophilic conditions. A separator is used to partially dewater the produced digestate, where the pasty fraction is used for producing compost (used internally as landfill cover) and the liquid fraction is stored until it is transported to farms where it is spread as biofertilizer.

The biogas is upgraded to vehicle fuel grade (about 98 % methane) and is sold to an energy company (E.ON) at the gate of the plant. The distribution of the upgraded biogas is taken care of by the energy company.

Based on this reference case, two scenarios were defined—representing the dry process and the wet process—and the results were compared and analyzed. The first scenario, scenario A, was based on the existing production data from VMAB, but to enhance the robustness of the results and to avoid “single values”, some intervals were added to the production data. The second scenario, scenario B, was based on a similar (but hypothesized) case, assuming that the production system was modified into a wet digestion process. Many of the underlying assumptions between the two scenarios were considered similar, but in scenario B the processes which are different from the dry process were modified to corresponding values from the Swedish literature regarding wet processes. There are a few important differences between the studied dry-process system (scenario A) and other typical large-scale biogas production systems from food waste in Sweden which are based on wet processes (Scenario B). These differences are mainly regarding pretreatment, digestion, and digestate management. For example, in the dry system, the substrate does not need to be diluted by water, but in some cases a minimal amount of water is added.

Since the data regarding the wet process does not belong to a single plant, the comparison between the two systems can show the performance of this dry digestion system relative to a range of other wet digestion processes.

Since the study focused on a specific pathway of treating source-sorted food waste—its anaerobic treatment—activities which occur *prior* to collection of food waste were excluded from the studied system. This means that the boundary of the system started from the point where waste was made available, that is, after the food waste was sorted within households.

On the *end-of-life* side, distribution and use of the upgraded biogas were not considered. Regarding digestate management, the life-cycle including treatment, application, and impact on the soil, was considered. All major intermediate activities and processes were included in the scope, including separate collection of source-sorted food waste, transportation to the plant, pretreatment, treatment of rejects, anaerobic digestion, upgrading of raw biogas to vehicle grade fuel, digestate management including storage and application as biofertilizers or other products, and emissions from the soil. It was assumed that

Figure 4.4: System of producing biogas from source-sorted municipal food waste. The processes with dotted border are not included in the wet-process.

emissions from the composting process of the solid-fraction of digestate at the VMAB plant were biogenic, although potential carbon sequestration, methane, and nitrogen-related emissions after it is applied on the soil were taken into account. The functional unit of the assessment was the production of 1 MJ of upgraded biogas from the anaerobic treatment of source-sorted food waste. In addition, the treatment system should ensure that the nutrient content of the food waste are returned to the soil (Figure 4.4).

The included environmental impact categories were *global warming potential* (GWP), *eutrophication potential* (EP), *acidification potential* (AP), and *non-renewable cumulative energy demand* (nr-CED). GWP was important because of the typical dependence of different processes on fossil energy, leakage of methane and nitrous oxide, and potential carbon sequestration in the soil. Usage of biofertilizers—or avoiding the use of mineral fertilizers—and a few other processes contribute to eutrophication and acidification. The net use of non-renewable primary energy (nr-CED) was also important because of its relevance in relation to the long-term effectiveness of biogas as a renewable energy carrier produced from food waste. For impact assessment, the EPD 2013 model was used, which is based on IPCC and CML 2001 characterization models (EPD, 2013).

Inventory data was presented in the form of fuzzy intervals (3.3.4), which were used as the basis for the stochastic propagation of parametric uncertainties using Monte Carlo simulation. In addition to the production data from the reference case, for each process, information was gathered from the literature and fuzzy uncertainty

intervals were constructed based on the collected sparse values. The results of the Monte Carlo simulation were collected in different output parameters, each with a cumulative probability distribution. Based on these distributions, each parameter could be defined with a fuzzy interval, a mean, a core interval, and a support interval. The core interval was constructed based on the 70 % confidence interval, which means the area between 15 % and 85 % of the cumulative probability distributions of the output parameter. The support interval was constructed based on the 99 % confidence interval, which means the area between 0.5 % and 99.5 % of the cumulative probability distributions of the output parameter. The core and support intervals can be used to describe the output parameters—from Monte Carlo simulation—with trapezoidal distributions (see Section 3.3.4).

For gaining more insight about the performance of the system, in addition to common LCA indicators such as GWP or EP per functional unit, seven key performance indicators (KPIs) were defined. These KPIs were defined in relation to methane production, energy use, total transportation requirement, and nutrient recycling potential.

For identifying the critical factors, an uncertainty importance analysis was performed. The criticality of parameters was defined based on their significance (for the results) and uncertainty. The significance was defined as the normalized contribution of the parameter to the total impact, while the uncertainty was defined as its support interval—from its cumulative probability distribution function from the Monte Carlo results—normalized to its mean value. For example, in relation to global warming potential (GWP), the relative contribution of different processes was calculated by dividing the individual CO₂-eq emissions by the total CO₂-eq emissions. This value represented the significance of that process, in relation to the GWP of the produced biogas. The criticality of the processes was quantified by the geometrical mean of their significance and uncertainty. Processes with a higher score were considered more critical, as they are both significant and uncertain. Consequently, the main parameters used for modeling the impacts of these processes were considered for scenario alteration.

As mentioned before, the compiled data for Scenario B (wet process) does not come from an actual biogas production plant. Hence, part of the uncertainties in Scenario B are due to this and may not be inherent in any particular wet digestion plant. If this point is considered in the interpretation of the results, the comparison of

Figure 4.5: Assessment of the critical uncertainties, defined as the geometric mean of their significance (contribution) and uncertainty.

these two scenarios can shed light on the performance of the dry process (as in the VMAB plant) compared to biogas systems which use wet processes.

Chapter 5

Integrated Assessment of the CO₂ Footprint of Cement

In this chapter, the results of the study on improving the CO₂ footprint of cement production are presented. These results are based on Papers I–III. First, the results of the multi-criteria assessment of different improvement measures in the studied cement production systems are presented. This is followed by a presentation of the results of the life-cycle assessment of the selected cement products, as well as several scenarios for future development.

5.1 *Multi-Criteria Assessment of Improvement Measures*

IN ORDER TO STRUCTURE the state-of-the-art knowledge about ways to improve the CO₂ footprint of cement, as well as define feasible future scenarios for Cluster West, a multi-criteria assessment framework was developed (Paper II). This framework allowed a systematic identification and assessment of the measures that could potentially improve the CO₂ footprint of cement production in general, and of Cluster West in particular. The identified measures fell into four broad categories: *production efficiency*, *input substitution*, *product development*, and *external synergies* (Figure 4.2). Each of these categories was further divided; for example, the *input substitution* strategy encompassed using alternative materials, fuels, or electricity.

A generic assessment of these measures was performed by looking at each measure from two perspectives, its *improvement potential* and generic *feasibility*. The *improvement potential* of a measure was assessed by a qualitative indicator called *CO₂ footprint reduction potential*, while the generic *feasibility* of a measure was characterized

Key area and key question	Item/Indicator
<i>Improvement options (generic)</i> - What are the measures that can potentially improve the CO ₂ footprint of cement production?	- Gross list of possible measures - Categorization scheme
<i>Improvement potential (generic)</i> - How effective are these measures in improving the CO ₂ footprint of cement production?	- CO ₂ emission reduction potential
<i>Feasibility (generic)</i> - Are these measures feasible for implementation?	- Degree of interconnectedness - Technological maturity
<i>Applicability (site-specific)</i> - Are these measures applicable for implementation?	- Technical applicability - Organizational applicability - Implementation maturity

Table 5.1: Multi-criteria assessment framework for identifying effective, feasible, and applicable measures for improving CO₂ footprint of cement (adapted from Paper II).

by two qualitative indicators. The first indicator was the *degree of interconnectedness*, reflected on the number of independent organizations which needed to collaborate with each other in order to implement that measure. This is a way to capture the organizational complexity and challenges of establishing new symbiotic relations with other industrial actors. The second indicator, *technological maturity*, assessed the commercial availability of the improvement measure.¹ The generic assessment can be used to map the *state of the art* of CO₂ improvement options in the cement industry.

The site-specific assessment was performed by looking at the applicability of the identified measures for Cluster West. Site-specific feasibility, which was referred to as *applicability*, was assessed through three qualitative indicators: *technical applicability*, *organizational applicability*, and *implementation maturity*. Technical applicability was related to the local conditions, including the availability of the required infrastructure and suitable geographic conditions. Organizational applicability was related to the alignment and compatibility of the measure within the business and organizational framing—for example, the strategy of the organization and capturing the degree that the main decision-makers were willing to allocate the necessary resources for the adoption and implementation of the measure. Implementation maturity was related to the extent that the new measure fits within the relevant processes or knowledge in the organization. For example, if a certain measure is already implemented, then further similar improvements might be easier, but this can also mean that less room for further development has remained; that is, the measure has high *implementation maturity* but low *technical applicability*.

¹ Technology Readiness Level (TRL) (EARTO, 2014; U.S. Department of Defense, 2011) is a closely related concept to technological maturity. The aim of TRL is to provide a common understanding of the status of the technology. However, as noted by Norris et al. (2013), technological readiness is not necessarily the same as technological maturity. Depending on the context, a more mature technology may have a higher or lower degree of readiness compared to a less mature one. In this thesis (in Papers I–III), a tailored and simple definition of technological maturity is used.

Rather than focusing on developing new technologies, the developed MCA framework aims to organize and prioritize the existing body of technological and managerial knowledge in relation to improving cement production (Table 5.1). The framework does not provide quantitative weighting and scoring, but does provide qualitative assessments, and can be used to produce summary tables and various diagrams (similar to Figure 5.1) 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.

Figure 5.1: An example of an overview diagram that can be produced based on the results of the multi-criteria assessment of potential improvement measures for cement production. In this diagram, the identified measures are compared from the perspectives of their potential for CO₂ improvement, degree of interconnectedness and technological maturity (from Paper II). For more information about the designation of the codes, see Figure 5.4.

THE APPLICATION OF THIS FRAMEWORK highlighted the *best candidates* for improvement in Cluster West, as well as an overview of the *industrial landscape*, that is, the state-of-the-art of CO₂ improvement measures in the cement industry at the time of the assessment. Cluster West was already a synergistic production system, but nevertheless, many of the best candidates for implementation in Cluster West were related to synergistic potentials—industrial symbiosis. These included further increasing the clinker substitution rate (PPC), which means producing cement products with a 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.

Regarding the industrial landscape, most of the measures that were based on the availability of mature technologies and required less interconnectedness—simpler to implement—had lower potential for improving the CO₂ footprint of cement (*Figure 5.1*). The focus of these measures was on the cement plant itself; that is, they were internal measures. The development of the cement industry all through the last century had improved the processes within the production plant, so that little room for further improvement was left. There were a few measures which were both technically mature and had high potential for reducing CO₂ emissions: clinker substitution (PPC); synergies among already co-located firms (SIC); improved properties of blended cements (PPB); integration, or co-location with waste treatment (SIW); and using of more renewable energy (electricity or fuels) (IER). More complicated solutions—demanding high inter-organizational cooperation and arrangements—were less mature and less implemented across the cement industry. Most of these measures have low feasibility for implementation (in the short term) due to their lower technological maturity. However, they demonstrate high potential for improvement. Examples of the most interesting of these measures are developing clinkerless/no-calcine cement (PNC), carbon sequestration/carbon capture and storage (SEC), biological production (SEB), and integration with power plant (SIP).

5.2 *Assessing the CO₂ Footprint of the Production System*

SEVERAL REPRESENTATIVE PRODUCTS were selected for the LCA of Cluster West in 2009: clinker, CEM I, CEM III/A, and CEM III/B. As expected, the majority of the input material and energy in Cluster West was related to the production of clinker in the Kollenbach plant. Almost all of the fuel was burned in the cement kiln. Electricity was used in all three plants, mainly for milling of the clinker and GBFS—to produce GGBFS—both needed for producing CEM III/A and CEM III/B.

In Kollenbach, production of one tonne of clinker required about 1.5 tonne of limestone, 50 kg of coal and lignite, 126 kg of alternative fuels—consisting of animal meal and bone meal, refused-derived fuels, and shredded tires—69 kWh of electricity, and 38 tonne-km of land

transportation. It also emitted 850 kg of CO₂-eq, of which 64 % was due to calcination and 24 % from the combustion of fuels.² Extraction, upgrading, and transportation of raw materials contributed to only 12 % of the CO₂ emissions for clinker.

Another aim of the study was to compare the present production system of Cluster West with its past (1997) (*Figure 5.2*), and make it possible to identify future development pathways and quantify the CO₂-eq footprint of those as well. As mentioned before (Chapter 4.2), a virtual cement product representing the average cement production of Cluster West was defined, referred to as Cluster West portfolio cement. This virtual product represented the whole Cluster West production system, including the internal relations between the three plants, as well as their symbiotic relations with other plants, such as the steel and iron plant in Schwelgern which provided Cluster West with GBFS.

Cement product	Production plant	Clinker to cement ratio (%)	Emissions (CO ₂ -eq/tonne)
Clinker	Kollenbach	100	850
CEM I	Kollenbach	90	779
CEM III/A	Dortmund	47	452
CEM III/B	Schwelgern	25	265
Portfolio cement	Cluster West	40	385

In addition, a simplified LCA model was created based on only six key performance indicators (KPIs) which could estimate the CO₂ footprint of Cluster West under varying conditions, including scenarios involving integration with other industries (*Figure 5.3* and *Table 5.3*). In 2009, the CO₂ footprint of the average product was 385 kg CO₂-eq/tonne cement (*Table 5.2* and *Figure 5.2*). Thus, the overall CO₂ footprint of Cluster West could be estimated by varying these six KPIs—depending on its present, historical, or future versions—instead of relying on more than 50 parameters which were used in the main LCA.

IN ORDER TO QUANTIFY THE POTENTIAL of Cluster West for reducing its CO₂ footprint in the future, the results of the multi-criteria analysis of different improvement options were used (see Section 5.1). Several feasible—that is implementable—future scenarios were defined (referred to as cases), and for each scenario, the CO₂ footprint of Cluster West was estimated by adapting (altering) the value of the six KPIs and using the simplified model (Paper III). These scenarios reflected different types and degrees of development in Cluster West in

² Since the alternative fuels partially contained organic wastes, the combustion CO₂ emissions of these organic fractions were considered biogenic, and excluded from the model.

Table 5.2: CO₂-eq emissions from selected cement products in Cluster West in 2009, including a virtual product representing the average production of Cluster West referred to as Portfolio cement.

Figure 5.2: LCA results comparing CO₂ footprint of clinker and portfolio cement produced by Cluster West in 1997 and 2009 (from Paper I).

Figure 5.3: The simplified LCA model of Cluster West based on six key performance indicators (adapted from Paper I).

future. Three scenarios (Cases 1–3) focused on simpler improvements within a few areas, manifested by changes in one or two KPIs. In order to illustrate the difference between emissions from one tonne of cement and the total emissions of Cluster West, two scenarios (Cases 4–5) were defined.

Finally, two scenarios (Cases 6–7) were defined to show the potential of radical developments, which were still considered to be relatively implementable in Cluster West. These scenarios, their corresponding changes in the KPIs, and total production volumes are summarized in *Figure 5.4*. The LCA results are summarized in *Figure 5.5*.

Clinker can be produced rather efficiently, as in Cluster West, but there are inherent emissions due to calcination and high fuel demand. Aside from CO₂ capture, the only way to radically reduce the CO₂ footprint of cement was through changes in the product portfolio; that is, produce cements which have less or no clinker

Key performance indicator	Unit/formula	Value in 2009
KPI ₁ : Clinker substitution rate	%	60
KPI ₂ : CO ₂ emission due to calcination	kg CO ₂ -eq/t clinker	541
KPI ₃ : Specific heat consumption	MJ/t clinker	3915
KPI ₄ : Share of renewable fuels	% thermal energy	40
KPI ₅ : Specific electricity consumption	kWh/t cement	112
KPI ₆ : Share of renewable electricity	% electricity	0

Table 5.3: Key Performance Indicators for cement production and their values for Cluster West in 2009

Improvement measures ↓		Key performance indicators →		Key performance indicators							Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7	
				KPI1	KPI2	KPI3	KPI4	KPI5	KPI6															
				Clinker substitution rate	CO ₂ emissions due to calcination	Specific heat consumption	Share of renewable fuels	Specific electricity consumption	Share of renewable electricity	Total clinker production	Total cement production	Efficient plant	Alternative raw materials	Renewable fuels	Clinker substitution	Increased production	More synergies	More and new synergies						
Production Efficiency	EEE	Electrical efficiency						X				EEE												
	EEH	Thermal efficiency			X							EEH											EEH	
	ERH	Pre-heating / drying			X																			
	ERE	Co-generation						X													ERE	ERE		
	ERR	Recycle / reuse		X	X																			
Input Substitution	ERP	Pollution prevention and control																						
	IFC	Low-temperature clinker production			X																			
	IFM	Alternative raw materials for clinker		X	X								IFM											
	IEF	Alternative fuels				X								IEF							IEF	IEF		
Product Development	IER	Renewable energy			X	X		X						IER										
	PPC	Clinker substitution	X												PPC	PPC	PPC	PPC						
	PPB	Improve blended cements	X												PPB	PPB	PPB	PPB						
	PNC	Clinkerless / no-calcine cement	X	X	X		X																	
External Synergies	SEC	Carbon capture and storage		X			X		X															
	SEB	Biological production					X																	
	SEH	Synergistic heating			X			X																
	SIP	Integration with power plant		X	X			X																
	SIW	Integration with waste treatment				X																		
	SIC	Synergies among co-located firms		X	X	X	X	X	X							SIC	SIC	SIC	SIC					
Case 1	Efficient plant			-15%			-10%																	
Case 2	Alternative raw materials			-10%	-10%																			
Case 3	Renewable fuels						50%																	
Case 4	Clinker substitution		7%							-10%														
Case 5	Increased production		25%								60%													
Case 6	More synergies		10%			20%	-10%																	
Case 7	More and new synergies		20%		-5%	50%	-30%	5%

Figure 5.5: LCA results of the Cluster West production system, comparing its past (1997), present (2009), and several future alternatives. For comparison, the global average CO₂ emissions per tonne of clinker and cement are provided (Moya et al., 2010; cf. GNR, 2016).

Cluster West was its collective success—all three plants together—in reducing its CO₂ footprint to a level which was far below the industry average (*Figure 5.5*). While both of these stories demonstrated the relevance of thinking and acting in the direction of industrial ecology and industrial symbiosis for the cement industry, the second story also highlighted their potential for radical improvements.

The integrated environmental systems analysis approach which was developed and tested in this research (Papers I–III) can be used for collecting, categorizing and assessing potential CO₂ improvement measures and their impacts within a cement production system. The multi-criteria approach allows for the structuring of relevant information, assessing the potential improvement measures, and identifying feasible and applicable development alternatives. It also allows for the definition of implementable scenarios which could be further used for quantitative assessment via LCA. Once one LCA is performed, the simplified LCA model based on six key performance indicators allows for simple quantitative estimations of different scenarios, including the ones involving industrial symbiosis. Instead of needing to keep track of more than 50 parameters, these six KPIs are sufficient for estimating the potential gains in each production configuration. This integrated approach ensures that the studied options are feasible and applicable, and facilitates the estimation of potential gains from innovations, including industrial symbiosis.

Chapter 6

Resource-Efficient Biogas Solutions

In this chapter, results of the studies related to biogas production are presented. First, the results of the multi-criteria assessment of suitable feedstock for producing biogas in Sweden are put forward, which are based on Papers IV & V. Next, the results of another study on life-cycle assessment of producing biogas from food waste using dry or wet digestion processes are offered. This study is based on Paper VI.

6.1 *New Feedstock for Expanded Biogas Solutions*

A MULTI-CRITERIA FRAMEWORK WAS DEVELOPED in order to assess the *suitability* of different feedstocks for biogas production. Suitability was used as an umbrella term consisting of several factors including reasonable potential for biogas production, feasibility, and economic and environmental performance. Suitability was assessed by combining two complementary perspectives: (1) biogas and biofertilizer producer, focusing on their business viability, and (2) a wider societal perspective concerning resource efficiency in a long-run, as well as institutional conditions.

As mentioned before (see Section 4.3), ten key areas were selected, each characterized by one or two key questions. Each key question was further represented by one or more qualitative (or semi-quantitative) indicators (for example, see *Figure 6.1*). These areas covered aspects related to *potential*, consisting of questions about the unit potential of feedstock for producing biomethane or biofertilizers, and its total realizable potential regarding biomethane production and its contribution to nutrient recycling. The framework covered aspects related to the *feasibility* of using the feedstock for biogas production. Feasibility was represented by key areas addressing physical

and geographical accessibility of the feedstock, as well as the technological feasibility considering the whole life-cycle chain. Other aspects were also considered, such as alternative uses of the feedstock and potential competition in the existing or forthcoming markets, as well as the institutional conditions—policy and societal acceptance—which can promote or hinder the use of this feedstock.

Figure 6.1: An illustration of qualitative scales which are defined for all indicators, in this case *nutrient content* (left) and *level of support and administrative implication* (right). The abbreviations used are: VG, very good; G, good; S, satisfactory; P, poor; VP, very poor; and VH, very high; H, high; M, medium; L, low; and VL, very low (from Paper IV).

Finally, the *performance* was included in the multi-criteria framework from several perspectives, namely the profitability—or cost efficiency—of using the feedstock for biogas production, as well as its environmental impacts. The profitability was focused on the biogas and biofertilizer producer. The environmental performance raised questions related to energy balance—which is typically associated with climate change, local/regional environmental impacts, and the potential for indirect land use change. An overview of this framework, including the identified key areas, key questions, and related indicators, is presented in *Table 6.1*.

This framework was applied on a number of selected feedstocks, namely, ley crops, straw, blue mussels, source-sorted food waste, and stickleback fish. The result of each assessment was presented in the form of summary tables presenting all the indicators—including their assessed value, variability, and uncertainty—as well as a short (a few words to a few lines) summarizing text regarding the most important aspects of the assessment.

OVERVIEW SUMMARIES were also presented in a larger table, with the aim of creating a strategic overview (*Table 6.2*) which facilitates analysis and interpretation of the results. Considering the structure of the overview table, in which the rows are the indicators (related to key areas) and the columns are different feedstock categories, such analysis could be performed either horizontally, vertically, or both.

Key area and key question	Item/Indicator
<i>Description of feedstock</i> - What are the defining characteristics of the assessed feedstock?	- Name, origin, composition, dry matter and organic content
<i>Biomethane yield and suitability for anaerobic digestion</i> - Is this feedstock good from a strictly biomethane yield perspective? - Is this feedstock suitable for anaerobic digestion?	- Biomethane yield - Suitability for anaerobic digestion
<i>Nutrient content and suitability for biofertilizers</i> - Is this feedstock good from a strictly nutrient content perspective? - Is this feedstock suitable for biofertilizer production?	- Nutrient content - Suitability for biofertilizers
<i>Accessibility</i> - Is the feedstock good considering the physical and geographical accessibility?	- Geographical and physical accessibility
<i>Amount of biomethane</i> - Is the estimated total amount of this feedstock large enough to significantly contribute to the total biomethane production?	- Amount of biomethane
<i>Amount and value of biofertilizers</i> - Is the estimated total amount of this feedstock large enough to significantly contribute to nutrient recycling?	- Amount of nutrients
<i>Technological feasibility</i> - Are the needed technologies and infrastructures available and applicable considering the whole life-cycle for biogas and biofertilizers produced from this feedstock?	- Technological feasibility
<i>Profitability or cost efficiency</i> - Is biogas and biofertilizer production from this feedstock contributing to profitability or cost efficiency for the producer (also considering other products and services/effects)?	- Profitability or cost efficiency
<i>Control and competition</i> - Is it possible for the biogas and biofertilizer producer to control or secure provision of this feedstock and is it good regarding competing interests (low competition for it)?	- Control and competing interests
<i>Institutional support and societal acceptance</i> - Is biogas production from this feedstock supported by the government and other institutions? - Is the public opinion about biogas production from this feedstock positive?	- Level of support and administrative implications - Planning horizon and clarity of implications - Public opinion
<i>Environmental and energy performance</i> - Is it reasonable from an energy and environmental perspective to produce biogas from this feedstock?	- Non-renewable energy balance - Local/regional environmental impact - Indirect land use change

The vertical analysis focuses on a single feedstock category, but shows its suitability for biogas production from many different, com-

Table 6.1: Multi-criteria assessment framework for assessing the suitability of feedstocks for biogas production (adapted from Paper IV).

Key area	Indicator	Ley Crops	Straw	Blue mussel	Food waste (NSR)	Stickleback fish (Västervik)
Biomethane yield and suitability for anaerobic digestion	Biomethane yield	Satisfactory (Good) ***	Satisfactory (Poor) ***	Satisfactory (Good) **	Good ***	Good ***
	Suitability for anaerobic digestion	Good (Satisfactory) ***	Satisfactory ***	Satisfactory **	Good ***	Satisfactory ***
Nutrient content and suitability for biofertilizers	Nutrient content	Poor-Satisfactory ***	Very Poor ***	Poor-Satisfactory ***	Poor-Satisfactory ***	Very Good ***
	Suitability for biofertilizers	Very Good ***	Very Good ***	Poor-Satisfactory **	Satisfactory ***	Good ***
Accessibility	Geographical and physical accessibility	Satisfactory ***	Satisfactory ***	Satisfactory **	Good ***	Satisfactory (Very Poor-Very Good) *
	Amount of biomethane	Very Good ***	Very Good ***	Poor-Satisfactory *	Satisfactory ***	Poor/Good **
Amount and value of biofertilizers	Amount of nutrients	Good-Very Good (Satisfactory) ***	Satisfactory (Poor) ***	Very Poor-Satisfactory *	Satisfactory ***	Very Good **
	Technological feasibility	Good ***	Good (Satisfactory) ***	Satisfactory (Poor) **	Satisfactory (Good) ***	Satisfactory (Good) **
Profitability or cost efficiency	Profitability or cost efficiency	Poor-Satisfactory **	Poor (Satisfactory) **	Poor **	Satisfactory-Good ***	Satisfactory **
	Control and competing interests	Satisfactory (Poor/Good) **	Good (Satisfactory) **	Satisfactory (Poor/Good) **	Very Good ***	Poor ***
Institutional support and societal acceptance	Level of support and administrative implications	Good *	Good ***	Satisfactory-Good *	Good (Very Good) **	Very Poor ***
	Planning horizon and clarity of business implications	Poor **	Very Poor ***	Very Poor ***	Very Poor *	Poor ***
	Public opinion	Satisfactory **	Satisfactory **	Satisfactory **	Very Good ***	Satisfactory ***
Environmental and energy performance	Non-renewable energy balance	Satisfactory **	Satisfactory **	Poor-Very poor **	Good **	Good (Satisfactory) ***
	Local/regional environmental impact	Good **	Satisfactory **	Good ***	Very Good ***	Very Good **
	Indirect land-use change	Satisfactory (Good) **	Very Good **	Good **	Very Good ***	Very Good **

plementary perspectives. For example, looking at the *Ley Crops* column in *Table 6.2*, nothing in the assessment indicates significant problems or weaknesses regarding its use as a feedstock for biogas production within the Swedish context. On the other hand, there are several areas that make the *Blue Mussel* a challenging candidate for biogas production. It yields a small amount of biomethane, has a low

Table 6.2: Results of the multi-criteria assessment of several feedstocks (adapted from Paper IV). “*” refers to high uncertainty, “**” refers to some uncertainties, and “***” refers to low uncertainty (see Section 6.1).

nutrient content, is hard to access, is costly, and has poor net energy gains.¹

Horizontal analysis is comparative: different feedstocks can be compared with each other with regard to a certain indicator. For example, the biomethane potentials of ley crops, straw, and blue mussels are all similar and lie in the medium range, but straw tends to have a slightly lower yield. Compared with other assessed feedstocks, harvesting wild stickleback fish (based on the Västervik case) represents an example which, despite having significant potentials in many areas—for example positive environmental impacts—is faced with unfavorable or unsuitable institutional conditions (*Table 6.2*).

THE DIVERSITY AND DIVERGENCE of the areas that influence the suitability of feedstocks for biogas production are an illustration of at least two points. The first point is about the dissimilarities and asymmetries that can be seen in relation to different feedstocks. In Sweden, biogas is already produced from some of the feedstocks such as food waste or ley crops, despite several challenges. This is mainly due to favorable factors, including the amount, accessibility, biomethane yield, and institutional conditions. But biogas production from some other feedstocks—such as stickleback fish—is not happening, although there are environmental and economic benefits to be gained from it. Here, as mentioned before, one of the main barriers is insufficient, unsuited, or uncertain institutional conditions which make it difficult for biogas solutions to play an active role in new applications and settings—for example, in relation to aquatic resources.

The second point, which is partly related to the first, is the fact that biogas production is not an established industrial sector in itself, and to a large extent is dependent on other established sectors—for example, waste management, agriculture, or transportation. Based on our observation, the studied feedstocks illustrate different types of challenges and opportunities. Some—like ley crops or straw—are strongly linked to the agricultural sector, food waste is an integrated part of municipal waste management, and blue mussel farming and stickleback harvesting are linked to both waste management systems and eutrophication reduction initiatives. Therefore, the relationship between the *biogas solutions* and different urban or industrial sectors, as well the institutional conditions regarding that relationship, can influence the *suitability* of producing biogas from any given feedstock.

Both of these points show the relevance of industrial symbiosis for biogas producers, not only at the level of individual actors, but

¹ *Table 6.2* is presented here in the cover essay to illustrate how the output of the MCA may be structured to create an overview. For details of how the particular assessments are performed and supporting information, see Paper V.

also on the policy and broad systems levels, where cooperation with other sectors and stakeholders is needed for furthering the integration of systems, infrastructures, and policies—a process which can lead to significant resource efficiency gains on regional or national scales. For example, the integration of national policies regarding water management, sustainable agriculture, and renewable energy allows biogas solutions to contribute to the resource efficiency of all three areas at the same time.

USING THIS MULTI-CRITERIA FRAMEWORK and assessing many feedstocks, both in generic Swedish conditions as well as through case-specific assessments, can provide a simple strategic overview map from which actors and decision makers—for example, biogas producers and potential investors—can highlight similarities and common patterns, identify potential areas for further research, or provide policy recommendations. After the assessment is performed once, the consequent assessments (updates) are rather easy and time-efficient. Discussion with an informed group of experts, or reviewing recent developments in the science, technology or policy areas related to biomass, bioenergy, or biogas production can provide information for updating the assessment.

The developed multi-criteria framework can be used for systematic and participatory identification, definition, structuring, and synthesizing of diverse and heterogeneous information about a complex and multi-faceted question, such as, *Is this feedstock suitable for biogas production?* Although this framework avoids weighting and sorting of the indicators in order to produce a *decision*, the summary and overview results provide a good support for discussion and strategic decision-making, and is a condensed, versatile, and re-usable tableau of information because an identical assessment can mean different things for different actors or decision-makers, depending on their purpose and priorities.² The developed framework is rather comprehensive, but its application is very flexible. The key questions and indicators can be discussed within a single workshop among a well-informed and well-represented group of experts and decision-makers, or it can be used for identifying knowledge gaps through a literature search or discussions with experts. Applying this framework on several feedstocks can not only increase our knowledge about feedstock potentials and suitability for biogas production, but also contribute to more uniform assessments, identification of knowledge

² It is obvious that the design of the framework, including the definition of scales, has not—and could not—be free from the value judgments of the researchers as well as project participants. However, formal attempts to assign quantitative weights to the indicators were deliberately avoided.

gaps, informed policy or business recommendations, and an overview of the related possibilities and risks which can help the strategic decision-making.

6.2 Resource Efficient Biogas Production from Food Waste

In all the studied impact categories—GWP, EP, AP, and nr-CED—and in so far as the mean values are concerned, the dry digestion scenario showed better or similar results compared to the wet alternative (see Figure 6.2). But, when the uncertainties are taken into account, the difference between the two scenarios becomes less obvious, although the dry process is still relatively good.

Figure 6.2: Global warming and eutrophication potential of biogas production from food waste, comparing wet and dry digestion processes.

In the presentation of the results, a distinction was made between the *technical* and *non-technical* parts of the biogas systems. The technical part included transportation (of feedstock and digestate), pretreatment, hygienization, digestion, upgrading and compression of biogas, storage, and spreading of digestate. The *non-technical* part included the processes and emissions occurring in the soil, after digestate is applied on the land—for example the spreading of digestate, carbon sequestration in the soil, and other emissions. The effect of substituting mineral fertilizers—system expansion—were also included in the non-technical part. The uncertainties in the non-technical part of the system were higher and could have a significant influence on the environmental performance of producing biogas

from food waste, in either dry or wet processes. This was particularly important in relation to eutrophication and acidification potential. In these two impact categories, the impacts from the non-technical part of the system were much higher than the impacts from the technical part.

Seven key performance indicators (KPIs) were defined in order to gain better understanding regarding the performance of the systems. The functional unit of the LCA was “production of 1 MJ of upgraded biogas”, but some of the produced biogas was used internally, for supplying the required heat. The sum of the biomethane content of the internally used biogas as well as the upgraded biogas was defined as *usable biomethane production*—losses due to slippage or flaring are not usable. The first indicator (KPI₁) shows the effective methane production of the biogas system. Three indicators (KPI₂₋₄) related to gas yield and energy consumption were defined to summarize the energy performance of the system. Another performance indicator (KPI₅) was defined based on the total material transportation in tonne ww-km. This indicator shows how many kilometers 1 tonne of material (food waste or digestate) is transported in the overall system, including collection and transport of food waste, transport of digestate to farms and its spreading. Finally, two more indicators were defined to show the nutrient recycling potential of the studied biogas systems (KPI_{6,7}), focusing on the share of the nitrogen and phosphorous content of the food waste which is applied on farm lands as biofertilizers. These indicators are shown in *Table 6.3*.

Key performance indicator	Unit	Scenario A (dry)	Scenario B (wet)
KPI ₁ : Effective biomethane output	Nm ³ CH ₄ /tonne vs	327 (293–369)	306 (222–394)
KPI ₂ : Electricity intensity	% (MJ el./MJ CH ₄)	9.0 (8.0–10.3)	11.9 (9.3–15.3)
KPI ₃ : Heat intensity	% (MJ heat/MJ CH ₄)	8.5 (7.3–10.0)	14.0 (8.1–20.1)
KPI ₄ : Cumulative energy intensity	% (MJ-eq/MJ CH ₄)	29.1 (25.1–33.7)	38.4 (29.3–50.4)
KPI ₅ : Transportation intensity	tonne-km/tonne ww	150 (126–174)	195 (163–233)
KPI ₆ : Nitrogen recycling potential	% (kg N, farm/total)	53 (52–54)	79 (60–97)
KPI ₇ : Phosphorous recycling potential	% (kg P, farm/total)	50 (49–50)	79 (60–97)

Since in both scenarios, the methane yield from “pretreated” food waste was assumed to be similar, the difference in the effective methane output (KPI₁) was mainly due to different reject rates in the pretreatment step, as well as the amount of thermal energy (heat) demand which consumes some of the produced biogas (internally). KPI₁ is of particular importance for this LCA, because it shows that

Table 6.3: Key Performance Indicators for biogas production from source-sorted food waste (mean values). Ranges are based on support intervals (99 % confidence.)

the two different systems lead to production of different amounts of biomethane. Therefore, all the LCA results (which are presented per functional unit—1 MJ of methane as upgraded biogas) are affected by it. Factors that have an influence on KPI₁ can directly influence the LCA results. Among the main factors are the composition of the received waste (its dry matter and organic content), which determines its theoretical methane yield; the amount of rejects in the pretreatment and the biodegradability of the rejects, which determines how much food waste is fed into the digesters³; and finally the methane yield efficiency of the digestion system, which determines what fraction of the lab-estimated yield can be achieved. Other factors that can influence KPI₁ are the amount of biogas used for internal processes (for example to provide the heat demand of the digesters and upgrading unit), and losses due to flaring and slippage.

For the LCA results, critical processes—in relation to GWP—were identified by estimating their contribution to life-cycle GWP (per functional unit), and their uncertainties (see Section 4.4). Once both

³ The rejected fraction may still be processed or used for energy recovery, and even possibly for production of biogas (Murto et al., 2013).

significance and uncertainties were considered (through the criticality scores), the most critical processes (for GWP) could be identified.

Figure 6.3: Impacts (significance) and uncertainty of different processes in relation to global warming potential of biogas production from food waste. Uncertainties are shown by the support intervals (99 % confidence).

Among them, “soil emissions”, including the fate of carbon and nitrogen content of the digestate after it was used for land applications was prominent. Other critical processes were gas slippage, transportation activities, and impacts of substituting mineral fertilizers.

Choices within the models and scenarios related to biogas production from food waste can have a significant impact on the results of the LCA. In this study, LCA, KPIs and a systematic approach to uncertainty management were used to investigate the performance of biogas production from food waste. As the case of VMAB shows, producing biogas and digestate from food waste, using a dry digestion process, can lead to competitive environmental performance compared to most existing systems which use a wet process. Nevertheless, regardless of the choice of a wet or dry process, there are large uncertainties in the non-technical parts of the system which are less dependent on the technical choices or scenario assumptions. Decision-making regarding the development of new or existing biogas solutions from food waste should take note of these uncertainties. Since some of the impacts of using food waste for biogas production and its digestate as biofertilizer lie in areas with high uncertainties—for example, impacts related to soil emissions—communication of the uncertainties to wider socio-political actors is important. As an LCA, this study focused on the environmental impacts. However, by introducing several key performance indicators, other aspects of the studied system which can be “economically relevant”, such as effective methane production, energy intensity, transportation intensity, and nutrient recycling potential, were introduced. By combining LCA, KPIs, and criticality assessment, the environmental (and indirectly, economic) performance of a dry biogas-from-food-waste system was compared with those using wet processes.

Chapter 7

Toward Integrated Systems Analysis

In this chapter, the insights gained from all the articles (Papers I–VI) are used to discuss the possibilities of integrated systems analysis of industrial production systems, using multi-criteria analysis and life-cycle assessment as two complementary methods.

TWO GENERAL APPROACHES TO ENVIRONMENTAL SYSTEMS ANALYSIS are utilized in this thesis, and to an extent have been tailored or developed: life-cycle assessment (LCA) and multi-criteria analysis (MCA). In the cement study, which dealt with improving the CO₂ performance of a cement production system (Cluster West), these two approaches were integrated. MCA was used to identify and structure the existing information and define feasible and applicable scenarios for implementation. LCA along with several quantitative indicators (KPIs), were used for quantifying the performance of this cement production system under those scenario projections.

Both of these approaches were also utilized in the two biogas studies. An extended MCA was used for analyzing the suitability of using different feedstocks for biogas production, where suitability was defined as conditions which encompass aspects such as potential, feasibility, and performance. In a parallel study, LCA was used for analyzing and identifying the uncertainties within biogas production from food waste, based on the first biogas plant in Sweden which uses a dry digestion process, and comparing it with other typical co-digestion plants which use wet processes. These biogas-related MCA and LCA were not integrated in the same way that the MCA and LCAs of Cluster West were. The main reason for the lack of such integration was due to the project design: unlike the cement studies (Papers I–III), the biogas studies were related to distinct project

setups (see Sections 1.6 and 4.1). Although these projects led to combined knowledge and fed each other, integrated analysis was not a formalized part of their goal. However, when these approaches are compared individually—that is, comparing the LCA of cement with the LCA of biogas, and the MCA of cement with the MCA of feedstocks for biogas—it becomes clear that each represents an extended approach to LCA or MCA. The MCA of feedstock for biogas production covered many more key areas and indicators. The LCA of biogas production from food waste, in contrast, used a systematic approach for capturing, representing, and propagating parametric (and other) uncertainties. Despite these dissimilarities and differences, it is interesting to ask about the methodological recommendations which can be made, based on the lessons of these studies, in relation to more integrative and robust environmental systems analysis.

As can be seen in the cement studies, it is possible to achieve a highly integrated systems analysis, where qualitative and quantitative data are used and a semi-structured approach such as MCA informs the more standardized approach of LCA. In the case of Cluster West, the marriage of these methods led to a more reliable scenario definition and more realistic future projections. But is it possible to have a similar approach when analyzing more complex and less mature systems such as the ones involving biogas solutions?¹ The answer depends on how *tightly* or *loosely* we want to integrate these two approaches.

When the studied system is relatively simple, *tight integration* of MCA and LCA may be possible: MCA and LCA can be analytically linked to each other (*Figure 7.1*). The result of MCA can be used to define feasible and applicable scenarios which are in turn analytically translated into quantitative inputs for the LCA. Examples of such relatively simple situations include: (i) industrial systems which have few inherent links with other systems and actors; (ii) when there are few epistemic uncertainties and limited variabilities—for example, when dealing with established and mature production systems; or (iii) when only one, or few aspects have to be considered—for example, only looking at climate impact.

Many of the traditional process-based industrial production systems may resemble these descriptions. In this thesis, it was shown that tightly integrated MCA and LCA approaches can be applied for CO₂ improvement measures of cement production, even when

¹ It is important to note that unlike the cement studies, the biogas studies were not part of the same project. Therefore, the integration of MCA and LCA methods was not part of the aim of the biogas studies. Nevertheless, in this chapter the integration of these two methods in the systems analysis of different types of industrial systems is discussed.

Figure 7.1: Loosely or tightly integrated environmental systems analysis approaches for investigating *simpler* or *more complex* industrial systems, based on LCA (life-cycle assessment) and MCA (multi-criteria analysis).

the production system is relatively complex and contains inter-organizational synergies, as well as synergies with external actors—that is, industrial symbiosis.

However, when the studied system is more complex, approaches for *loose integration* of MCA and LCA might be more favorable (Figure 7.1). In this type of integration, the two analytical approaches of LCA and MCA are viewed as complementaries of each other, and *no hard link* is established between the two. Depending on the nature of the problem and the specific characteristics of the studied system, the analyst may decide to elaborate more or less on each of these approaches. Loose integration allows—even welcomes—asymmetric emphasis on MCA or LCA, with the purpose of maximizing flexibility and simplicity in dealing with emerging, multi-faceted, and complex industrial systems as study objects. A few examples of complex situations are (i) when interaction with several systems or among many actors are inherent or unavoidable; (ii) when there are lots of epistemic uncertainties or great variabilities—for example, when dealing with emerging technological solutions; or (iii) when several aspects have to be considered—for example, when environmental impacts other than climate change are important.² Such loose

² It is important to note that the expressed distinctions between tight and loose integrations, or complex and simple systems, should be not be viewed literally. These are archetypes which can be used as a rough conceptual guide.

integration of MCA and LCA can be beneficial in studying complex and emerging technological solutions—such as some of the emerging biobased technologies, where lack of structured information and high uncertainties regarding potential, feasibility, and applicability of different alternatives may reduce the effectiveness of using structured, quantitative and in-depth approaches such as LCA. Hence, developing and applying a multi-criteria framework can be used for organizing the knowledge and uncertainties, and shed light on the feasible and applicable trajectories that the real or hypothetical system may take. This provides a better basis for defining the goal and scope of an LCA, including the scenarios that are considered for quantitative investigation. The general steps of such a loosely integrated approach are summarized below:

- Step 1 *Background domain study*: The existing studies related to the studied technological solution and closely related areas are reviewed. The review is performed from the perspectives of industrial ecology, industrial symbiosis, resource efficiency, circular economy, and sustainability, but also from merely technical or scientific perspectives in order to gain a better understanding regarding the basics, as well as the state of the art. The main source of information in this step is literature (and experts), but the process of selecting relevant participants in the research is started in parallel, where these participants can support the background domain study—and act as research partners.
- Step 2 *Multi-criteria framework*: Through dialog with the participants, a list of “key questions” and a set of measurable “indicators” regarding the suitability of different development options are identified and defined. The general question of suitability may include aspects related to potential, feasibility, and performance, but also any other aspect which is considered important. The combination of the key questions (criteria) and indicators forms the foundation of the assessment framework for multi-criteria systems analysis of the studied solutions. This step mainly relies on the inputs from participants (domain experts) and the literature, but can be complemented—by the main researchers—with aspects which are considered important from a normative, theoretical, or conceptual standpoint.
- Step 3 *Qualitative assessments*: The multi-criteria framework is used for assessing many different development options that are identified

in the background domain study (Step 1). The result shows the strengths and weaknesses, opportunities and challenges, drivers and barriers, areas of knowledge and expertise as well as knowledge gaps and uncertainties. An overview map is produced which can be used for strategic decision-making, including further orientations of the systems analysis. It can also highlight certain scenarios for in-depth quantitative systems analysis, using LCA or other similar methods.

Step 4 *Quantitative assessments:* A quantitative systems analysis, such as LCA, is performed on the selected technological solutions or scenarios, as highlighted in Step 3. These analyses may include quantification of environmental or economic impacts of production scenarios, including uncertainty and risk assessment.

WHEN THE SYSTEMS ARE MORE COMPLEX or less known, uncertainty management in systems analysis is more important. Uncertainty can be identified and represented qualitatively. Semi-structured and qualitative underpinning of the multi-criteria approach provides ample space for commenting on variabilities and epistemic uncertainties, as it is illustrated in the multi-criteria assessment of new feedstock for biogas production (see Section 6.1). In addition, MCA is compatible with commonsensical, intuitive, subjective, heterogeneous, and sparse information—as well as common technical or scientific evidence which is explicitly stated in the literature. Incorporation of uncertainty assessment in MCA neither significantly adds to the complication of the assessment itself nor to its presentation. Moreover, provided the qualitative space, it is possible to simply stress some of the important issues which are not captured by the pre-defined scales in an unstructured verbal form (such as short remarks). As a result, MCA can be used as an amendable tool for identifying and structuring the state of the art as well as key uncertainties.

Similarly, uncertainty management in a quantitative systems analysis, such as LCA, is important. As discussed in Section 3.3.4, possibility and probability theories can be used for formalizing uncertainty. When data is subjective, intuitive, or sparse, possibility intervals are more suitable in data collection. Otherwise, known patterns of variability from frequent data can be modeled by probabilistic models. Either approach can be used for further uncertainty propagation by Monte Carlo simulation. The results of Monte Carlo simulation can be expressed as possibility intervals for more effective communication.

Figure 7.2: Loosely integrated systems analysis may be performed in parallel, resembling a double helix.

LOOKING AT INTEGRATED SYSTEMS ANALYSIS AS THE LOOSE INTERPLAY of MCA and LCA, rather than a concrete framework which can fit all applications, is a more versatile and practical approach to the systems analysis of complex industrial systems. The inherent flexibility of this approach allows the practitioner to define resource efficiency from different aspects, and provide valuable, broad, or specific information for strategic decision-making. In practice, such a loosely integrated approach to systems analysis may occur in parallel, resembling a contrapuntal development of two melodies, or simply a double helix consisting of these two complementary approaches (*Figure 7.2*).

Chapter 8

Discussion

In this chapter, the findings and implications of this research are discussed in relation to the aim and research questions of the thesis (Research Question 1 (RQ₁) and Research Question 2 (RQ₂)).

8.1 Lessons from the Cement and Biogas Industries (RQ₁)

Cement production and biogas solutions represent different types of industrial development and challenges. Generally speaking, the challenges of cement production are about its already large resource use and CO₂ emissions, which should be decreased. The challenge of biogas solutions, viewed as part of the transition toward a biobased economy, is about finding suitable roles and going through the process of maturation. Both types of industrial systems can gain by emphasizing resource efficiency, but one hopes to reduce its already large environmental impacts, while the other has the ambition of maturing as a solution in a societal transition involving a significant reduction of environmental impacts. Secondary resources are relevant for the development of both types of systems.

8.1.1 Cement Production and Industrial Symbiosis (RQ_{1a})

Since the secondary resources have already been used once and caused their main environmental impact, their reuse can effectively reduce the environmental impacts of cement production. Industrial symbiosis is crucial for the development of the cement industry, because it promotes collaboration over sharing or reusing of secondary resources and can provide opportunities for decreasing the climate impact of cement production and increasing its resource efficiency.

The studied cement case in this thesis is a manifestation of the move toward industrial symbiosis, and the gains that can be achieved by it. Comparing the performance of this production system in 1997 and 2009, the portfolio of the cement production moved from “Portland cement dominated” to “slag cement dominated”, as a result of material and energy synergies with an iron and steel producer, as well as intera-organizational industrial symbiosis among the three cement plants. As it was shown in Papers I–III, the CO₂ footprint of cement can be reduced radically by avoiding the use of primary raw materials such as limestone. By using the limestone which is already consumed in iron and steel production, that is granulated blast-furnace slag, and secondary fuels, mainly consisting of refused and organic materials, it was possible to significantly decrease the CO₂ footprint of cement production.

In Cluster West, blended cements with a high clinker substitution rate not only had similar—or better—qualities than ordinary Portland cement, but also had a lower CO₂ footprint. Thus, producing cement products with lower clinker content appears to be an effective strategy for reducing the CO₂ footprint of the cement industry. Globally, the clinker substitution rate increased from 15 % in 2003 to 23 % in 2010, and is predicted to rise about 30 % in the long run (Harder, 2006; WBCSD, 2009). This shows that reducing the clinker content of cement is an ongoing trend and is pursued by the industry. However, several issues can be discussed in this regard.

The first issue is related to the characteristics of blended cements, which tend to have slower strength development over time (Schneider et al., 2011). This is in contrast with the general preference of the actors within the construction sector, who prefer to use a cement with a faster hardening time: a tendency which favors Portland cement. From a resource efficiency perspective, it is undesirable that an issue which will be resolved in matter of a few days or weeks—the hardening of the fresh concrete—determines the life-cycle performance of a building which may last for several decades. Therefore, reducing the clinker content of the cements used in the construction sector requires collaboration with relevant actors along the value chain, particularly on the demand side.

This is linked to the second issue, which is about the role of the cement industry as part of the construction industry. The construction industry is the largest consumer of raw materials and constructed objects, and represents between 25 and 40 % of global anthropogenic carbon emissions (WEF, 2016). About a third of the construction

and demolition wastes are recycled, and most of these materials—part of which could be used as secondary resources in many applications, including cement supplements and cement substitutes—are dumped (European Commission, 2011d; WEF, 2016). Through research, development, and collaboration with different actors within the construction industry, there is great potential for improving the resource efficiency and CO₂ footprint of the cement industry, as well as the construction sector (Galbenis and Tsimas, 2006; Tam and Tam, 2006). Thus, the construction industry is not only a consumer of the cement products, but also can be viewed as a supplier of secondary materials for cement production.

The third issue is about the availability of the secondary materials with adequate qualities which can be used as clinker substitutes. On the global scale, cement production is a gargantuan enterprise, and its production has been generally expanding. Continuing this trend in a way which is compatible with the increasingly tighter climate and resource constraints requires extraordinarily large amounts of secondary resources and renewable fuels—even if the resource efficiency of producing 1 tonne of cement continues to improve. Since not enough secondary materials and fuels can be supplied to match current global cement production levels, in addition to improving the efficiency and use of alternative materials and fuels, the strategy of carbon capture and storage (CCS) is proposed (WBCSD, 2009). CCS may turn out to be a necessary part of the strategies for climate change mitigation (Haszeldine, 2009; IEA, 2015). Nevertheless, it appears to be incompatible with the principles of industrial ecology and resource efficiency because it requires more (fossil) energy to function (House et al., 2009), and is based on the assumption of linearity—as opposed to circularity. In other words, CCS may become an end-of-pipe solution with limited effectiveness.

And finally, the question of allocation may become relevant if secondary materials such as blast-furnace slag cease to be viewed as waste and turn into byproducts or resources with economic value—a process which is already happening, as highlighted by the World Steel Association (2012). Actors who participate in industrial symbiosis may want to have a specific answer about who should get the benefits (Martin et al., 2015). For example, regarding Cluster West, it might be asked *Who should be credited for the reuse of blast-furnace slag? the iron and steel producer, the cement producer, or both?* In LCA, the environmental impacts of the product and byproducts of an industrial activity can be split according to their economic value, or

by some physical properties such as energy content or mass. But discussions regarding the allocation of benefits—or burdens—should not become a hindrance for the real issue, which is the reduction of the resource use and environmental impacts of all industrial actors who are involved in the exchange and reuse of secondary resources. Therefore, from the perspective of resource efficiency, it might be better to avoid the allocation issue by expanding the boundaries of the studied system so that the byproducts are considered as alternatives to other products obtained from the market. This means that instead of asking “*how can this cement plant improve its resource efficiency by using the secondary materials from the iron and steel plant?*”, it is better to ask “*how can these cement plant and iron and steel plant improve their resource efficiency by engaging in industrial symbiosis?*”. As highlighted in Paper III, a radical reduction of CO₂ emissions requires going beyond the production site-level (the single-actor view). This means moving from a narrow focus on cleaner production toward the broader perspective of industrial symbiosis.

8.1.2 Biogas Solutions and Industrial Symbiosis (RQ_{1b})

Many types of biogas solutions are manifestations of industrial symbiosis. In Sweden, producing biogas from municipal food waste demands collaboration with municipal waste management agencies as suppliers of feedstock, public transport organizations as customers of the produced biogas, and representatives from farmers as customers of the biofer-tilizers. Biogas solutions can fit within a distributed biorefinery or an industrial cluster, and serve as a resource-efficient way of treating wastes or low-grade residual biomass.

The industrial symbiosis of biogas solutions, as seen in several Swedish examples, is also interesting from another perspective. Whereas most famous international cases of industrial symbiosis are built around fossil-based energy systems, there are several symbiotic systems involving a biogas plant which are based on renewable energy systems (Martin et al., 2014; XPOSE, 2015). There is an inherent tendency in these systems for linking several infrastructures together. Therefore, these solutions can contribute to several regional and national goals at the same time.

In Sweden, biofuels, including biogas, are typically framed in relation to producing renewable energy carriers with a particular focus on climate impact (Martin et al., 2015). However, from the perspective of industrial ecology and resource efficiency, it is also important to consider their contributions to nutrient recycling and

waste management. This will allow further analysis of the role that biogas solutions can play in relation to existing, seemingly disparate issues, such as the eutrophication of the Baltic Sea. As seen in Paper IV, harvesting stickleback fish from the Baltic Sea can have several positive environmental impacts (see *Table 6.2*). Although the idea of harvesting this fish from the Baltic Sea is not implemented, this example illustrates how looking at the nutrient recycling—in this case, recovering excess nutrients from the sea—can reveal new opportunities for resource-efficient solutions.

Even when biogas is framed primarily as a source of renewable energy, its environmental performance needs to be discussed in comparison with the existing, often fossil-dominated, *reference* systems. While it is important to compare the environmental performance of biogas with other renewable energy sources, the main issue is to align and combine the efforts to increase the resource efficiency and volume of all renewable energy carriers in order to reduce dependency on fossil fuels. Continuous and in-depth investigation of the impacts from biogas production, including various types of impacts, emissions, and leakages, is important; however, it is also important to pay a similar level of attention to impacts of the fossil reference systems.¹ Disproportionate focus on the weaknesses of emerging renewable solutions—such as biogas—and ignoring or downplaying the huge environmental impacts of fossil systems is counterproductive.

8.1.3 *Similarities and Differences Between Cement Production and Biogas Solutions*

Cement production and biogas solutions have many differences. Cement is an industry with a long history. It is typically produced at very large-scale plants; for example, the studied cement plants in Papers I–III produced about one million tonne of cement per year. Traditionally, cement has been dependent on primary resources, such as limestone and fossil fuels. The combination of emissions from calcination and fuel combustion has been the main reason for its high CO₂ footprint.

On the other hand, biogas production systems are relatively new and have a shorter history. Compared to cement, biogas is produced at smaller plants which mainly rely on local or regional bio-resources. In different countries and contexts, biogas solutions have emerged from different bases and origins: in some places they are rooted in the waste management sector (for example, in Sweden), while in others

¹ According to the US EPA (2015), oil and gas production systems emit 29 % of the total release of natural and anthropogenic methane to the atmosphere. According to some estimates, about 4–8% of the methane produced over the lifetime of a shale gas production well is leaked into the atmosphere (Howarth et al., 2011). Methane emissions from oil and gas systems are significant (Larsen et al., 2015), while the amount of gas leakage from natural gas production and distribution systems in Europe and Russia is not well known, and requires further investigation (IASS Potsdam, 2016).

they are developed in relation to the farming sector (for example, in Denmark or Germany). In many cases, biogas solutions are strongly linked to (secondary) biomass and renewable energy, and can play a role in the biobased economy.

Compared to cement production systems, biogas systems are broader and tend to be more heterogeneous and complicated. As a result, we know less about the key parameters that influence the performance of the biogas production system, and in some areas, such as the *impact of applying biofertilizers on soil* as shown in Paper VI, there are high uncertainties.

In discussing cement and biogas production systems, we should not forget the broader dynamics of industrial developments in general. Regardless of the moment when we reach *peak fossil energy* or *peak other non-renewable resources*, it is becoming evident that the golden era of fossil-based industrial systems is passing (Hall et al., 2014; Heinberg, 2007; Murphy and Hall, 2011). The defining characteristic of the fossil-based systems is the fact that their side-effects will be increasing—and can only increase in the long run and on the broader scale. In other words, there is no shining long-term prospect for the fossil-based systems. On the other hand, biobased—and renewable—industrial solutions are emerging and have a long future in front of them. If developed properly—for example, following the principles of industrial ecology and resource efficiency and monitored via systems analysis approaches—they have the potential to exhibit good environmental performance in the future and have minimal undesirable impacts. In addition, it will be possible to internalize their positive externalities into the economic systems. In short, the externalities of fossil-based systems—beyond particular local or short-term improvements—will be getting worse and worse, but the externalities of biobased solutions—such as biogas solutions from low-grade organic resources, with nutrients recycled back to the farm—have the potential to become better and better. This is not a guaranteed or pre-determined outcome: it depends on our choices about trajectories and types of eco-industrial development.

THE GOOGLE NGRAM VIEWER² is an Internet-based tool for analyzing the historical trends related to the development of ideas, concepts, or even cultural phenomena (Michel et al., 2011; Smallwood, 2015). A comparative search for the two bigrams³ “cement production” and “biogas production” provides a rough picture of how these two concepts have developed in the last century.⁴ The cement bigram has

² The Google Books Ngram Viewer (books.google.com/ngrams) is a search engine that visualizes the frequencies of given search strings by showing the annual counts of n-grams found in printed sources between 1500 and 2008. The database from which Ngram operates includes texts published in American English, British English, French, German, Spanish, Russian, Hebrew, or Chinese (Google, 2013).

³ A bigram is an n-gram with two words.

⁴ It should be noted that the results are based on the Google Ngram database, which may be biased toward English and European conditions, simply because the included languages do not cover the developments in all parts of the world.

much higher hit rates compared to the biogas one, but since the purpose is to show how each concept has evolved, the values are normalized.⁵ As illustrated in *Figure 8.1* (left), cement production emerged in the late 19th century and its references in the literature peaked around 1980. Almost at the same time that terms such as “Portland cement” or “cement production” peaked and their references began to decline, terms such as “blended cement” or “supplementary cementitious materials” started to gain traction, which reflects the shifting emphasis of the cement industry (see *Figure 8.1*, right). Biogas production is a much newer concept in the literature. It emerged in 1970 and peaked around 1985, but has experienced another rising trend since the late 1990s. Combining these results from the Google Ngram viewer with the fact that cement production has been continuously increasing (see *Figure 2.1*) shows that industrial cement production is much more mature compared to biogas production.

⁵ Normalized by the formula: $\hat{x}_{i, 0 \text{ to } 1} = \frac{x_i - X_{\min}}{X_{\max} - X_{\min}}$, in which x_i is the original data point, $X_{\min}$ and $X_{\max}$ are the minimum and maximum of all the data points, and $\hat{x}_{i, 0 \text{ to } 1}$ is the normalized data point.

Figure 8.1: Historical search results for “cement production” and “biogas production” (left), and “blended cement” and “supplementary cementitious materials” (right), using the Google Books Ngram viewer search engine (normalized), 1870–2008.

Although cement and biogas production systems are very different, there is an interesting similarity between the two.

Focusing on improving the resource efficiency of producing a single unit of industrial output—for example 1 tonne of cement, or 1 MJ of biogas—should not cloud our judgment regarding the performance and impact of the overall industrial output and the possible rebound effects (Holm and Englund, 2009). Effective “eco-industrial development”, that is, the transition of existing industrial activities toward economic and ecological ones, requires improving resource efficiency at the level of the overall industrial throughput.

Ideally, this important aspect should be taken into account in decision-making regarding eco-industrial development of both cement and biogas production systems.

Both the cement and biogas production systems can be viewed as industrial scavengers—although differently. This is because they can use many different forms of materials: cement production can take in many different organic and non-organic materials—as raw material or fuel—while biogas solutions can process a diverse range of organic materials. This diversity of inputs suggests that there might always be some type of secondary or lower-grade materials that can suitably be processed via these systems. In both cases, it is essential to consider the resource efficiency and waste/resource hierarchy: although these production systems can receive many types of resources, it can be argued that the priority should be given to secondary or low-grade ones. In other words, the scavenger role of both systems should be used in a resource-efficient manner. Enhanced interconnectedness with the surrounding urban and industrial infrastructures and production systems can facilitate the flow of increasingly lower-grade secondary materials toward these scavengers.

8.2 *Systems Analysis for Eco-Industrial Development (RQ₂)*

Systems analysis methods can facilitate strategic decision-making for eco-industrial development, if they take into account real-world conditions and practices; for example, by avoiding excessive abstraction, considering the perspectives of the involved actors, and maintaining a strong connection to the potentials and feasibility aspects of the development ideas.

Multi-criteria analysis can be used to systematically search for and identify a wide array of development options, estimate their potential, and assess their feasibility for implementation (as in Paper II or Papers IV & V). The main challenge of MCA is the breadth of the knowledge—about many different issues—that needs to be compiled, structured, summarized, and interpreted. Information from different domains and disciplines has to be gathered and processed, a task which can only be reliably achieved by incorporating experts and practitioners as research participants. As the amount of information grows, information management becomes essential for the study.

Assessing the life-cycle environmental performance of an idea—or a scenario—for implementation can also provide support for decision-making regarding eco-industrial development. Life-cycle assessment

can be used for in-depth and systematic studies of the environmental performance of the systems (as in Paper I or Paper VI). It can compare different alternatives, identify critical factors and key uncertainties, and provide relevant input for decision-making regarding eco-industrial development. LCA can be used to define key performance indicators (KPIs) which are relevant to both environmentally and economically. KPIs can enrich the LCA study and can be used in benchmarking of different production systems.

Depending on the aim and design of the systems analysis, both MCA and LCA can be used in a standalone manner and provide useful results (Figure 8.2). Performing a standalone MCA can be the main aim of a systems analysis (as in Papers IV & V). Similarly, and in many applications, where the background information about the systems is sufficiently known, performing a standalone LCA can lead to useful and reliable results.

Figure 8.2: Standalone and complementary systems analysis using multi-criteria analysis (MCA) and life-cycle assessment (LCA).

The LCA standard does not demand anything be done before or alongside performing the LCA. This means it is possible to perform an LCA of several scenarios for eco-industrial development without proper investigation of the contingencies and contextual factors that can influence their feasibility. Performing a *pre-LCA* can increase the usefulness of the study. This can be in the form of another LCA, for example a screening LCA. But if the studied system is complicated, or belongs to an emerging industry with a lot of epistemic uncertainties, performing a multi-criteria analysis before or alongside the LCA may be beneficial. As illustrated in Paper II, the multi-criteria approach can be used for the structuring and evaluation of different aspects of the studied system, for example identifying the main options for

improvement, their feasibility of implementation, and their performance. The result of the multi-criteria analysis can be used to develop realizable and realistic scenarios, which can be used in the LCA study for in-depth analysis (*Figure 8.2*).

These two approaches—LCA and MCA—are complementary to each other. LCA is a systems analysis approach with a relatively narrow focus (and wide scope): the systematic quantification of environmental impacts by following the material and energy flows. It is a versatile, widely used, and powerful tool for in-depth investigation of the environmental performance of an industrial activity over its full life-cycle. But since it is focused on quantifiable phenomena, it is not suitable for taking into account contextual and contingent factors such as potential, feasibility, and applicability of the studied activities. For this purpose, a systems analysis approach with much wider focus and higher flexibility in dealing with non-quantifiable knowledge is needed. MCA can be viewed and used as such a systems analysis approach, which will ensure that the LCA study is not “disembedded” from its non-quantifiable context. The combination of these two approaches can be viewed as an integrated approach to the systems analysis of industrial systems. This integrated approach allows (i) the structuring of the existing knowledge—both explicit and tacit or intuitive knowledge—in a meaningful and simple way in order to gain a strategic overview about suitable development options (MCA), and (ii) quantification of the life-cycle impacts of an industrial system (LCA). Quantification can provide extra support for decision-makers in distinguishing priorities for development, or envisioning the impacts of the forthcoming changes.

When the studied system is relatively simple, or the scope of the study is limited, tight integration of LCA and MCA is simpler to achieve. An example of such tight integration was performed in Papers I–III, where MCA was used for identifying feasible options for improving the CO₂ footprint of cement, and LCA was used to quantify these options. In the study of biogas systems, integration was not performed as part of the articles—due to different project designs for the two biogas-related studies—however, it was suggested that integrated systems analysis may also be possible when the studied system is complex, emerging, and with lots of uncertainties.

The idea of integrated systems analysis using two complementary approaches is not limited to using LCA and MCA as particular methods, as was the case in this thesis. Arguably, a similar insight can be

applied to other complementary systems analysis approaches. For example, methods with relatively narrow focus and wide scope such as life-cycle costing (Gluch and Baumann, 2004; Rebitzer and Hunkeler, 2003; Swarr et al., 2011), energy analysis (Bullard et al., 1978; Murphy and Hall, 2010; Ramesh et al., 2010), or material flow analysis (Brunner and Rechberger, 2004) can be viewed as complementary with more encompassing and flexible methods such as life-cycle sustainability assessment (UNEP, 2011) or technology assessment (EPTA, 2015; Klüver et al., 2000).

Chapter 9

Conclusions

In this final chapter, the main conclusions of this thesis are summarized. In the end, a few areas for furthering this research are suggested.

DUE TO THE CALCINING PROCESS AND COMBUSTION OF FUELS, production of clinker emits large amounts of CO₂ to the atmosphere. It is possible to reduce fuel-related emissions by improving the kiln efficiency or by using more renewable fuels, but CO₂ emissions due to calcining can only be effectively reduced by substituting primary limestone with secondary materials—such as blast-furnace slag. This approach provides the highest potential for reducing the climate impact of cement. Sustained collaboration with other industrial actors and new partners who own cementitious secondary materials, along with improving the market acceptance of alternative cement products, are of strategic importance for eco-industrial development of cement production systems. The studied cement production system demonstrates how a typical cement plant can achieve a very low CO₂ footprint through increased inter and intra-organizational synergies, generally known as industrial symbiosis.

THE PRODUCTION OF RENEWABLE ENERGY CARRIERS is often viewed as the main reason for treating organic materials through anaerobic digestion, but biogas solutions can also contribute to better waste management and nutrient recycling and other synergy effects. These contributions can indirectly lead to positive environmental impacts, but are rarely translated into economic rewards for biogas and biofertilizer producers. If biogas solutions are simultaneously viewed as *producers of renewable energy carriers* and *recyclers of nutrients*—and in some cases *industrial enablers*—their unique roles in improving the resource efficiency of different urban or industrial systems can be

better appreciated. The links of biogas solutions to other systems show the importance of industrial symbiosis for realizing their true potentials in the emerging biobased economy.

The multi-criteria study of selected feedstocks, including ley crops, straw, farmed blue mussels, household food waste, and a non-edible fish from the Baltic Sea, provided a strategic overview of different aspects of producing biogas from these types of biomass. These aspects include energy and nutrient potentials, feasibility, and the resource efficiency of using different feedstocks for biogas production. Despite favorable conditions in many areas, the expanded production of biogas from some of the assessed feedstocks is hindered due to unclear or unfavorable institutional conditions, for example in relation to the utilization of aquatic biomass such as non-edible fish as a way to remove excess nutrients from the Baltic Sea as well as producing biogas.

In another study, the environmental performance of producing biogas from municipal food waste using dry and wet digestion processes was compared. In all the studied environmental categories including the global warming potential, the dry process demonstrated better or comparable performance—per unit of biomethane produced—compared to typical wet digestion processes in Sweden. This study shows that dry digestion processes can also be considered as a viable alternative for eco-industrial development of anaerobic treatment of food waste in Sweden. However, the performance of both systems was greatly influenced by large uncertainties regarding the impacts of using digestate as biofertilizer. Assumptions and choices related to these uncertainties can greatly influence the environmental performance of biogas solutions; therefore, it is important for all systems analyses, including LCA, to ensure that proper measures are adopted to take into account these uncertainties.

TWO COMPLEMENTARY APPROACHES TO SYSTEMS ANALYSIS were used in this thesis.

Multi-criteria analysis (MCA), as presented in this thesis, is a flexible and systematic approach which allows the organization of existing knowledge and identification of resource-efficient and feasible options for industrial development in relation to a given industrial cluster (such as the studied cement production cluster) or a given industrial solution (such as the assessment of different feedstocks for biogas production). MCA is an effective approach to the systematic analysis of emerging industrial solutions, where a lack of enough

information about features of the system adds to the existing uncertainties and can make decision-making more difficult. Its flexible structure allows the synthesis of both qualitative and quantitative information, which are collected from different sources, including domain experts and other actors related to the industrial development. MCA allows identification and summarization of the most important aspects of a system, and can facilitate strategic decision-making.

Life-cycle assessment (LCA) is an important tool for the systematic investigation of the impacts of industrial activities over their full life-cycle. While in many applications a standalone LCA can lead to useful and reliable results, sometimes LCAs are designed without sufficient understanding of important aspects of the studied system. The robustness and utility of LCA can be considerably enhanced if it is based on a better understanding of the contextual and contingent characteristics of the studied system. Multi-criteria analysis (MCA) and development of relevant criteria and indicators regarding key aspects of the system can provide a good basis for consequent life-cycle assessment. This integrated systems analysis assigns complementary roles to LCA and MCA. MCA allows structuring and synthesis of contextual knowledge about the system; creates an overview of key factors that influence its performance, feasibility and applicability; and can lead to better formulation of scenarios for the LCA. This approach to systems analysis allows better understanding of the studied systems and can lead to the formulation of more realistic and implementable scenarios.

9.1 Future research

The methodological insights gained from this research can be used in studying other industrial cases, particularly in relation to the role of a single industrial activity (cement or biogas production) in improving the overall resource efficiency of a group of inter-related industrial activities. Depending on the nature of the question and the level of understanding about the characteristics of the studied case, multi-criteria analysis, life-cycle assessment, or both (integrated) can be performed. For example, a new eco-industrial development project may consider to add a biogas plant to boost the activities of the existing operations of an industrial cluster. Multi-criteria analysis can be used to identify and assess the potential, feasibility, and resource efficiency (performance) of different development alternatives, and help the decision-makers to focus on the few strategic areas of the

development. Once better understanding of the contingent issues related to potential, feasibility and performance are present, in-depth quantitative analysis of few scenarios can be performed in order to provide more specific knowledge about certain aspects of the eco-industrial development project—for example, better understanding of critical factors and uncertainties that influence nutrient flows, energy balance, or economic performance.

Endnotes

Notes for chapter 1

- i. The term *development* is a keyword (Bennett et al., 2005; Williams, 1988) which in the last decades has been linked to the expansion of market economies, implying a particular meaning of *development as economic growth* (Sachs, 2010). In this thesis, the term *development*, in *eco-industrial development*, is used to refer to the dynamics and changes which can occur within already industrialized spheres in order to increase their environmental and ecological performance. In other words, rather than studying the ways that the horizons of industrialism can expand in general, this thesis is concerned with the ways that existing industrial spheres can transform into more sustainable ones.

Notes for chapter 3

- ii. Prior to 1840, waste had a different meaning: the destruction of something good—such as abusing a piece of fertile land until it becomes unfruitful, or spilling a cup of milk on the kitchen floor. After that time, waste began to be used for referring to different things: the stuff produced in industry that is so “no-good” that it has to be removed and managed at almost any cost. Waste became a mainly economic concept. Pre-industrial peasant societies and towns did not know of this type of waste (Illich, 1991).
- iii. All forms of economics are based on the assumption of scarcity (Robbins, 1932; Samuelson and Nordhaus, 1989; cf. Gustavo, 2010). Economics cannot value what that is not considered as scarce. Economics totally disregards non-scarce phenomena as valueless, and therefore frequently permits them to be severed by the externalities of other economic activities. Ecological economics attempts to fix this issue by redefining them as scarce resources. But this also means the further expansion of economic thinking into traditionally or ecologically non-economic domains. Economic approaches, including industrial ecology, are powerful tools for the analysis of scarce resources, but they should not mask the importance of non-economic domains which have been increasingly under attack by the expanding economic activities of the last centuries. Nevertheless, if the limits of economic thinking are acknowledged and well understood, it can play an important role in the transition toward sustainability.
- iv. “System” is a complicated word with many meanings and applications. It can refer to “a group or set of related or associated *things* perceived or thought of as a unity or complex whole”, or “a set of *persons* working together as parts of an interconnecting *network*”, or “a collection of *artificial objects* organized for a particular *purpose*, as components of a mechanism, roads, architectural features, etc.”, or “a collection of *natural objects, features, or phenomena* considered as or forming a connected or complex

whole” or “a group of *natural objects* moving in relation to one another under the *laws of nature*.” Sometimes system simply means an “orderly arrangement or *method*; systematic form or order” (OED Online, 2016)(emphases are added).

According to system theorists such as Heylighen et al. (1993), a basic definition of system is “a group of units so combined as to form a whole and to operate in unison”, but they add that many other definitions from different philosophical perspectives exist. Some definitions are realist, assuming the existence of the system outside the human mind, as in: “a system is a set of objects together with relationships between the objects”, while others prefer anti-realist definitions, and do not describe the system with objective attributes. They define systems as concepts envisioned by the perceptions and assumptions of people, that is cognitively constructed entities. Regardless of these controversies, Heylighen et al. (1993) enumerate some of the common requirements of a system as: (i) a system consists of several distinct entities called elements; (ii) some kind of relation exists among these elements; and (iii) as a result of this relation, a new, distinct entity, at a new systemic level of analysis emerges.

- v. The issue of complementarity is noted in quantum physics following the works of Niels Bohr (initially in the form of wave-particle duality) (Bohr, 1949), Werner Heisenberg’s uncertainty principle (the limit of simultaneous measurement of paired qualities), and the Copenhagen interpretation that considers everything to be pair-like (dual) and not unitary. However, the historical prevalence of a scientific tradition which seeks causal, unified and orderly kernels in the fabric of the universe, and the rise of the market society (Polanyi, 1944) in which different values are increasingly transformed into money-purchasable commodities (based on a unitary measure of money), make it difficult to take the principle of complementarity seriously. This is particularly so with macro-level phenomena in the economy, technology, politics, and environment. Still, the principle of complementarity may suggest that these macro-realities are also shaped by fundamental complementarity. As Wolfgang Pauli observes (Pauli, 1994, p.260), “modern science [referring to quantum physics] may have brought us closer to a more satisfying conception of the relationship between psyche and physis, by setting up, within the field of physics, the concept of complementarity. It would be most satisfactory of all, if physis and psyche could be seen as complementary aspects of the same reality.” Examples of fundamental complementarities exist in the so-called macro-spheres as well. The least controversial is perhaps the concept of the left and right side of our body, as manifested in our hands, but also in the asymmetric organization of our others. We use our right hand for certain types of activities and our left hand for other types of activities. Although the left and right hands look symmetrical, the activities that we perform by them are asymmetric and complementary. Another example can be found in the psychology of Carl Jung, which posits a complementarity between the conscious and unconscious minds, and in the archetypes of man and woman (McFarlane, 2000; Sanford, 1980; von Franz, 1964). Similarly, Illich (1983) highlights the complementary roles of men and women in all gendered societies throughout history. He speaks of the desirability of restoring a multi-dimensional and complementary balance of human life in relation to our tools and institutions (Illich, 1973) in order to avoid a single mode of production, a single mode of thought, or the radical monopoly of certain institutions (David Cayley, 2014).

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Glossary

Anaerobic digestion The biological degradation of organic matter by anaerobic microorganisms and in the absence of oxygen, which produces biogas (mainly methane and carbon dioxide)

BFS blast-furnace slag

Biodegradable A material that can broken down through biochemical processes, and by microorganisms

Biogas A gaseous mixture of several gases—mainly methane and carbon dioxide—that is produced through anaerobic digestion of organic materials

Blended cement Cement types such as CEM III which contain more than 5 % clinker substitutes.

BRC Biogas Research Center is a center of excellence hosted by Linköping University

CaO calcium oxide

CEM I Portland cement; with clinker content of 95–100 % and up to 5 % of additional constituents.

CEM II Portland composite cement; which is a blended cement with clinker content of 65–94 % and up to 35 % of certain other single constituents.

CEM III Blast-furnace cement; which is a blended cement with clinker content of 5–94 % and higher proportions of blast-furnace slag compared to CEM II cement.

CEM III/A Blended cement with clinker content from 65 % to 94 %.

CEM III/B Blended cement (blast-furnace cement) with clinker content from 20 % to 34 %.

ESA environmental systems analysis

ETM Environmental Technology and Management

Feedstock Mainly organic matter (biomass) which is fed into biobased production systems, such as a biogas plant

GBFS granulated blast-furnace slag

GGBFS ground granulated blast-furnace slag

IE industrial ecology

IS industrial symbiosis

KPI key performance indicator

LCA life-cycle assessment

LCC life-cycle costing

Limestone Limestone is a sedimentary rock and is largely composed of calcium carbonate (CaCO_3) in the form crystal and mineral calcite.

MCA multi-criteria analysis

MFA material flow analysis

OPC ordinary Portland cement

RE resource efficiency

RQ_{1a} Research Question 1_a

RQ_{1b} Research Question 1_b

RQ₁ Research Question 1

RQ_{2a} Research Question 2_a

RQ_{2b} Research Question 2_b

RQ_{2c} Research Question 2_c

RQ₂ Research Question 2

SCM supplementary cementitious material

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Appendix (Articles)

Articles

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