Industrial symbiosis for a low carbon economy

Learnings from the cement industry

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INDUSTRIAL SYMBIOSIS FOR A LOW CARBON ECONOMY

LEARNINGS FROM THE CEMENT INDUSTRY

BY
YANA KONSTANTINOVA RAMSHEVA

DISSERTATION SUBMITTED 2021

AALBORG UNIVERSITET

INDUSTRIAL SYMBIOSIS FOR A LOW CARBON ECONOMY

LEARNINGS FROM THE CEMENT INDUSTRY

by

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AALBORG UNIVERSITY
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Dissertation submitted 2021

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Bulgarian	mother tongue
Russian	moderate
Italian	beginner

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- ✓ SimaPro and OpenLCA
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- ✓ GIS
- ✓ SPSS
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32 years
Bulgarian citizenship
Applied for Danish citizenship
Married to a Dane,
with two children

Hiking
Running
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WORK EXPERIENCE

April 2021
Project leader • NIRAS

Sept 2016 - Feb 2021
Phd Fellow • Aalborg University • Department of Planning

I have conducted academic research within sustainable development, green partnerships and circular economy in collaboration with Aalborg Portland. My work is published in internationally recognized journals.

Sept 2015 - Sept 2016
Sustainability Consultant • Grundfos

I was responsible for the integration of circular economy principles and strategies within the organization, and the development of circular business models in collaboration with external partners.

Sept 2013 - Aug 2015
Grundfos Global Graduate • Grundfos

I was selected from among hundreds of applicants as one of only six candidates for the Grundfos Graduate Program. In an intensive career path, during 2 years, I had the opportunity to work on 4 different projects with a focus on sustainable development across the organization. I also spent six months at one of Grundfos’ subsidiaries in San Diego, CA.

EDUCATION

July 2012 – June 2013
Aalborg language centre, Aalborg, Denmark

I attended an intensive language course, which qualified me for the Danish labour market. I completed the education passing a final test in Danish #3 – required for citizenship.

Sept 2010 - July 2012
Aalborg Universitet, Aalborg, Denmark *Grade: 11,5/12*

MSc. Environmental Management and Sustainability Science

Autumn, 2011
Universitat Autònoma de Barcelona, Barcelona, Spain
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Università Commerciale Luigi Bocconi, Milano, Italy

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Fudan Universitet, Shanghai, China
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“Each one of us make an impact on the planet every single day and we can choose what sort of impact we want to make”

Dr. Jane Goodall

ENGLISH SUMMARY

Through studying the cement industry, this research aims to further academic knowledge and public awareness on how industries could reach carbon neutrality. The environmental impact of the construction sector is growing due to rising population and urbanisation. Cement is a widely used building material due to its performance, cost, and availability, but its production process is highly energy intensive and emits vast amounts of greenhouse gases. The sector faces major challenges with meeting the climate target of the European Union (EU) on reaching carbon neutrality by 2050.

Industrial symbiosis is considered central for transitioning industries towards a low carbon economy. Industrial symbiosis is about establishing partnerships for the exchange of diverse waste, by-products and information between industries. Today, industrial symbiosis between cement producers and other industries contributes to the reduction of waste and greenhouse gas emissions. Such cross-sector partnerships are widely seen as a prime facilitator for circular economy, which as a development strategy has the potential to decarbonize the industry. Thus, understanding the role of industrial symbiosis in the cement industry may help to unveil knowledge on how to transition towards a low carbon economy, in cement production as well as in other industries. The main research question of this dissertation reads:

What new knowledge can be gained from the cement industry on the role of industrial symbiosis for realizing a low carbon future?

The main research question is answered through four sub-questions, which are explored in five academic papers on the following themes of industrial symbiosis: value potentials, constrains, prerequisite and the need to apply a system perspective in realizing circular economy strategies. Aalborg Portland, the single grey and white cement producer in Denmark, was the main source of data for the academic studies.

The first paper analyses industrial symbiosis value potentials through a case study on twelve industrial symbioses at Aalborg Portland. Results show value potentials of economic and resource character. Yet, it is found that value potentials of socio-economic and political character also exist in particularly local industrial symbiosis partnerships. The findings advance the understanding of the role of industrial symbiosis by identifying value potentials of such diverse character.

Industrial symbiosis constraints are analysed in the second paper through a study on the excess heat supply to the district heating network of Aalborg. Legal and economic constraints were found to hinder the carbon footprint reduction potential of the district heating network by up to 93%. Yet, lifting those constraints and sourcing more excess heat from industry could result in more than a 40% price increase in comparison to current heat prices. This relationship between substantial environmental potentials at the expense of high increases in heating prices calls for a political and academic discussion on the role of industrial symbiosis in developing local, sustainable heating sources for a low carbon future.

Trust is considered a prerequisite for establishing industrial symbiosis partnerships. The third paper offers a conceptual framework on developing trust, which may be useful for firms to understand the complexity of inter-organizational relationships and the central role that trust may have as a prerequisite for establishing collaborative activities.

The fourth and fifth papers concern applying a broader ‘system’ perspective on the concrete industry value chain as opposed to merely a product perspective on cement. The fourth paper presents the state-of-the-art literature on circular economy strategies for the concrete industry. The fifth paper presents a conceptual framework on 'product', 'service' and 'system' levels as a tool for realizing circular economy strategies. The framework is applied to the case of the Danish concrete industry, and it is found that especially a broad ‘system’ perspective supports realizing circular economy strategies through stakeholder collaboration across the value chain. This calls for the establishment of learning platforms across value chains, which are based on stakeholder collaboration and common goals.

Returning to the main research question, it is found across the five papers that new knowledge was generated from the case on the role of industrial symbiosis in transitioning toward a low carbon economy. This research contributes to the academic literature and field of industrial symbiosis by further diversifying the understanding of value potentials, by assessing legal and economic constraints, by conceptualizing trust as a prerequisite, and by both conceptualizing and exemplifying the need for collaboration across the value chain on a ‘system’ level.

DANSK RESUME

Forskningen bag denne afhandling bygger på studier fra cementindustrien og har til formål at udbygge både det nuværende vidensniveau og den offentlige bevidsthed om, hvordan vi som samfund opnår CO_2-neutralitet. Byggesektoren har en stigende miljøpåvirkning som følge af befolkningstilvækst og urbanisering. Cement er et populært byggemateriale grundet dets byggetekniske egenskaber, lave pris og almene tilgængelighed, men dets produktion er energikrævende og en kilde til store udledninger af drivhusgasser. Sektoren står derfor overfor betydelige udfordringer med at efterleve EU's målsætning om CO_2-neutralitet i 2050.

Industriel symbiose betragtes bredt som en et centralt redskab i den grønne omstilling af industrien mod målet om en mindre klimapåvirkende økonomi. Industriel symbiose handler om at etablere partnerskaber mellem industrivirksomheder, hvorigennem der udveksles affaldsfraktioner, biprodukter og viden. Allerede i dag bidrager industriel symbiose mellem cement producenter og andre industrier til reduktion af både affald og drivhusgasser. Sådanne partnerskaber på tværs af sektorer er bredt anerkendt som en facilitator for cirkulær økonomi, der som strategi har et stort potentiale i forhold til at sænke industriers CO_2-udledning. Derfor kan en bedre forståelse af industrielle symbiosers rolle i cementindustrien bidrage med viden om den grønne omstilling mod en mindre klimabelastende fremtid; for cementproduktion såvel som for anden industri. Afhandlingens primære forskningsspørgsmål lyder derfor:

Hvad ny viden kan opnås fra cementindustrien om industrielle symbiosers rolle i realiseringen af en mindre klimabelastende fremtid?

Afhandlingens primære forskningsspørgsmål besvares gennem fire underspørgsmål i fem videnskabelige artikler, der omhandler de følgende aspekter af industriel symbiose: potentialer for værdiskabelse, barrierer, forudsætning og behovet for at anvende et systemisk perspektiv i realiseringen af strategier indenfor cirkulær økonomi. Cementproducenten Aalborg Portland var den primære kilde til data i alle studierne.

I den første artikel analyses der potentialer for værdiskabelse gennem et casestudie af tolv industrielle symbioser ved Aalborg Portland. Som forventet blev der fundet potentialer for økonomisk og ressourcemæssig værdiskabelse. Der blev dog tillige fundet potentialer af socioøkonomisk og politisk karakter i specielt lokale partnerskaber. Resultaterne udbygger den eksisterende viden om industrielle symbiosers rolle med netop denne diversificering af potentialerne for værdiskabelse.

I den anden artikel analyseres der barrierer for industrielle symbioser gennem et studie om levering af overskudsvarme til fjernvarmesystemet i Aalborg. Det blev fundet, at juridiske og økonomiske barrierer forhindrer en reduktion af fjernvarmenetværkets CO_2-fodspor på op til 93%, men at en ophævelse af disse barrierer med øget overskudsvarme til følge ville kunne resultere i en prisstigning på over 40% i forhold til de nuværende varmepriser. Dette forhold imellem store potentielle miljømæssige besparelser på bekostning af tilsvarende store prisstigninger for fjernvarme nødvendiggør en videre politisk og akademisk diskussion om industrielle symbiosers rolle i udviklingen af lokale bæredygtige kilder til fjernvarme.

Gensidig tillid mellem parter er en forudsætning for at etablere industrielle symbioser. I den tredje artikel udvikles der en konceptuel analyseramme for udvikling af tillid, der kan hjælpe firmaer med at forstå kompleksiteten i tvær-organisatoriske samarbejder og deraf den centrale rolle netop tillid har som forudsætning for udviklingen af samarbejder.

Den fjerde og femte artikel omhandler anvendelsen af et systemisk perspektiv for betonsektorens værdikæde fremfor udelukkende et produktorienteret fokus på cementproduktion. Artikel fire præsenterer det nuværende vidensniveau i den videnskabelige litteratur om strategier for cirkulær økonomi i betonsektoren. I artikel fem udvikles der en konceptuel analyseramme for et produkt-, service- og systemniveau, der kan anvendes som redskab til at realisere strategier indenfor cirkulær økonomi. Analyserammen anvendes på et casestudie af den danske betonsektor, og det ses heraf, at netop det brede systemiske perspektiv muliggør realisering af cirkulær økonomi gennem samarbejder på tværs af værdikæden. Dette peger på et behov for udvikling af nye udviklingsfællesskaber på tværs af værdikæder, der baseres på samarbejde om fælles mål.

Vendes der tilbage til afhandlingens primære forskningsspørgsmål, kan det konkluderes på tværs af de 5 artikler, at det har været muligt at opnå ny viden gennem den analyserede case om industrielle symbiosers rolle i den grønne omstilling mod en mindre klimabelastende fremtid. Afhandlingens forskning bidrager til den akademiske litteratur og praksis om industrielle symbioser ved at diversificere forståelsen af potentialerne for værdiskabelse, ved at analysere juridiske og økonomiske barrierer, ved at konceptualisere tillid som en gengående forudsætning samt ved både at konceptualisere og eksemplificere behovet for at samarbejde på tværs af værdikæder på et systemisk niveau.

БЪЛГАРСКО РЕЗЮМЕ

Чрез изучаване на циментовата индустрия, този дисертационен труд има за цел да повиши академичните знания и обществената информираност, относно достигане въглероден неутралитет свързан с индустриална дейност. Строителният сектор увеличава въздействието си върху околната среда, което се дължи на нарастващото население и урбанизация. Циментът е широко използван строителен материал поради своите характеристики, цена и висока наличност, но процесът на производство е силно енергийно интензивен и отделя огромно количество емисии на парникови газове. Секторът е изправен пред големи предизвикателства за постигане на целта на Европейския съюз (ЕС) за намаляване на парниковите газове и за постигане на неутралност по отношение на климата до 2050 г.

Счита се, че индустриалната симбиоза играе централна роля за прехода на индустриите към достигане въглероден неутралитет. Индустриалната симбиоза е свързана с установяването на партньорства за обмен на различни отпадъци, съпътстващи продукти и информация между индустриите. Индустриална симбиоза между производителите на цимент и други индустрии, допринася за намаляване нивото на отпадъчните потоци, както и за намаляване на емисиите на парникови газове. Този тип междусекторни партньорства са широко разглеждани като основно средство за развитие на т.н. “кръгова икономика”, тъй като те предлагат стратегия за постигане на въглероден неутралитет свързан с индустриална дейност.

Изучаване на ролята на индустриалната симбиоза в контекста на циментовата индустрия може да спомогне за разкриване на нови знания за това как да се намали количество емисии на парникови газове свързани с производството на цимент, както и с други индустриални дейности. Основният изследователски въпрос на тази дисертация гласи:

Какви нови знания могат да бъдат получени от изучаване на циментовата индустрия относно ролята на индустриалната симбиоза за реализиране на ”нисковъглеродно бъдеще”?

Основният изследователски въпрос е свързан с четири под-изследователски въпроса, които са изследвани в пет академични статии, които разглеждат следните аспекти на индустриалната симбиоза: потенциали, бариери, предпоставка и необходимостта от прилагане на ’системна’ перспектива при реализиране на стратегии за кръгова икономика. Олборг Портланд, единственият производител на сив и бял цимент в Дания, е основният източник на данни за извършените академичните изследвания.

Първата статия анализира дванадесет индустриални симбиози в Олборг Портланд и изучава тяхната потенциална значимост. Резултатите от анализа показват потенциална значимост от икономически и ресурсен характер. Въпреки това е установено, че съществува и потенциална значимост от социално-икономически и политически характер, особено що се отнася до партньорства в близък географкси план. Получените резултати допринасят с нови знания за ролта на индустриалната симбиоза, чрез идентифициране на потенциалната ѝ значимост от много разнообразен характер.

Бариерите свързани с развитието на индустриалната симбиоза се представят във втората академична статия. Анализива се излишната енергия от производсвтото на цимент, която се усвоява от мрежата за топлофикация на Оолборг. Установява се, че правни и икономически бариери възпрепятстват потенциала за намаляване на въглеродния отпечатък на централната топлофикационна мрежа с до 93%. Премахването на тези ограничения и снабдяването с повече излишна топлина от промишлената индустрия може да доведе до повече от 40% увеличение на цената на топлофикация, в сравнение с настоящата цена. Тази връзка между значителния потенциал, който излишната енергия от индустриалната дейност предоставя за сметка на увеличенията на цените за отопление, изисква както политическа, така и академична дискусия. Тази дискусия трябва да се фокусира върху ролята на индустриалната симбиоза за развитието на местни, устойчиви източници за отопление, за да се постигне бъдеще с ниски въглеродни емисии.

Доверието се счита за предпоставка при установяване на партньорства в контекста на индустриалната симбиоза. Трерата академична статия предлага концептуална рамка за развиване на доверие. Тази концептуална рамка може да бъде полезна за осъзнаване сложносста на отношенията между организациите, както и за централната роля, което доверието има като предпоставка за установяване на съвместни дейности.

Четвъртата и петата академична статия са свързани с прилагането на по-широка „системна“ перспектива върху веригата на стойността на конкретната индустрия, за разлика от досегашния фокус върху цимента основно като продукт. Четвъртата статия представя литература за стратегиите на кръговата икономика за конкретната индустрия. Петата статия представя концептуална рамка за нивата „продукт“, „услуга“ и „система“ като инструмент за реализиране на стратегии за кръгова икономика. Концептуалната рамка е приложена върху случай от датската бетонна индустрия. Установява се, че особено широката „системна“ перспектива подкрепя реализирането на стратегии за кръгова икономика чрез сътрудничество между заинтересованите страни по веригата на стойността. Това изисква създаването на платформи за общуване и придобиване на нови знания, които се основават на сътрудничеството между заинтересованите страни, както и на общи цели.

Връщайки се към основния изследователски въпрос, чрез петте статии се установява, че изследователската дейност допринася с нови знания за ролята на индустриалната симбиоза при прехода към нисковъглеродна икономика. Този дисертационен труд допринася за академичната литература и областта на индустриалната симбиоза чрез по-нататъшно диверсифициране на разбирането за потенциална значимост, чрез оценка на правни и икономически бариери, чрез считане на доверието като предпоставка, както и чрез концептуализиране и илюстриране на необходимостта от сътрудничество по веригата на стойността на „системно“ ниво.

PREFACE AND ACKNOWLEDGEMENTS

This dissertation is the result of a three-year PhD fellowship at the Sustainability Innovation and Policy (SIP) research group, Department of Planning at Aalborg University. In September 2016, I began my PhD work, which was interrupted by two 10-month maternity leave periods in 2017 and 2019/2020, respectively. I finalized the PhD thesis in February 2021.

My passion for sustainability began back in 2009, when during my bachelor studies in Milan, I joined the non-governmental student organization ‘Green Light for Business’. I am deeply thankful for the opportunity to be part of a team of young students and professionals driven by sustainable innovation. I decided to continue my studies at Aalborg University, where I obtained a M.Sc. degree in Environmental Management and Sustainability Science in 2012. After a few years working within the Danish industry, I gained further motivation to dive into academic research within the sustainability field, and went back to university.

I had the pleasure to receive a PhD fellowship in collaboration with the cement company Aalborg Portland and Manufacturing Academy Denmark (MADE). I would like to express my sincere gratitude to Aalborg University, MADE and Aalborg Portland for selecting me as a PhD candidate for this research project and for giving me the opportunity to explore how energy-intensive industries can make the transition towards more sustainable practices.

I have been lucky to have a team of three supervisors, who provided incredible support throughout the PhD process. I am grateful to prof. Arne Remmen for his valuable help and guidance from the start to the end of this long journey. Arne’s genuine kindness and positive mind-set was most needed during the long paper review processes and revision of the thesis chapters. Furthermore, I would like to thank prof. Brian Vejrum Wæhrens for his professional supervision and valuable comments to my work, as well as for his efforts in establishing numerous study circles where researchers can feel involved, share knowledge and insights. Last, but not least, I would like to thank assoc. prof. Rebeka Kovačič Lukman for her support and helpful input during the last few months before delivering my dissertation.

My research work had a steep learning curve, filled with unforgettable memories, numerous exciting and at times stressful moments. I thank all my colleagues at Department of Planning and especially at SIP. Special thanks go to assoc. prof. Søren Kerndrup, for his professional feedback to my research. Thanks to all peers at the ‘SIP PhD office’ and to the researchers at Centre of Industrial Production (CIP) for the end-less “circular economy” discussions and ‘hygge’- chats.

I would like to thank Romain Sacchi and Ernst-Jan Prosman for the fruitful collaboration and friendship. The same goes for Rikke Marie Moalem and Leonidas Milios – it was an extreme pleasure to conduct research with you both, despite only meeting online.

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Last, but not least, I would like to thank my Bulgarian and Danish family, my children Helena and Bjørn, and all my friends, for their unconditional support and care. Exceptional gratitude goes to my husband, Morten, for always believing in me, for his help and encouragement, and endless mid-night academic discussions. I could not have done this without you!

Yana K. Ramsheva
February 2021
Aalborg

LIST OF PUBLICATIONS

Paper I. **Ramsheva, Y.K.**, Remmen, A., Industrial symbiosis in the cement industry - Broader value potentials and linkages to circular economy.
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An initial version of this paper was presented at the 2018 TMBCE Conference and published in the peer-reviewed conference proceedings *Technol. Bus. Model. Circ. Econ*. 35–53. https://doi.org/10.18690/978-961-286-211-4.4 **Chapter 4**

Paper II. Sacchi, R., **Ramsheva, Y.K.**, 2017., The effect of price regulation on the performances of industrial symbiosis: a case study on district heating. *Int. J. Sustain. Energy Plan. Manag*. 14, 39–56.
https://doi.org/10.5278/ijsepm.2017.14.4 **Chapter 5**

Paper III. **Ramsheva, Y.K**., Prosman, E.J., Wæhrens, B.V., 2019., Dare to make investments in industrial symbiosis? A conceptual framework and research agenda for developing trust. *J. Clean. Prod.* 223, 989-997.
https://doi.org/10.1016/j.jclepro.2019.03.180 **Chapter 6**

Paper IV. **Ramsheva, Y.K**., 2019.**,** Applying the principles of CE in the context of concrete: A review. *Proceedings of the 19th European Roundtable for Sustainable Consumption and Production (ERSCP 2019)*
Institute for Sustainability Science and Technology, Universitat Politècnica de Catalunya, Barcelona, pp. 219–228. **Chapter 7.1**

Paper V. **Ramsheva, Y.K.**, Moalem, R.M., Milios, L., 2020., Realizing a circular concrete industry in Denmark through an integrated product, service and system perspective. *Sustainability* 12, 9423.
https://doi.org/10.3390/su12229423 **Chapter 7.2**

CONTRIBUTION REPORT

Paper I. Main author. Main contributor to data collection, data interpretation, discussion, manuscript revision.

Paper II. Second author. Main contributor to literature review, data collection, manuscript draft, final manuscript revision.

Paper III. Main author. Main contributor to literature review, conceptual framework development, data collection, data interpretation, discussion, proposal for future agenda, manuscript revision.

Paper IV. Sole author.

Paper V. Main author. Main contributor to conceptual framework development, data collection, data interpretation, discussion.

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CHAPTER 1. INTRODUCTION

This chapter briefly introduces the context within which this research is conducted, the research aim and the raised research questions. A reading guide for the PhD dissertation is also provided.

1.1. THE LIMITS OF MODERN SOCIETY

The industrial revolution about two hundred years ago led to the introduction of highly mechanised and efficient production processes (Stahel and Reday-Mulvey, 1981). Those brought economic welfare of industrialised societies at the cost of the environment. The economic growth model is to a large extent characterised by a linear flow of resources as a 'one-way' stream of 'take-make-dispose' (Ghisellini et al., 2016; Stahel, 1982) and relies on fossil fuels and infinite resource supply, making it unsustainable in the long run (Korhonen et al., 2018). The mass production, oversupply of goods and their disposal after relatively short period of usage demands resource and energy, and poses severe challenges among which are resource depletion, carbon emissions and waste accumulation (UN Environment, 2019). Today, the linear economy model is still dominating as the global annual demand for materials is estimated at about 90Gt and expected to double in the next 40 years (OECD, 2019). Such an increase in resource use would lead to a rise of global greenhouse gas (GHG) emissions, putting the ambitions of the Paris Climate Agreement for staying "well below the 2 degrees" and for keeping a sustainable global economy under question (WBCSD, 2018).

In search for solutions for decoupling growth from resource use, the idea of re-circulating resources in the economy emerged (Frosch and Gallopoulos, 1989; Giarini and Stahel, 1993). Yet, the idea of material flows in closed circles is not new. Back in 1966, Boulding (1966) suggested viewing the Earth as a closed system in which, except for energy, the availability of resources can be considered constant and waste can be assimilated to a certain extend by the natural environment. This idea of a closed system has been acknowledged by Meadows et al. (1972), Pearce and Turner (1989) and later by Rockström et al. (2009).

Thereafter, the term "circular economy" gained further momentum by the think-tank Ellen MacArthur Foundation, which presented a renowned definition of the concept. Circular economy is considered based on the basic principles of nature, aiming at closed-loop flow of resources and keeping them at their highest possible value for as long as possible (Ellen MacArthur Foundation, 2012). Ellen MacArthur Foundation (2013) defined circular economy as:

> *"…an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models"*

A number of principles and strategies, which support realizing the potentials of circular economy, are unfolded in section 2.2. Collaboration across sectors and establishing partnerships between stakeholders along the value chain are considered crucial in making a radical shift from optimizing the currently established linear production and consumption patterns, towards building a system based on circular solutions (Adams et al., 2016)

This PhD study focuses on the role of inter-organizational partnerships for facilitating circular economy principles and strategies that can subsequently lead to carbon emission reductions. The PhD project is financed by Aalborg University and is conducted in cooperation with a research and innovation platform MADE (Manufacturing Academy of Denmark). In the course of the PhD project, the Danish cement company Aalborg Portland became primary source of data for three of the studies and was an inspiration for two more studies that are part of this dissertation.

The next section introduces the role of the cement industry for today's society and elaborates on the pressing need for more circular solutions that support carbon neutrality.

1.2. THE CEMENT INDUSTRY IN A LOW CARBON ECONOMY

By 2050, the world population is expected to rise to 10 billion people and an expansion of the middle class, followed by urbanisation and formation of megacities, will occur with a more rapid speed than happening today (UN Environment, 2019). Those trends will place the building sector in a central role, and if strategies for improving resource efficiency and emissions reduction are absent, the impact of buildings and building materials is only expected to increase (OECD, 2019).

Due to the rising population and urbanisation, the role of the built environment is growing, and with it, also is the use for cement. Cement is the key ”ingredient” in concrete, binding the aggregates together. Cement is a preferred building material due to its technical performance, cost-efficiency, wide availability (Damtoft et al., 2007). In only a decade, the use of cementitious materials has tripled (Scrivener et al., 2017). This trend is expected to last, as the demand for cement is estimated to increase by 12-23% by 2050 comparted to today's numbers (IEA, 2018).

Despite the numerous advantages of cement, the industry is facing a major challenge in meeting the ambitions of a low carbon global future. Cement production is considered an energy-intensive industry (Boesch et al., 2009; Van Oss and Padovani, 2002), alike the sectors of steel, iron, aluminium, fertilisers, plastics, power generation, paper pulp (Åhman et al., 2017). Each stage of the cement production requires energy especially for the calcination of limestone, during which clinker is made. That generates emissions both from the combustion of fuels and from the release of CO_2 locked in chalk when heating the material up. Together energy-intensive industries account for 15% of the total GHG emissions of the European Union (EU) (IES, 2018). Energy-intensive industries, and as such the cement industry, aim at achieving the ambitions for a carbon-neutral economy. Since the 1990s, energy-intensive industries have managed to reduce their direct emissions by more than 35%, mainly by moving away from the use fossil fuels and improving energy efficiency of production processes (IES, 2018).

As a respond to the increasing need to face the resource challenges, the Cement Sustainability Initiative (CSI) was launched in cooperation between the World Business Council for Sustainable Development (WBCSD) and the Global Cement and Concrete Association (GCCA). Today, CSI involves the world's largest cement and concrete producers. The aim of the partnership is to facilitate more sustainable and resource-efficient development of the cement and concrete production and of the respective value chains of the sector (WBCSD, 2020).

As part of the European Green Deal for transforming the European Union (EU) into a more sustainable economy, the European Commission (EC) presented a number of proposals and action plans that affect the future of the cement industry. "A new Industrial Strategy for a globally competitive, green and digital Europe", published in March 2020, sets ambitious goals for carbon neutrality by 2050 (European Commission, 2020a). Also in March 2020, the new "EU Circular Economy Action Plan" directed attention on the need to scale up circular economy for *"achieving climate neutrality by 2050 and decoupling economic growth from resource use while ensuring the long-term competitiveness of the EU and leaving no one behind*" (European Commission, 2020b).

As a respond to the set EU goals, the European Association of Cement Producers, Cembureau, presents a position paper stating that *"circular economy goes hand in hand with carbon neutrality"* (Cembureau, 2020a). A report by the Swiss Federal Institute of Technology (ETHZ) assesses the potentials of the European cement and concrete industry to reach full decarbonisation by 2050. Results from the conducted study highlight that if all stages in the cement value chain are considered and relevant stakeholders act collaboratively, emission reductions of up to 80% in comparison to 1990 levels could be achieved by 2050, even without carbon capture and storage (CCS) technologies in place (Favier et al., 2018).

Lowering the environmental impact of cement production supports the principles and strategies of circular economy in diverse ways. Cembureau's vision for reaching carbon neutrality by 2050 include an integrated focus on a number of areas (Cembureau, 2020b). Firstly, emissions associated with fuel consumption account for about 40% of the total CO_2 emissions from production of clinker (Favier et al., 2018; Sacchi, 2018). At present, about half of this fuel demand can be satisfied by alternative fuels (Cembureau, 2020b). Since the 1970s it has been possible to partially substitute conventional fuels and clinker content in cement with waste and by-products from other industries, which can act as alternative fuels and raw materials in the production of cement (Yap and Devlin, 2017). This utilization of wastes and by-products from other industries is known as industrial symbiosis (Chertow, 2000). Today, industrial symbiosis plays a central role for the cement industry, enabling the reduction of waste volumes in general, and support lowering GHG emissions associated with cement production (Hashimoto et al., 2010; Iacobescu et al., 2016; Martin et al., 2015; Supino et al., 2016)

Secondly, Cembureau (2020b) underlines the need for further improvements of the thermal efficiency of cement kilns and electrical efficiency of cement production through upgrading the design of existing preheaters and kilns, recover heat from production, generate renewable energy at cement cites. Such improvements are needed as the consumption of energy is expected to increase if carbon capture, utilization and storage (CCUS) technology is to be implemented (IPCC, 2018).

Thirdly, new cement types with lower clinker content or non-cement based binders need to be developed. There are already several innovative cement types on the market, showing a carbon footprint reduction of about 30% compared to Ordinary Portland Cement (CEM I) (Cementir Group, 2020; European Commission, 2014).

Fourthly, since cement is used as a main "ingredient" in construction of buildings (Supino et al., 2016), there is a need to implement improvements beyond the gates of the cement production plant. Future buildings need to be more energy efficient, designed to be flexible and adaptable to existing needs, deconstructed instead of demolished at end-of-use (Cheshire, 2016). Those circular economy principles demand a shift of focus from the product (cement) towards the whole (building) when improvements are to be implemented. The entire life cycle of buildings and the involved stakeholders along the value chain need to be considered (Leising et al., 2018).

Lastly, between 5-20% of the CO_2 is emitted during the production of cement, and is very slowly re-absorbed by concrete during its use phase through the natural process of recarbonation (Cembureau, 2020a). Research indicates that proper concrete waste sorting and recycling can ease the recarbonation process further, as more CO_2 can be absorbed through recycled concrete aggregates due to their large surface area (Cembureau, 2020b).

Through the course of this PhD study, the topic of industrial symbiosis became central for accessing the opportunities for transitioning the cement industry towards a low carbon economy. Aalborg Portland, the single grey and white cement producer in Denmark, was a main source of data for the conducted academic studies. In fact, this PhD project is part of a wide agenda on industrial symbiosis in the Danish cement industry. That incorporates research within new supply chain capabilities that industrial symbiosis demand (Prosman, 2018), as well as industrial symbiosis as an opportunity to lower environmental footprint associated with cement production (Sacchi, 2018). Details about the company and their activities towards more sustainable cement production are presented in section 1.3.

1.3. THE CASE OF AALBORG PORTLAND

Aalborg Portland was established over 125 years ago and is located in Aalborg, northern Denmark. The cement factory and surroundings can be seen in figure 1.1 and figure 1.2. The company is part of Cementir Holding, a large corporate group, which owns cement and concrete production sites around the world.

Figure 1.1. Aalborg Portland cement factory with access to Limfjorden. Image sourced from Aalborg Portland archive

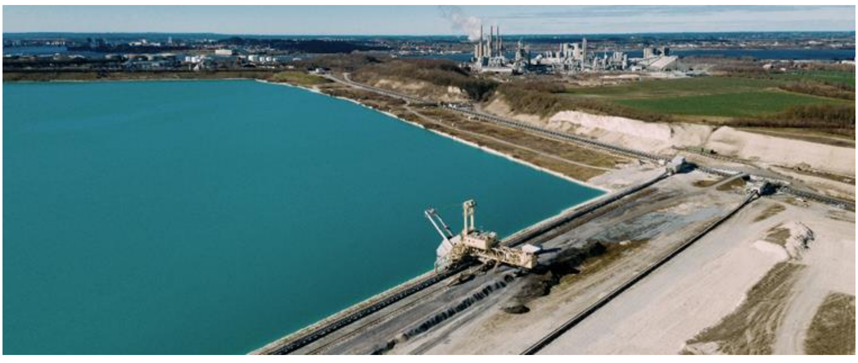

Figure 1.2. Aalborg Portland chalk pit. Image sourced from Aalborg Portland archive

Being the world's largest white cement producer and having a wide array of both grey and white cement products, Aalborg Portland is Denmark's single largest CO_2 emitter. The cement production process is highly energy demanding. The cement production process is illustrated in figure 1.3.

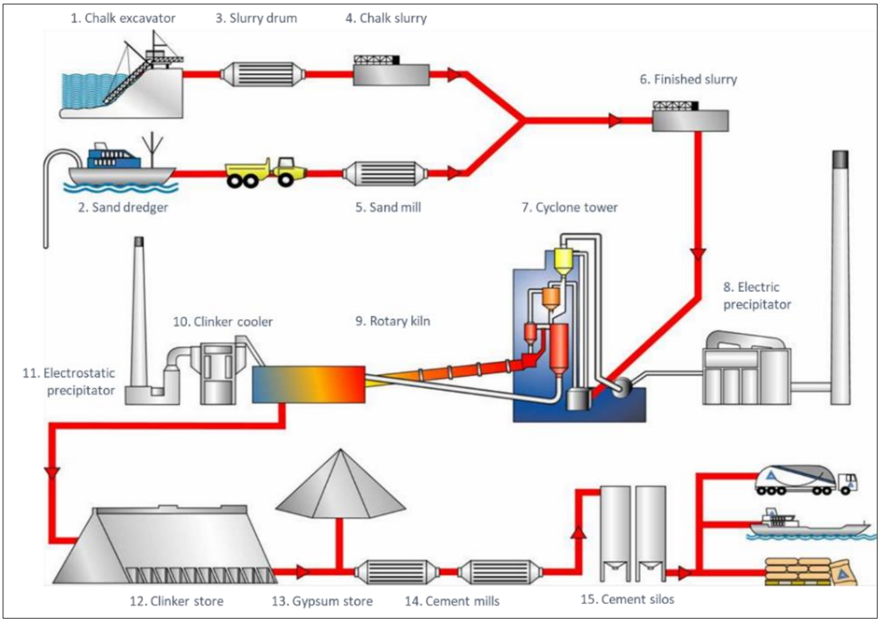

Figure 1.3. Representation of the cement production process at Aalborg Portland. Adapted from Aalborg Portland (2016)

The excavated limestone is sourced from a nearby quarry, making the process a semi-dry one, meaning that additional energy is required to vaporize the water in the limestone. A mix of limestone and sand are calcinated in kilns gradually heated up to 1500 degrees Celsius, and as a result, clinker is produced. Cement is then produced by blending clinker with gypsum.

Aalborg Portland has the capacity to produce about two million tons of clinker per year, and the demand for fuel for production of that clinker accounts for 14% of the overall energy demand of Danish industries (Sacchi, 2018). Half of the GHG emissions generated by Aalborg Portland are linked to the use of fuels. The other half is associated with the process of clinker production when limestone is heated and CO_2 locked inside is released.

The EU emission trading system (EU ETS), also known as the 'cap-and trade' system, covers the energy intensive sector. That puts certain restrictions on Aalborg Portland in terms of the yearly GHG emissions that the company is permitted to generate.

Each year, the overall number of GHG allowances slowly decreases as a way to motivate companies to reduce their emission levels. Furthermore, in 2020 the Danish parliament adopted a Climate law with legally binding targets for all sectors, putting pressure especially on energy-intensive industries. A main objective of the Climate law is GHG emissions to be reduced by 70 per cent by 2030 compared to 1990s levels, climate-neutrality to be achieved by 2020 and by that keep up to Paris Agreement's objectives (Danish Ministry of Climate, 2020).

As a respond to the current political ambitions for low-emission society and industry, Aalborg Portland recently published a "Roadmap for sustainable cement production in Denmark". The company sets a goal of a 30% reduction of CO_2 levels by 2030 compared to 1990 levels that account for savings of about 660.000 tons of CO_2, with a further ambition of achieving carbon-neutrality by 2050 (Aalborg Portland A/S 2020). Cutting emissions is considered possible by substituting conventional fuels with alternative fuels, replacing chalk with alternative materials, as well as by establishing collaboration with stakeholders along the whole value chain of the construction industry – distributors, concrete producers, construction companies, etc. (Aalborg Portland A/S 2020). Aalborg Portland has also been investing in research and development of new green cement types – FutureCem, which through clinker replacement, brings reduction of CO_2 associated with production of more than 30% per tonne of cement compared to ordinary Portland cement (Cementir Group, 2020)

Aalborg Portland considers industrial symbiosis plays a central role as a way forward in achieving those ambitions. The company has already established industrial symbioses for sourcing diverse wastes and by-products from close and distant partners. Those industrial symbioses partnerships aim at minimizing the emissions from the production of cement and help reduce waste quantities. Today, the company satisfies 28% of its demand for fuel through the use of 200.000 tons of alternative fuels, as well as 450.000 tons of alternative raw materials (Aalborg Portland A/S, 2019). Diverse waste fractions from industry, dried sewage sludge, meat and bone meal are utilized as alternative fuel sources. Since waste from biomass is considered a CO_2-neutral source of fuel, 100% of the alternative fuels for Aalborg Portland white cement production is already from biomass (Aalborg Portland A/S, 2019; Sacchi, 2018). FGD gypsum, fly ash, iron oxide are only some of the exchanged resources utilized as alternative raw materials.

A number of local industrial symbioses (i.e. occurring in close geographical proximity) place Aalborg Portland in a central for local resource exchanges, see figure 1.4. Some of the resources are constrained in supply due to the demand and level of consumption for the primary product that they originate from. Recovery and utilization of excess heat from industries is one of the primary local "resources" exchanged through industrial symbiosis.

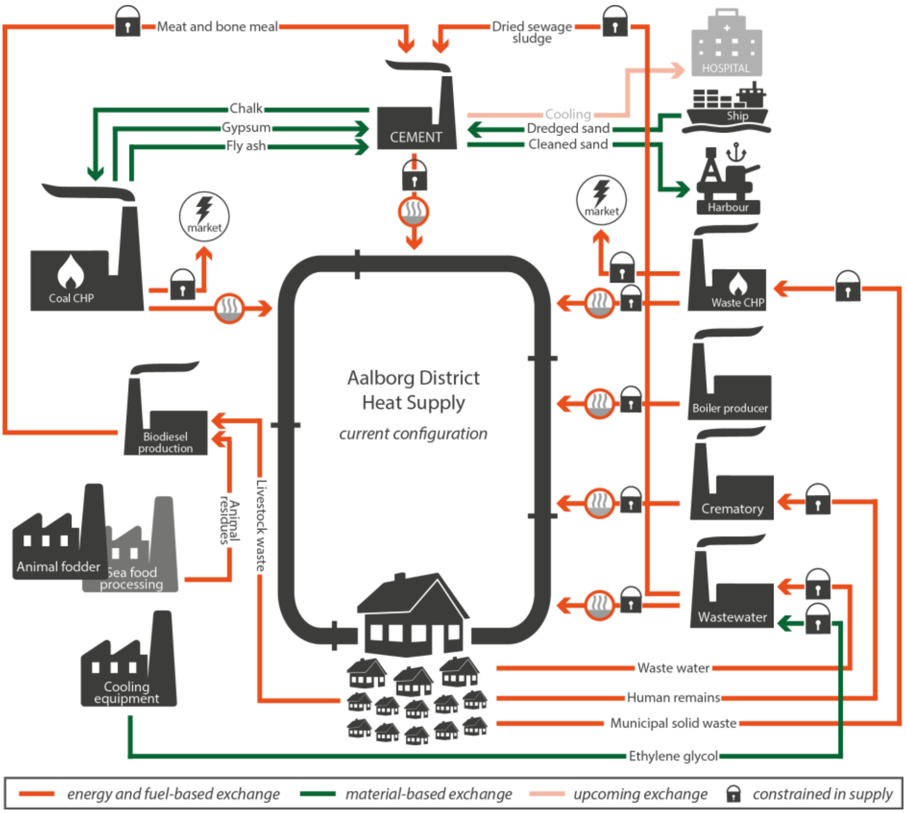

Figure 1.4. Resources (materials and energy) exchanged through industrial symbiosis in the industrial area of Aalborg. Sourced from Sacchi and Ramsheva (2017)

Among others, Aalborg Portland is a major supplier of excess thermal energy as heat to the local district heating network of Aalborg. This industrial symbiosis partnership, between the cement company and the local utility company was established back in 1970s and covers the demand of 25.000 households, with the potential to double that supply in the future (Aalborg Portland A/S, 2019). District cooling is soon to be supplied through an industrial symbiosis partnership. Cold water will be sourced from the chalk quarry for cooling purposes of the new regional university hospital.

Further potentials of industrial symbiosis partnerships for the cement industry, and more specifically – for Aalborg Portland, will be unfolded in the conducted academic studies, included in Chapter 4, 5 and 6. Chapter 7 would provide an analysis on how a broader 'system' perspective, beyond the value chain of cement production, could help realize circular economy strategies, support collaboration and joint action towards decarbonizing the economy.

1.4. AIM OF THE PHD STUDY

Collaboration between actors along the whole value chain is regarded important for operationalising the potentials of circular economy (Brown et al., 2019). Cross-sector partnerships, such as for example industrial symbiosis, are considered a prime facilitator for circular economy principles and strategies, which in turn have the potential to decarbonize the economy (European Commission, 2020b; Konietzko et al., 2020a).

This PhD study aims to further broaden academic research and public awareness on how industries could reach carbon neutrality through analysis of the cement industry in Denmark, in terms of current collaborative circular activities and future plans. Understanding the role of industrial symbiosis in that context demands further exploration. In line with the aim of the PhD study, the following main research question is raised:

What new knowledge can be gained from the cement industry on the role of industrial symbiosis for realizing a low carbon economy?

The main research question is further explored through four sub-questions, which focus on analysing industrial symbiosis partnerships in terms of their value potentials (sub-Q1), constrains (sub-Q2) and prerequisite (sub-Q3). The last sub-question aims at analysing the role of collaboration when broadening the perspective from the ‘product’ cement towards a ‘system’ perspective when realizing circular economy principles and strategies (sub-Q4).

Table 1.1. presents the research sub-questions, which are answered through five academic papers. The knowledge gaps that each of the four sub-questions aim to address are presented further in Chapter 2.

Table 1.1. Overview of research sub-questions and related publications

Research sub-question	**Related publication**		**Authors**	**Year published**
sub-Q1: What value potentials does industrial symbiosis offer the cement industry?	Paper I	Industrial symbiosis in the cement industry - Broader value potentials and linkages to circular economy *J. Clean. Prod.*	Ramsheva, Y.K., Remmen, A	Accepted, subject to revision
sub-Q2: To what extend do legal and economic constraints hinder the full deployment of industrial symbiosis potentials for carbon footprint reductions of the cement industry?	Paper II	The effect of price regulation on the performances of industrial symbiosis: a case study on district heating *Int. J. Sustain. Energy Plan. Manag.*	Sacchi, R., Ramsheva, Y.K	2017
sub-Q3: How to develop trust when setting up industrial symbiosis partnerships?	Paper III	Dare to make investments in industrial symbiosis? A conceptual framework and research agenda for developing trust *J. Clean. Prod.*	Ramsheva, Y.K., Prosman, E.J., Wæhrens, B.V	2019
sub-Q4: How can a 'product', 'service', and 'system' perspective support realizing circular economy strategies?	Paper IV	Applying the principles of circular economy in the context of concrete: A review *Peer-reviewed proceedings of ERSCP 2019*	Ramsheva, Y.K	2019
	Paper V	Realizing a circular concrete industry in Denmark through an integrated product, service and system perspective *Sustainability*	Ramsheva, Y.K., Moalem, R.M., Milios, L.,	2020

1.5. READING GUIDE

This dissertation consists of five parts, which provide a scientific whole that link the five academic studies.

INTRODUCTION

Chapter 1. Introduction

This chapter introduces the context within which this academic work is conducted, followed by the aim of the PhD study.

FRAMING THE RESEARCH

Chapter 2. Conceptual Framework

The concepts of industrial symbiosis and circular economy are presented. Literature gaps are identified and research questions are raised.

Chapter 3. Research design and Methodology

This chapter includes an outline of the PhD project, followed by a presentation of the scientific positioning of the research. Research methods, data collection methods and tools employed in each of the five academic papers, and reflections on research reliability and methodological delimitations are furthermore included.

RESEARCH FINDINGS

Chapter 4. Industrial symbiosis in the cement industry – Broader value potentials and linkages to circular economy

This chapter addresses *'sub-Q1: What value potentials does industrial symbiosis offer the cement industry?'* through an analysis of twelve industrial symbiosis partnerships of Aalborg Portland.

Chapter 5. The effect of price regulation on the performances of industrial symbiosis: a case study on district heating

The full potential for heat recovery from cement production is analysed and *'sub-Q2: To what extend do legal and economic constraints hinder the full deployment of industrial symbiosis potentials for carbon footprint reductions of the cement industry?'* is addressed in this chapter.

Chapter 6. Dare to make investments in industrial symbiosis? A conceptual framework and research agenda for developing trust

The chapter addresses *'sub-Q3: How to develop trust when setting up industrial symbiosis partnerships?'* by proposing a conceptual framework on trust in the context of up-front cross-industry partnerships.

Chapter 7. The need for a 'system' perspective in realizing circular economy strategies

In this chapter a broader 'system' perspective on the concrete industry value chain is suggested as a way to help realize circular economy strategies, providing an answer to *'sub-Q4: How can a 'product', 'service', and 'system' perspective support realizing circular economy strategies?'.*

DISCUSSION

Chapter 8. Discussion

The gained learnings from the five academic papers open up for a broader discussion on the case representativeness and the role of industrial symbiosis for a low carbon economy.

CONCLUSION

Chapter 9. Conclusions and Recommendations

The last chapter of this PhD thesis provides an overall conclusion, and presents the main contributions and possible avenues for future research.

CHAPTER 2. CONCEPTUAL FRAMEWORK

This chapter outlines the conceptual framework applied in this PhD project. The chapter starts with an introduction of the roots of industrial symbiosis and circular economy within different scientific concepts. The definitions of circular economy and the associated circular strategies are then presented, followed by the role of industrial symbiosis partnerships in supporting the transition to a low carbon economy. Finally, an overview of the raised sub-questions is provided.

2.1. ROOTS OF INDUSTRIAL SYMBIOSIS AND CIRCULAR ECONOMY

Taking responsibility of own carbon footprint and creating awareness of the long-term effects of resource overconsumption is what has become known as circular economy. The roots of circular economy date way back. In the late 1790s, in "An Essay on the Principle of Population", Thomas Malthus makes an important point on the future challenges in providing sufficient food and resources to the increasing world population (Malthus, 1798). That argument has been further developed by diverse influential thinkers of that time, such as Harold Hoteling, who stressed the issue of resource depletion and the need for shifting the economy towards responsible management of our resources (Hotelling, 1931).

More recently, the perception of the Earth as a closed system and its resources circulating in a closed loop emerged within the scientific field of ecological economics (Ayres, 1999; Boulding, 1966), environmental economics (Pearce and Turner, 1991) and industrial ecology (Frosch and Gallopoulos, 1989; Lifset and Graedel, 2002; Stahel, 1982). Each of these schools have contributed to shaping circular economy and its guiding principles and strategies.

Both ecological economics and environmental economics concern themselves with understanding the dynamics between society, economy and the environment. Environmental economics is a sub-set of economics, based on a neo-classical model in which the environment is an integrated part of the economic system (Venkatachalam, 2007).

From **environmental economics** perspective, material flows in a circular economy have an economic value and generate economic benefits, which drive the management of material flows (Andersen, 2007). From the perspective of economics, Pearce and Turner (1991) suggest looking at the economy as a closed system and consider the environment fulfils certain functions in it, by providing a base of both renewable and non-renewable resources. Both renewable (biological) resources, as well as non-renewable resources (such as fossil fuels) are utilized for the production of consumer goods and even though they are recycled and re-enter the system as new resources, they can still be overconsumed or end up as waste (Andersen, 2007; Pearce and Turner, 1990). Introduction of taxes on resource extraction and pollution are considered instruments for defining the value of the environmental services (Pearce and Turner 1991).

Ecological economics is also a sub-field of economics, but considers economy a subsystem of a broader and more complex global system, and does not try to integrate society and environment in an economic framework (Venkatachalam, 2007). The economist Georgescu-Roegen provided ecological economics with a conceptual framework linking economy to entropy (second law of thermodynamics). Entropy (or "disorder") in a closed system can never decrease over time, but is always increasing towards thermodynamic equilibrium (Pearce and Turner, 1990). Georgescu-Roegen (1971, 1960) argues that all resources become degraded once they enter the economic system. Motivated by Georgescu-Roegen view that the economy needs to function within a system, Boulding reasons towards the need to consider the world as a closed system and acknowledges the limits of the natural resources (Boulding, 1966). Boulding compares the closed system to a 'spaceship economy' with a fixed amount of resources, which instead of being wasted, need to continuously re-circulate in the system (Boulding, 1966).

The understanding of circular economy from an **industrial ecology** perspective differs from that of environmental economics and ecological economics (Andersen, 2007). Industrial ecology emerged as a field around 1980s, considering industrial activities such as raw material extraction, product manufacturing, their use and waste generation as an integrated industrial eco-system that resembles the biological ecosystem (Frosch and Gallopoulos, 1989). Frosch and Gallopoulos (1989) suggest in this "industrial eco-system", waste generated from industrial activities to be prevented or if not possible, reduced or utilised by other product streams. That in turn can lead to an overall reduction of the use of virgin resources (Andersen, 2007). Therefore, industrial ecology directs attention towards understanding the flow of resources (materials and energy) through the economy, or as Erkman (1997) defines the aim of industrial ecology is to:

> *"understand how the industrial system works, how it is regulated, and its interaction with the biosphere; then, on the basis of what we know about ecosystems, to determine how it could be restructured"*

Back in 1993, Graedel et al. (1993) suggested three ecosystem typologies differentiating between the linear and the cyclic system, see figure 2.1. Ecosystem type I represents a linear process, associated with unlimited resource input and unlimited waste as output (Graedel et al., 1993). Ecosystem type II can be considered more efficient than ecosystem type I, as resource input and generated waste are limited, yet in the long run that system cannot be considered sustainable (Graedel et al., 1993). Ecosystem type III represents the highest degree of resource re-circulation that can be achieved stressing the importance of closed material loops (Graedel et al., 1993). A central point made by Graedel et al. (1993) is that in order to shift from a linear ecosystem (type I) towards quasi-cyclic (type II) or cyclic (type III), requires the material and resource loops to be closed and fewer resources to be used when providing the same output.

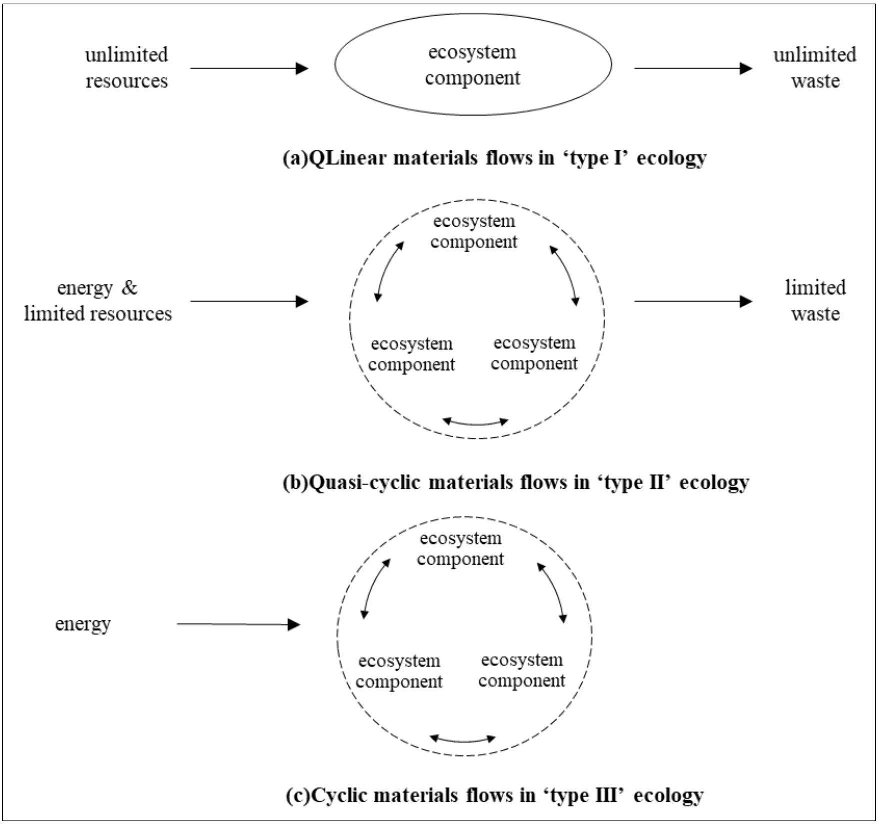

Figure 2.1. Three ecosystem types. Initially presented by Graedel et al. (1993) and later adapted by Lifset and Graedel (2002)

These considerations of a 'system' and the material flows within it are further applied in the concept of circular economy and related circular economy strategies described in the proceeding section.

2.2. CIRCULAR ECONOMY STRATEGIES

Circular economy is considered an “umbrella concept” (Blomsma and Brennan, 2017), as it incorporates strategies of resource-life extension - reduce, reuse, recycle. Those strategies are initially described by the prominent industrial ecologist W. R. Stahel. In the award-winning paper “The product-life factor”, W. R. Stahel, presents his views on the need for shifting from a linear system (“fast-replacement system”) to a circular system (“spiral-loop system” or “self-replenishing system”) (Stahel, 1982). This economic system should aim at reducing resource and energy flows and environmental degradation, while supporting economic, social and technological development (Stahel, 1982). Four loops of reuse, repair, recondition and recycle, are introduced by W. R. Stahel, emphasising on the importance of keeping the loops as small as possible in order to retain resources at their highest possible value, see figure 2.2. (Stahel, 1982)

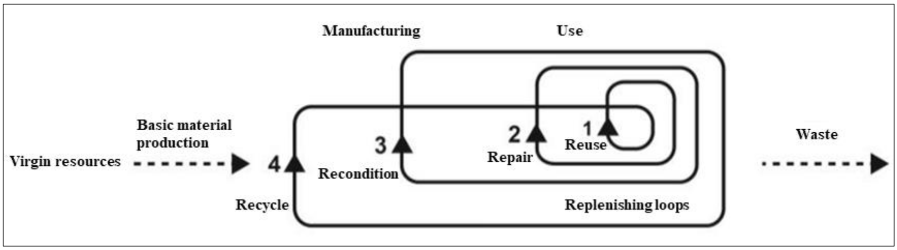

Figure 2.2. The self-replenishing system. Adapted from Stahel (1982)

Closely linked to W. R. Stahel’s work on defining circular economy, ‘cradle-to-cradle’ emerged as a concept mirroring the natural ecosystem (Braungart et al., 2007). In nature waste does not exist, but can be seen as “food” or as a resource (McDonough and Braungart, 2002). All materials from a cradle-to-cradle perspective are considered either biological or technical resources and products need to be designed in such a way that at the end of their use phase materials can either end up either as biological or as technical nutrients (McDonough and Braungart, 2002). The cradle-to-cradle concept is based on the perception that improving efficiency is not enough to sustain growth, and that there is a need to design products in the way that they can end up either in the biological or technical system at the end-of-life (McDonough and Braungart, 2002).

Back in the 1970s, Drucker (1967) defined the difference between resource efficiency and resource effectiveness as respectively “doing things right” vs. “doing the right thing”, which echoes just as relevant in today’s context of seeking sustainable solutions. Later, Braungart et al. (2007) highlighted further the important difference in understanding resource efficiency and resource effectiveness, proven central when designing the most suitable strategy for managing resources.

According to Braungart et al. (2007) eco-efficiency strategies aim at improving the economic output while at the same time reducing negative impact from the economic activity. In contrast, cradle-to-cradle design is about the effective utilization of resources through an intelligent transformation of material flows from linear to cyclical ones (Braungart et al., 2007).

The two concepts of eco-efficiency and eco-effectiveness are later compared by Bockholt et al., (2020), who suggest eco-efficiency focuses on minimizing expenses in utilizing resources in the best possible way, while eco-effectiveness is about improving the value of the resources available. Inspired by the concept of resource effectiveness, cradle-to-cradle and regenerative design, biomimicry, Ellen MacArthur Foundation also suggests the division of biological and technical nutrients, and defines circular economy as one that is *"restorative or regenerative by intention and design"* (Ellen MacArthur Foundation, 2013).

Building on the work of Boulding (1966), Stahel (1982) and McDonough and Braungart (2002), Braungart et al. (2007), Bocken et al. (2016) outline three circular economy principles of 'narrowing', 'slowing' and 'closing' loops. 'Narrowing' refers to reducing the resource input per unit of output, 'slowing' is about designing with a focus on durability and prolonging the product lifetime through repair or reconditioning, which results in slowing the flow of resources throughout the economy (Bocken et al., 2016). 'Closing' loops is about minimizing the leakages of the economy system through recycling of products or the residual value in materials (Bocken et al., 2016). Konietzko et al. (2020), develops further the ideas set by Bocken et al. (2016), Ellen MacArthur Foundation (2013), Geissdoerfer et al. (2017) and McDonough and Braungart (2002). Konietzko et al. (2020) adds two more circular economy principles - 'regenerate' (using renewable, low-carbon, non-toxic materials, and renewable energy) and 'inform' (use data as a supporting tool), see figure 2.3.

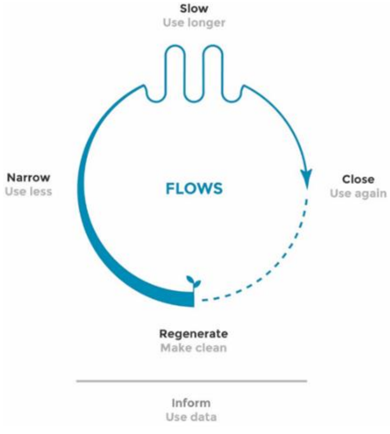

Figure 2.3. Circular economy principles of narrow, slow, close, regenerate and inform resource flows (Konietzko et al., 2020a)

The five circular economy principles and associated strategies can help organizations *"decarbonize and dematerialize their business activities"* Konietzko et al. (2020). Collaboration across sectors and establishing partnerships between stakeholders along the value chain are considered crucial in making a radical shift from the currently established linear way of production and consumption, towards a systemic integration of circular strategies (Brown et al., 2019).

The principle of 'regenerate' links to transforming goods manufacturing processes by removing toxic materials and basing production on renewable energy sources (Konietzko et al., 2020b, 2020a). A fifth principle of 'inform' represents the importance of technologies and big data as a supporting tool in a circular economy, e.g. through monitoring product performance, enabling product take-back and resource recovery, etc. (Konietzko et al., 2020a). According to Bocken et al. (2016), Konietzko et al. (2020a) and Murray et al. (2017), the five circular economy principles are interconnected and a 'system' view over the economy can make it possible to grasp the true effect of their application.

2.3. CIRCULAR ECONOMY - PRINCIPLES AND ASSOCIATED STRATEGIES

My interpretation of circular economy and the associated principles and strategies build on the above-described work of Stahel (1982), Braungart et al. (2007), Ellen MacArthur Foundation (2013) and Konietzko et al. (2020a). I define circular economy as a:

- *closed-loop regenerative system that*
- *aims at transforming resource flows,*
- *aims at minimizing negative environmental impact, through e.g. reducing waste, emissions, energy leakage,*
- *aims at using non-toxic materials, renewable energy,*
- *aims as reducing overconsumption of resources, and*
- *does not hinder growth (neither from an economic, nor from a social, or even from a technological perspective)*

The technical resource flow and the related circular economy strategies are presented in figure 2.4., adapted Stahel (1982) and Ellen MacArthur Foundation (2013). Emphasis is placed on technical materials, as they are a prime focus in this dissertation. The smaller loops need to be prioritised – 'repair/maintain' should be considered before 'reuse/redistribute' and 'refurbish/remanufacture', and if that is not possible, then the product should be 'recycled' and its residual value should be 'recovered' (Ellen MacArthur Foundation, 2013). That prioritisation is defined by Ellen MacArthur Foundation as the *"power of the inner cycle"* and the *"power of cycling longer"*, and reflects the waste hierarchy (Ellen MacArthur Foundation, 2013; European Commission, 2008).

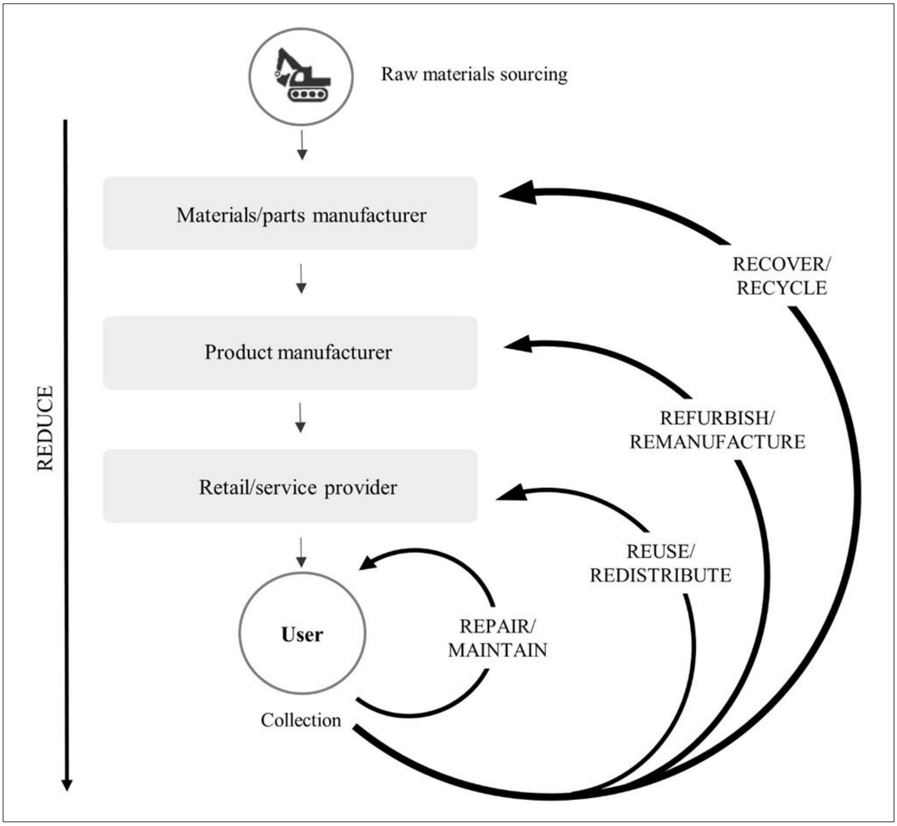

Figure 2.4. A visualization of circular economy strategies, adapted from Stahel (1982), Ellen MacArthur Foundation (2013) and Bundgaard, (2016)

The circular economy model proposed by Ellen MacArthur Foundation (2013) is assumed to mirror the biological cycle of nutrients, which is only based on renewable energy. Yet, current economy is still highly reliant on non-renewable materials and energy. Bundgaard, (2016) proposes introducing a fifth 'reduce' strategy that highlights the need to put an additional focus on increasing the efficiency of resource use, and reduced consumption of materials and energy.

Bocken et al. (2016) also highlights the importance of reducing environmental impact of products through the principle of 'narrowing' resource flows. In line with Bundgaard, (2016) and Bocken et al. (2016), a downward arrow is included in figure 2.4., highlighting the 'reduce' strategy. Table 2.1. merges the five circular economy principles, proposed by (Konietzko et al., 2020a) and the above-described circular strategies. Circular economy suggests existing interrelation between the circular strategies and the need for considering the possible synergies between them, and trade-offs they may bring (Blomsma and Brennan, 2017).

Table 2.1. Circular economy principles and associated circular strategies, based on (Blomsma et al., 2019; Konietzko et al., 2020a)

Circular economy principles	**Circular strategies**	**Definition**
Narrow	Reduce	Use less: using fewer products, components, materials and energy during the whole life cycle
Slow	Repair Maintain Refurbish Remanufacture	Use longer: extending the use period of products, components and materials
Close	Reuse Redistribute Recover Recycle	Use again: creating a circular flow of resources through reuse and recycling of products, components and materials
Regenerate		Make clean: sustaining natural ecosystems through using renewable and nontoxic materials, and renewable energy
Inform		Use data: information technology as a supporting tool for circular economy

The included re-strategies focus mainly on improving resource efficiency and innovation on a product level or product-service level, yet there is a need to shift focus on transforming resource flows through design for system innovation (Ceschin and Gaziulusoy, 2016). For example, re-strategies of ‘reinvent’, ‘reconfigure’, ‘rethink’, ‘refuse’ proposed by Blomsma et al. (2019) spread farther than the principles of ‘narrow’, ‘slow’, ‘close’, ‘regenerate’ or ‘inform’, and entail a more systemic action for reinventing, reconfiguring and rethinking existing frames. Such strategies call for a transformation of the current ways of consumption, and entail the adoption of collaborative models that involve shared responsibility between multiple stakeholders (Ghisellini et al., 2016).

2.4. INDUSTRIAL SYMBIOSIS AS A WAY FORWARD IN ADDRESSING THE CHALLENGES OF THE CEMENT INDUSTRY

The field of industrial ecology emphasises the importance of material and energy flow throughout the economy. According to, among others, Domenech et al. (2019), Saavedra et al. (2018), Ghisellini et al. (2016) and Bocken et al. (2017), industrial ecology can support circular economy through creating a closed industrial system for the exchange of excess resources (materials, energy, water, information, etc.), also known as industrial symbiosis. ‘Symbiosis’ refers to the synergetic relationships or also called ‘mutualism’ found in nature, where two or more otherwise distinct species exchange resources for their mutual benefit (Chertow, 2000). Similarly, in an industrial symbiosis exchanges, businesses establish partnerships that *“yield a collective benefit greater than the sum of individual benefits that could be achieved by acting alone”* (Chertow, 2004).

There is an abundancy of cases of both self-organized and planned industrial symbiosis for the purpose of gaining economic, environmental and social benefits (Albino et al., 2015; Côté and Cohen-Rosenthal, 1998; Schlüter et al., 2020). One of the most renowned case of industrial symbiosis is Kalundborg Symbiosis in Denmark, which represents a self-planned network of industrial partners, exchanging more than thirty diverse resources (Sacchi and Remmen, 2017).

The topic of industrial symbiosis in the context of the cement industry has been examined through a number of studies (Ammenberg et al., 2015; Hashimoto et al., 2010; Zhu et al., 2007) that demonstrate the significant benefits of by-product exchanges and their utilization. As already mentioned in section 1.2, the cement production process is both resource demanding and energy-intensive (Oggioni et al., 2011), and alone account for about 8% of the CO_2 emissions on a global level, making the industry one of the largest GHG-emitters (Andrew, 2018). Industrial symbiosis can play a role addressing those challenges by rethinking production and establishing resource partnerships with otherwise non-related industries (Chertow, 2000; Yu et al., 2015). For example, through industrial symbiosis partnerships, cement plants can exchange material and energy by-products, ‘closing’ the resource flows and resulting in GHG emission reductions. Having defined industrial symbiosis as a key strategy to facilitate low carbon production through partnerships, this dissertation explores the subject through the context of the cement industry. The proceeding sections unfold the topics of underlying value potentials, constraints and prerequisites of establishing industrial symbiosis partnerships that demand further analysis.

2.4.1. INDUSTRIAL SYMBIOSIS VALUE POTENTIALS

Industrial symbiosis partnerships get established primarily due to economic reasons, regulatory requirements or resource availability constraints (Chertow et al., 2008). Yet, the benefits generated through industrial symbiosis exchanges can go beyond simply reduction in resource costs, waste costs, emission levels. A number of studies investigating collaborative activities between diverse industries, suggest that industrial symbiosis can generate broader 'socio-economic' value potentials, such as employment opportunities, improved working conditions, technological advancements, innovation, new market prospects (Desrochers, 2001; Mirata, 2004; Mirata and Emtairah, 2005). Creating awareness of the broader value potentials of industrial symbiosis is considered key for facilitating inter-organizational trust, shared knowledge that can develop further into joint vision towards facilitating circular economy principles and strategies (Baas and Boons, 2004; Chertow et al., 2008).

In the context of the cement industry, studies uncover primarily the economic, regulatory and resource value potentials of industrial symbiosis (Hashimoto et al., 2010; Iacobescu et al., 2016; Martin et al., 2015; Supino et al., 2016). The potentials of industrial symbiosis for reducing GHG emissions released during the cement production process have been widely examined. Prosman and Sacchi (2018), Ammenberg et al. (2015), Aranda Usón et al. (2013) are some examples of studies on the substitution of conventional fuels and clinker with wastes and by-products from industry through inter-organizational partnerships.

Still, industrial symbiosis literature on the broader value potentials within the cement industry seem to be somewhat limited. Chertow and Lombardi (2005) highlight this literature gap through their quantitative study on environmental, economy and regulatory benefits of the industrial symbiosis network in Guayama, Puerto Rico. Furthermore, Fraccascia et al. (2016) explore the business models firms can implement to gain value from industrial symbiosis exchanges and advocates for exploring further the value potentials linked to industrial symbiosis.

In order to uncover the broader value potentials of industrial symbiosis, the first sub-question is raised:

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sub-Q1: What value potentials does industrial symbiosis offer the cement industry?

2.4.2. INDUSTRIAL SYMBIOSIS CONSTRAINTS

Industrial symbiosis is recognized as *"an important strategy for low-carbon development"* (Walls and Paquin, 2015). Academic literature suggests that despite the acknowledged value potentials that industrial symbiosis can bring, establishment of industrial symbiosis partnerships does not always occur without obstacles (Desrochers, 2001; Harris, 2007; Lehtoranta et al., 2011). Constraints of legislative, economic, or even organizational and geographical character are considered hindering the emergence or full expansion of industrial symbiosis (Bojsen and Ulhøi, 2000; Chertow, 2004; Madsen et al., 2015). Yet, existing literature on industrial symbiosis constraints seem obscure or theoretical, lacking sufficient demonstrative case studies on the actual extent to which the development of industrial symbiosis can be obstructed (Huang et al., 2019). In the case of Aalborg Portland, an industrial symbiosis partnership with the local utility company for the exchange of excess heat has been a fact for more than thirty years. However, the potential for the cement company to retrieve more of its excess heat from the rest of its production lines has not been capitalized due to a number of constraints.

The second sub-question points at the need to address the effect of legal and economic constraints on the full deployment of industrial symbiosis potentials for lowering the carbon footprint of the cement industry:

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sub-Q2: To what extend do legal and economic constraints hinder the full deployment of industrial symbiosis potentials for carbon footprint reductions of the cement industry?

2.4.3. TRUST AS A PREREQUISITE IN INDUSTRIAL SYMBIOSIS PARTNERSHIPS

An industrial symbiosis partnership is identified as a form of a cross-industry buyer-supplier relationship (Ehrenfeld and Gertler, 1997; Hiete et al., 2012). Industrial symbiosis often requires upfront investments in certain infrastructure, waste treatment equipment, or other technological solutions, for the supply and use of waste and by-products (L. W. Baas and Boons, 2004; Bansal and Mcknight, 2009; Ehrenfeld and Gertler, 1997; Schwarz and Steininger, 1997; van Beers et al., 2007; Zhu et al., 2007). That is often the case when cement companies source waste and by-products, as they may require further treatment or ensuring proper storage facilities prior to their utilization. Supply of excess heat recovered from the cement producer recovery units also requires extensive pipelines to be in place before to the industrial symbiosis exchange is initiated.

Trust is acknowledged essential in establishing industrial symbiosis partnerships (Ashton and Bain, 2012; Ehrenfeld and Gertler, 1997; Hiete et al., 2012). The cross-industry and upfront nature of new industrial symbiosis requires a certain level of trust in the ability, integrity and benevolence of the potential partner (Vanpoucke et al., 2014). Ability (or competence trust) refers to the belief that the other is able to perform a certain task; integrity (or contractual trust) is the belief in the other to follow the mutual agreement or contract; benevolence (or goodwill trust) is the belief that the other will not act opportunistically in their own interest (Crane, 2018). For example, a potential supplier of waste and by-products to a cement company has a motivation to dispose of that waste to avoid landfill taxes and may deliver waste and by-products of quality that is not sufficient for the cement producer to use as a conventional fuel or raw material substitute. Poor ability and integrity to supply in accordance to certain agreed parameters, in terms of quality, time, quantity, etc., or opportunistic behaviour to act in own interest, may put capital-intensive investments at risk (Walker and Jones, 2012).

Despite the accepted importance of trust in industrial symbiosis, its role when setting up those partnerships remains unclear. Management literature analyses how trust develops when setting up inter-organizational partnerships, also those that may require capital-intensive investments (Nooteboom et al., 1997; Sako, 1992; Vanpoucke et al., 2014). Yet, industrial symbiosis partnerships differ from other buyer-supplier relationships analysed by management literature due to two reasons - their cross-industry and upfront investment setting. As previously mentioned, the cross-industry context may act as a barrier in understanding the other's ability, integrity, benevolence (Brinkhoff et al., 2015). In addition, compared to other buyer-supplier relationships, industrial symbiosis partnerships often require investments to be made upfront (L. W. Baas and Boons, 2004; Bansal and Mcknight, 2009; Ehrenfeld and Gertler, 1997; Schwarz and Steininger, 1997; van Beers et al., 2007; Zhu et al., 2007), which means trust cannot develop based on prior experiences.

In order to provide new insights on how trust develops in setting up industrial symbiosis partnerships of upfront and cross-industry nature, the following sub-question is raised:

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sub-Q3: How to develop trust when setting up industrial symbiosis partnerships?

2.4.4. A SYSTEMIC PERSPECTIVE ON THE CONSTRUCTION INDUSTRY

Product-service systems is considered a strategy that can enable the reduction of consumption and waste (Joensuu et al., 2020) and facilitate circular economy through product-life extension and opportunity for resource/product sharing (Bocken et al., 2017).

The concept of product-service systems does not bear a unified definition, yet it is widely acknowledged as a system that combines products and services *"designed to be economically, socially and environmentally sustainable, with the final aim of fulfilling customer's needs"* (Annarelli et al., 2016). Still, product-service systems does not necessarily lead to a reduction in resource use (Kjaer et al., 2019), which as highlighted in section 2.2., is a key principle in a circular economy. Furthermore, this limited view of the system, as one that solely integrates tangible products and services to generate economic value (Goedkoop et al., 1999), does not put focus on the role of collaboration in a circular economy. Collaboration between stakeholders in a system is considered a way forward in providing circular solutions that match broader societal needs and challenges, and not only meet current customer demands (Kristensen and Remmen, 2019). Establishing partnerships is needed, as in a circular economy, collaboration along the value chain could generate joint benefits (Tate et al., 2019), as is the case with industrial symbiosis partnerships.

A wider view on the system than traditionally suggested may be needed to address the above described issues. Kristensen and Remmen (2019) propose viewing product-service system as a concept consisting of three dimensions of 'product', 'service' and 'system', through a focus shift from the tangle product, towards the broader solutions, which those products and services can provide. Looking at cement, and inevitably also concrete, circular economy strategies are already being implemented through recycling of concrete aggregates (Akhtar and Sarmah, 2018; Li, 2009; Tam, 2008; Zhao et al., 2020), reuse of concrete (Ghaffar et al., 2020; Huuhka et al., 2015), using durable concrete for extending building lifetime (Maerckx et al., 2019). Still, those activities alone are neither sufficient to fully address the pressing resource and pollution challenges, nor provide a systemic solution for sustainable construction (Leising et al., 2018).

Applying a system perspective may cast new light on the underlying circular economy potentials of the construction sector (Scrivener et al., 2017), raising the following sub-question:

---

sub-Q4: How can a 'product', 'service', and 'system' perspective support realizing circular economy strategies?

2.5. OVERVIEW OF THE RAISED RESEARCH QUESTIONS

This section provides an overview of the four sub-questions, which will be answered in order to address the main research question of this PhD dissertation.

What new knowledge can be gained from the cement industry on the role of industrial symbiosis for realizing a low carbon economy?

Setting out to explore the state of the art within existing literature, it was found that there is a need for further research on industrial symbiosis **value potentials**, **constraints, prerequisites** and a wider **system perspective** for realizing circular economy strategies. These four "themes" are the prime focus of this dissertation and explored through four associated, case-specific sub-questions, which the academic papers target. The relationship between research questions, themes and papers are depicted in figure 2.5.

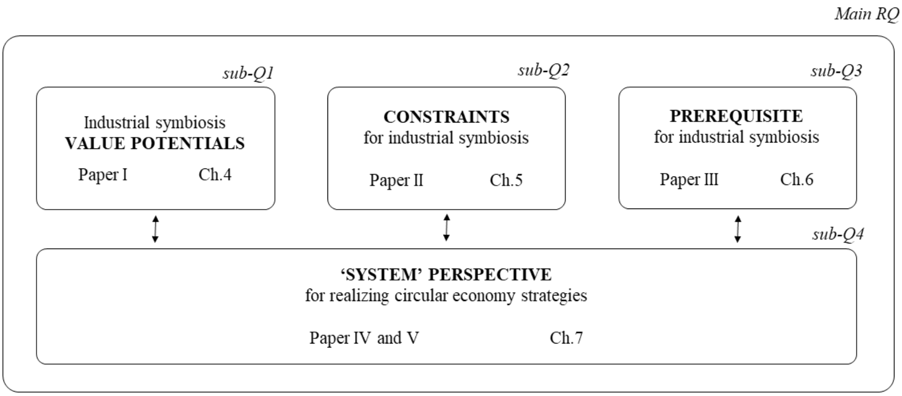

Figure 2.5. Mapping of the research themes, research questions and academic papers

Each of the three boxes at the top represents respectively 1) industrial symbiosis value potentials (Paper I) legal and economic constraints (Paper II) and 3) trust as a prerequisite for industrial symbiosis (Paper III). Paper IV and V are both linked to 4) the role of a broader 'system' perspective on realizing circular economy strategies. The wide box at the bottom and the double arrows indicate that addressing circular economy from a 'system' perspective can directly or indirectly influence the three facets of industrial symbiosis. Learnings from Paper I-III can feed in valuable insights on how to identify value potentials, overcome constraints and develop trust between stakeholders for realizing circular economy strategies in a 'system'. Likewise, looking beyond merely the value potentials, constraints or prerequisites of inter-organizational collaboration may be a way forward for establishing fruitful partnerships in a circular economy.

CHAPTER 3. RESEARCH DESIGN AND METHODOLOGY

This chapter starts with an outline of the PhD project, followed by theoretical considerations, a description of the research methods, data collection methods and tools employed throughout the research. Furthermore, reflections on the research reliability and methodological delimitations are presented.

3.1. THE PROCESS OF THE PHD PROJECT

The PhD project was initiated in Sept 2016 and ended in start Feb 2021. The PhD process was interrupted by two maternity leave periods between July 2017 – May 2018 and Apr 2019 – Feb 2020. From the start of my professional career in autumn 2013 as environmental engineer in the market-leading circulation pump producer Grundfos, and over the course of the last 4½ years in research, I have observed an ever growing attention by academia, businesses, politicians, media and private citizens on circular economy and carbon neutrality. This attention creates a new reality for the cement industry where change is needed to not only cope with the constraints of future regulation but ideally to grasp the opportunities and harvest value potential.

During the Paris agreement in 2015, the cement industry committed to focus attention on sustainable production, while in 2018 the International Energy Association (IEA) laid a technology roadmap for a low carbon transition of the cement industry (IEA, 2018). In 2019, the Danish government adopted a Climate law, committing to carbon neutrality by 2050 (Folketinget, 2020). In respond to that, in 2020, Aalborg Portland set a goal to cut GHG emissions with at least 30% by 2030 compared to 1990 levels, and aim at carbon neutrality by 2050 (Aalborg Portland, 2020). Those recent political and industry developments in the context of the cement industry are reflected in the choice of topics and methods for analysis throughout this PhD project.

This PhD project is sponsored by Aalborg University, and is associated to the business initiative MADE (Manufacturing Academy of Denmark). MADE is a wide research and innovation platform involving research institutions and a wide number of companies with the aim of developing of innovative manufacturing solutions. The PhD project had an initial broader scope on energy intensive industries, including two of the largest Danish resource consumers - the cement company Aalborg Portland and stone wool producer Rockwool Group. As members of MADE, Aalborg University, Aalborg Portland and Rockwool Group have highlighted the relevance and need of conducting academic research on the underlying circular economy potentials within energy intensive industries.

In the course of the PhD process, however, Aalborg Portland took a more central role as a company case on which I based my research work. During the whole period of conducting the PhD project, I had an office space at Aalborg Portland Research and Technology Centre (RTC). Being involved in the daily working environment at Aalborg Portland made it possible to initiate dialogues and plan interviews with company employees, gain access to internal data sources, learn about future sustainability plans and activities of the company. In addition, two fellow PhDs from Aalborg University conducted research on developing sustainable solutions for the cement industry. That opened up the possibility for establishing academic collaboration on topic of mutual interest. The output of the established collaboration is particularly visible in Paper II and III, which are both co-authored with academic peers. Furthermore, the flexibility to be part of both the research environment at Aalborg University, as well as the corporate environment at the cement company Aalborg Portland gave the opportunity to develop transdisciplinary research. Transdisciplinary research is defined in this PhD thesis as one in which academic and non-academic actors temporary collaborate and offer multiple perspectives for bringing a solution to a sustainability challenge or provide valuable insights to an existing knowledge gap (Miller et al., 2008; Sakao and Brambila-Macias, 2018). Further theoretical considerations are unfolded in the proceeding section.

3.2. THEORETICAL CONSIDERATIONS

Research is led by paradigms that present researchers' views regarding the world and the role of individuals in it (Guba and Lincoln, 1994). Philosophical discussions differentiate between four different paradigms: positivism, critical realism (post positivism), critical theory, constructivism (Guba and Lincoln, 1994). Each of those paradigms have different views in terms of ontology, epistemology and methodology, which in turn influence the research design, applied methods, analysis of data and interpretation of results (Guba and Lincoln, 1994). In the context of this PhD project, it is of central importance to identify and reflect upon the paradigms guiding the research when integrating diverse disciplines (of industrial ecology and circular economy) (Bryman, 2012).

As the author of this PhD thesis, I consider my position is between two paradigms – critical realism and social constructivism. The adoption of such a 'pluralistic' perspective is considered appropriate when conducting transdisciplinary research, in which complex sustainability issues are analysed and existing knowledge can be enriched with new perceptions (Miller et al., 2008). In the context of this PhD thesis, the disciplines of industrial ecology and circular economy are regarded central for transforming the current production and consumption system and current research on the topics still lacks critical analysis (Korhonen, 2004; Korhonen et al., 2018). On the one hand, critical realism perceives new knowledge to be generated through gathering of facts and testing theories (Given, 2008).

On the other hand, the researcher is aware of that one can never be completely certain of whether this new knowledge is the ultimate "truth" (Bryman, 2012). Positivism and as such critical realism studies reality through critical examination (Moon and Blackman, 2014) and assumes *"reality exists but can never be understood perfectly"*. As such, through a social constructivist approach, the findings of this PhD project can to a large extend be regarded context specific, providing new understanding on how the cement industry can adopt more sustainable practices.

The scientific positioning of this research (within critical realism and social constructivism) is further described through ontological, epistemological and methodological considerations, presented in the following sections.

3.2.1. ONTOLOGY

Ontology originates from the Greek "*ont*", meaning *'being '* (Oxford University Press, n.d.) and is a philosophical branch dealing with the question on '*What is the form and nature of reality, and therefore, what is there that can be known about it?'*. The research follows the ontological position of a critical realist, since it is acknowledged that "real" reality exists, yet it can only be partially comprehended. Therefore, uncovering new knowledge and making claims about the 'reality' are subject to 'critical' examination. Therefore, raising the following questions: sub-Q1: '*What value potentials does industrial symbiosis offer the cement industry?*' and sub-Q2: '*To what extend do legal and economic constraints hinder the full deployment of industrial symbiosis potentials for carbon footprint reductions of the cement industry?*'.

Throughout the course of the PhD project, the author also recognises the social constructivist paradigm as part of this research. From a social constructivist position, multiple, even in some cases conflicting 'realities' (or "knowledges") can co-exist, due to their specific nature, social and local biasness (Guba and Lincoln, 1994). Sub-Q3: *'How to develop trust when setting up industrial symbiosis partnerships?'* and sub-Q4: *'How can a 'product', 'service', and 'system' perspective support realizing circular economy strategies?',* seek to provide new insights to a specific industry context, by building on already existing knowledge. It is important to recognise that the form and content of social 'realities' are reliant on the individual researcher or group of researchers, and as such they *"may change as their constructors become more informed and sophisticated"* (Guba and Lincoln, 1994).

3.2.2. EPISTEMOLOGY

As a philosophical "study of knowledge", epistemology concerns itself with questions of how knowledge on particular topics can be obtained, and what is the relationship between the researcher and object of analysis (Audi, 2003).

Following the critical realism paradigm, the author recognises the dependency between the two and their somewhat mutual influence on each other (Guba and Lincoln, 1994). Selecting the object of analysis and drawing the boundaries of the studies are influenced by the researcher's own understanding of the problem and by other scholars and their opinions on '*What value potentials does industrial symbiosis offer the cement industry?*', or '*To what extend do legal and economic constraints hinder the full deployment of industrial symbiosis potentials for carbon footprint reductions of the cement industry?*'. Nevertheless, emphasis is placed on the importance of objectivity during the research process and ensures critical examination of the findings through multiple iterations with both academic and industry experts (also defined by Guba and Lincoln (1994) as 'external guardians'). Supervisors, peer-reviewers, colleagues, experts within the cement industry are considered 'external guardians' throughout conducting the research.

Following the logic of the social constructivist paradigm, the researcher and object of research are considered linked, as new findings and learnings is shaped in the course of the study (Guba and Lincoln, 1994). New learnings on *'How to develop trust when setting up industrial symbiosis partnerships?'*, as well as *'How can a 'product', 'service', and 'system' perspective support realizing circular economy strategies?',* are generated as the research process is carried out and as findings gradually unfold new knowledge and understanding of the topics.

3.2.3. METHODOLOGY

In order to address the epistemological concerns of the critical realist paradigm noted above, this PhD thesis employs triangulation (Guba and Lincoln, 1994). Triangulation is considered increasing objectivity of the research process and reducing results bias (Maxwell, 2005). In this PhD thesis, triangulation is used in three ways to avoid subjectivity and ensure reliability of the obtained results (Denzin, 1978; Maxwell, 2005):

- **Data triangulation** – collecting data from multiple sources, period, space, persons (summarized in section 3.3, table 3.1.)
- **Methodological triangulation** – employing multiple methods of data collection (summarized in section 3.3, table 3.1.)
- **Investigator triangulation** – involving multiple researchers in the interpretation of the data and results of all conducted studies, which are part of this PhD project. Paper II in particular involved active collaboration both between the two researchers/co-authors of the paper, as well as between the researchers and a number of external experts, who assisted in checking and confirming the identified heat demand changes, market equilibriums, heat prices in the developed scenarios. Further reflections on the role of triangulation are unfolded in section 3.5 *Ensuring research reliability and validity*.

With regard to the social constructivist paradigm, constructions (i.e. conceptual framework for developing trust in the context of up-front cross-industry industrial symbiosis investments; conceptual framework for realising circular economy in ‘product’, ‘service’, and ‘system’) are developed and refined through interaction between the researcher and the research object. Personal values and perceptions can have a certain impact on the constructions (Guba and Lincoln, 1994). For instance, the researcher’s individual values can influence the choices of case for analysis or the choice of interviewees who share similar views on the importance of setting up circular initiatives in the cement industry.

3.3. RESEARCH METHODS

This section briefly presents the methods employed in this PhD thesis and summarised in table 3.1. on the following page. More specific details about the research procedures of the conducted studies can be found in each of the individual papers in Chapter 4 – Chapter 7.

3.3.1. CASE STUDY

Conducting a case study is considered a useful methodological approach for both exploratory and explanatory research (Saunders et al., 2009). Case studies are particularly suited for gaining an in-depth understanding of a particular phenomenon and its context, and when cases are strategically chosen, obtained findings from the conducted case study analysis can be generalizable (Flyvbjerg, 2006).

This PhD thesis employs a single case study design (Paper I, II and V) for obtaining empirical evidence about realizing circular economy principles and strategies in the context of the cement industry. Paper I and II are based on the case of Aalborg Portland and more specifically - on the established industrial symbiosis relations of the company with local and distant partners. Being the only cement producer in Denmark and the largest producer of white cement worldwide, Aalborg Portland has a relevant role from both an industry and society perspective. The case findings, even though context specific, are considered valuable in providing general insights on the broader industrial symbiosis potentials of the cement industry, as well as the existing legal and economic constraints that hinder their full exploitation. Paper V proposes an integrated ‘product’, ‘service’, and ‘system’ perspective for realizing circular economy strategies, and suggests broadening the industry focus from cement to include concrete. The researcher considers the results of Paper V, despite not fully generalizable to all industry contexts, to provide new insights on how circular economy principles and strategies can be realized through a broader ‘systemic’ industry focus.

Table 3.1. Overview of applied research methodology throughout the PhD project

Paper #	Paper I	Paper II	Paper III
Research method	Case study	Case study	Conceptual study
Methods and tools for data collection	**7 semi-structured interviews** • Cement producers • Utility company • Consulting company • Municipal authority **Dialogues with company employees and management** **Document analysis** • Academic literature • Industry reports • Internal company data on amounts and quality of exchanged wastes and by-products • Company sustainability reports • Legislative and regulatory papers	**3 semi-structured interviews** • Heat suppliers • Municipal authority representative **Dialogue with company employees** **Consequential LCA** **Market equilibrium models** **Document analysis** • Local and national energy plans • Environmental and financial reports on energy supply • Housing typologies	**Systemic review of industrial symbiosis and management literature**
Strategies for ensuring reliability	Recording and transcription of interviews Multiple review rounds with supervisor	Detailed documentation of collected data and calculations Interview recordings and transcription Contact with data source providers Feedback from academic experts during the process of data analysis	Multiple review rounds with co-authors Engaging in discussions with co-supervisor and peers
Timeline	2016-2021	2018	2018-2019

Table 3.1. cont.

Paper #	Paper IV	Paper V
Research method	Literature review	Case study
Methods and tools for data collection	**Systemic review of circular economy literature**	**9 semi-structured interviews** • Cement and concrete producers • Waste company • Municipal authority representative • Architect • Concrete industry association representative **Dialogues** • Employees at concrete production companies • Academics at national building research institute **Review of product service system & circular economy literature** **Document analysis** • Interviewee data on material properties; established circular economy initiatives (reuse, recycling) • Industry reports
Strategies for ensuring reliability	Documentation of literature search results Presentation of results at ERSCP 2019 Conference Engaging in discussions with academic peers	Detailed documentation of collected data Recording and transcription of interviews Follow-up discussion with academic and industry representatives Collaboration with academic peers
Timeline	2019	2020

3.3.2. CONCEPTUAL STUDY

The contribution of conceptual studies typically builds on existing research, multiple literature streams and theories (Jaakkola, 2020). Paper III merges industrial symbiosis literature and management literature to explore how trust can be developed when setting-up industrial symbiosis partnerships and proposes a conceptual framework for developing trust. A number of studies from management literature examine how trust can be developed in buyer-supplier relationships (Ireland and Webb, 2007), and industrial symbiosis is recognized a type of a buyer-supplier relationship (Ramsheva et al., 2019). Based on the findings of Paper III: *"research on trust in industrial symbiosis literature is still in its infancy especially when compared to management literature"* (Ramsheva et al., 2019). Therefore, the method of integrating the two research streams of industrial symbiosis and management literature is considered relevant for gaining new knowledge regarding trust in the context of industrial symbiosis.

3.3.3. LITERATURE REVIEW

Present literature can be critically examined through the literature review method (Alan Bryman, 2008). Review of literature is applied in diverse detail and level of comprehensiveness throughout the PhD project. Literature review is considered a useful tool for determining the state-of-the-art and research gaps, which are then addressed by the conducted academic studies.

A review of state-of-the art literature on trust in the research fields of industrial symbiosis and management was conducted. That helped gain background knowledge on the topic of trust and was used as a foundation for building the conceptual framework in Paper III.

Literature review was conducted in Paper IV to help identify the circular economy potentials and barriers in the context of the concrete industry. To ensure the transparency and replicability of research, the method for conducting a literature review follows a specific procedure in terms of selected databases, search terms, time span, etc. (Jesson et al., 2011). Ninety-eight academic publications, nine technical reports and two directives were analysed in Paper IV.

Paper V also employs a brief literature review on the existing academic studies on circular economy and product service systems. Such an overview assists in building on existing perception of product service systems and proposing a more holistic view of product service systems from a three-dimensional ('product', 'service', and 'system') perspective.

3.4. METHODS AND TOOLS FOR DATA COLLECTION

Both qualitative and quantitative methods are applied in this PhD thesis and summarised in table 3.1. Qualitative methods, such as interviews, dialogue with experts and document analysis, are a main source of data for the conducted studies of this PhD thesis. The advantages of each method are outlined in the following sections.

3.4.1. INTERVIEWS AND DIALOGUES

Semi-structured interviews were planned and conducted as a main method for data collection in Paper I, II and V. Interviews are considered a valid way to get the interviewees' understanding on a topic or a description of certain actions and their outcome (Maxwell, 2005). When conducting semi-structured interviews, a number of questions that guide the conversation were prepared, however supplementary questions often arose during the interview (Bryman, 2012). The semi-structured interviews conducted throughout the PhD project involved employees at both public and private organisations. The interviewees were approached due to their knowledge and expertise on precise topic under analysis. Paper I and II analysed the industrial symbiosis partnerships of Aalborg Portland. Semi-structured interviews were held to gain an understanding of the potentials of industrial symbiosis both in relation to lowering the environmental impact of cement production, as well as the broader industrial symbiosis potentials for the surrounding area, local society and industrial partners.

As a supplement to the data collected through the semi-structured interviews for Paper I, II and V, dialogues with experts from the cement industry were also conducted. For the case study on district heating in Aalborg (Paper I and II), dialogues were initiative with employees and management representatives at Aalborg Portland, as well as with excess heat suppliers. For the case study on the concrete industry (Paper V), dialogues were initiated with industry representatives responsible for the development of sustainable concrete materials, as well as academic professionals from a leading research institute for built environment in Denmark. All the dialogues were in a form of informal interactions or took part during joint meetings, supplementing the empirical data and providing crucial insights on the analysed problems. Recording the dialogues was not possible, yet detailed notes were taken. Detailed description of the method for conducting the interviews and dialogues for each study can be found in the respective papers in Chapter 4 - 7.

3.4.2. DOCUMENT ANALYSIS

A large number of documents were identified as relevant data source throughout the research. Sustainability reports, internal company data from Aalborg Portland, legislative and regulatory papers were used as a supplementary data source for Paper I. Document analysis in terms of local and national energy plans, environmental and financial reports on energy supply, housing typologies, helped model the ten scenarios for district heating supply with varying shares of diverse heat sources in Paper II. Internal data from interviewed companies on material properties and results from circular economy initiatives on reuse and recycling of own materials and waste, was considered relevant for Paper V. In addition, the building industry, and as such also the cement industry, are in an early process of adopting a more circular mind-set and setting up diverse pilot activities in terms of designing for easier disassembly, deconstruction instead of demolition, reuse of concrete for diverse applications (Cembreau, 2016; Huuhka et al., 2015; Zhao et al., 2020) . Those initiatives are at large driven by the industry itself and numerous reports are being published presenting the obtained findings. Those were considered relevant to analyse, especially when studying the circular economy potentials in the concrete industry (cf. Paper V).

3.4.3. LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) is a quantitative assessment tool for measuring the environmental impacts associated with the life-cycle stages of a product or service (The International Organization for Standardization, 2006). Baumann and Tillman (2004) describe LCA follows the product "*from its 'cradle' where raw materials are extracted from natural resources through production and use to its 'grave', the disposal*."

There is a variety of LCA methods, yet two main types can be identified: attributional LCA (ALCA) and consequential LCA (CLCA). In ALCA, products are attributed the functional unit of a product system. ALCA does not allow for extrapolations of the environmental impacts of potential increased use of by-products, for example through industrial symbiosis exchanges. CLCA, on the other hand, assumes the environmental impacts of activities to be included in the product system to the degree that they are estimated to change as a consequence of a change in demand (Sonnemann and Vigon, 2011). Therefore, CLCA is considered in scientific circles to be better applicable to access and compare environmental impact of diverse scenarios of district heat supply, as conducted in Paper II. In Paper II, CLCA is applied to compare the environmental impact of ten scenarios of district heat supply including diverse share of excess heat from industry. CLCA proves to be a potential valuable for decision-making. The CLCA conducted in Paper II helps identify the potential carbon footprint of heat production in Aalborg in case of an increase in the supply of excess heat. Such results can be used by both municipal authorities and industries for developing roadmaps for the future district heat supply in Aalborg.

3.4.4. EQUILIBRIUM MODELS

The market for district heating in Aalborg is modelled (cf. Paper II). Market equilibrium models may seem theoretic, yet they appear useful when evaluating the economic effect of potential changes in demand and supply of excess heat. Market equilibriums for ten scenarios with different share of excess heat in the district heating system of Aalborg are provided. The market equilibriums are determined by a match between the total demand for heat and the total supply of heat, linked to a new district heating price for the end-user (Sacchi and Ramsheva, 2017).

3.5. ENSURING RESEARCH REALIABILITY AND VALIDITY

The reliability of the conducted research is ensured through a number of strategies. The process of data collection and data analysis is documented and a step-by-step procedure of the research design is presented in each of the five academic papers. All conducted interviews are recorded, transcribed and detailed notes are taken to ensure the validity of the collected data. LCA data and CLCA results are archived. The literature review process in Paper III and Paper IV is comprehensively described to ensure transparency and replicability of results.

Information obtained by industry reports and internal company data are not undoubtedly accepted as factual. The corresponding authors and editors, as well as the data assessment methods applied in each industry report were carefully analysed. Furthermore, the content of internal company data was confirmed by employees to ensure validity.

Numerous interactions with supervisors and industry representatives provided valuable feedback on the quality and relevance of the conducted studies. Collaborating with academic peers helped strengthen the reliability of the data, as well as the conducted analysis throughout the different studies. For example, Romain Sacchi has in-depth knowledge and expertise in LCA. Co-authoring Paper II with Romain Sacchi made it possible to collect and assess precise raw data instead of use average values from an inventory life cycle database. That made the obtained results more accurate and case-specific.

Moreover, international relevance of the conducted research is reflected in two ways. First, though multiple peer-review rounds of the international scientific journals in which the academic papers are published. Second, through establishing collaboration with academics from another research institute at Aalborg University (cf. Paper III), as well as on an international level (cf. Paper V).

3.6. METHODOLOGICAL DELIMITATIONS

Apart from Paper II, this PhD project mainly employs qualitative methods, such as interviews, dialogues, document analysis. These methods are useful for gaining a comprehensive understanding of the role of industrial symbiosis in the context of the cement industry (Maxwell, 2005). Yet, qualitative methods are not capable of providing clear quantitative measurements, as demonstrated through Paper II. Assessment through quantitative methods of the value potentials of industrial symbiosis at Aalborg Portland, the required trust levels in IS, the opportunities a broader industry 'system' perspective could be conducted. Such calculations can bring relevant insights and supplement the already obtained results of Paper I, III and V.

Furthermore, the author acknowledges the geographical delimitation of the conducted case studies (Paper I, II and V). Both the case of Aalborg Portland, as well as the case of the concrete industry are based in Denmark. The cement and concrete industry in Denmark cannot be considered particularly different from that of other countries. Yet, the obtained data is context specific, and as such the results of the studies may not be universally applicable. For example, the local industrial symbiosis (Paper I and II) of district heating are established given certain local political and technological prerequisites.

CHAPTER 4. INDUSTRIAL SYMBIOSIS IN THE CEMENT INDUSTRY - BROADER VALUE POTENTIALS AND LINKAGES TO CIRCULAR ECONOMY

This chapter includes paper I titled: "Industrial symbiosis in the cement industry – Broader value potentials and linkages to circular economy" (**Ramsheva, Y.K.**, Remmen, A., 202x)*, which is accepted and subject to revision in the *Journal of Cleaner Production.* An early version of this paper was presented at the 2018 International Conference on Technology and Business Models for Circular Economy (TMBCE), Slovenia and included in the peer-reviewed conference proceedings.

**paper is omitted in online version*

Through an analysis of twelve industrial symbiosis partnerships of the cement company Aalborg Portland, Paper I aims to address sub-Q1: '*What value potentials does industrial symbiosis offer the cement industry?'*. In the context of the cement industry, industrial symbioses are often established for economic (raw material savings), resource (gain access to wastes and by-products) and environmental (reduce emission levels from production) reasons. Value potentials of 'socio-economic' character, such as employment possibilities, improved working conditions, technological advancements, innovation, have be examined by scholars. Yet, analysis of the broader 'socio-economic' value potentials of industrial symbiosis still demand attention, especially in the context of the cement industry. Recognizing those value potentials can facilitate further the establishment of trust and sharing expertise between industrial symbiosis partners that can in turn enable realizing circular economy principles and strategies in the cement industry.

All the twelve industrial symbiosis partnerships of Aalborg Portland were found to hold both economic and resource value potentials. The largest number of Aalborg Portland industrial symbiosis are established with closely located partners. Seven industrial symbioses occur locally - between Aalborg Portland and organizations in the surrounding area. Those local industrial symbiosis partnerships generate socio-economic value potentials. Results indicate that value potentials of local industrial symbiosis can even be of wider political nature, as Aalborg Portland has the possibility of close interaction with local authorities and actively contribute to developing the future strategies of the surrounding area. Those findings add new insights to the ongoing discussion of the role of geographical proximity in industrial symbiosis.

Furthermore, this study links the industrial symbioses of Aalborg Portland to circular economy principles and strategies. All the twelve industrial symbiosis partnerships appear to bring environmental improvements through “reduction” and “recovery” of resources from diverse industries, yet not linking to the ‘inner’ circles – regarded as having priority in a circular economy (Ellen MacArthur Foundation, 2012). Thus, the study opens a relevant discussion on the need to broaden the ‘system’ perspective from the product cement to include concrete, if circular economy principles and strategies are to be realized further.

CHAPTER 5. THE EFFECT OF PRICE REGULATION ON THE PERFORMANCES OF INDUSTRIAL SYMBIOSIS: A CASE STUDY ON DISTRICT HEATING

This chapter contains Paper II titled: "The effect of price regulation on the performances of industrial symbiosis: a case study on district heating" (Sacchi, R., **Ramsheva, Y.K.**, 2017)*, which is published in *International Journal of Sustainable Energy Planning and Management*.

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In order to address sub-Q2: '*To what extend do legal and economic constraints hinder the full deployment of industrial symbiosis potentials for carbon footprint reductions of the cement industry?,* a case study of industrial symbiosis is conducted in Paper II.

Through industrial symbiosis, excess heat is supplied by industry to the utility company of Aalborg, and utilized for district heating purposes. Aalborg Municipality has an ambitious strategy to provide heating based on fossil-free source. Excess heat from industrial activity is considered part of a solution for achieving that ambition, as excess heat recovered from industry is not assigned with any environmental burden. The reason is that a potential marginal increase in heat supply, achieved through investments in heat recovery, does not lead to visible changes in the primary activity of the supplier for excess heat.

Nevertheless, a number of legal and economic constraints hinder the full exploitation of the potentials for heat recovery in Denmark. Firstly, initial investments in heat recovery infrastructure or equipment, as well as transaction costs are very high for industries to often consider profitable in the long-run. Secondly, at the time of conducting the study, the existing legislative framework (Heat Supply Act) did not fully support additional recovery of excess heat from industries, by posing a tax on recovered energy, which was generally transferred to the end-users. Lastly, a price ceiling on the recovered heat limited the economic incentive to invest in heat recovery infrastructures. A so-called 'substitution principle' set a legal limit to the price for heating for the end-user, which often reflects the lowest purchase price given to a conventional supplier - most commonly a coal-fired power plant.

In the city of Aalborg, the cement company Aalborg Portland is one of the main suppliers of excess heat recovered from the production lines of the white Portland clinker. If additional infrastructure and technology are in place, Aalborg Portland has the potential to recover double the amount of excess heat as they do today, that can, to a large extend satisfy the district heating needs of the surrounding area. Nine scenarios of district heating supply are modelled to analyse that potential. Market equilibriums for each of the scenarios are calculated, since depending on the share of excess heat supplied, the end-user price fluctuates. Furthermore, the environmental impacts of the different scenarios are compared by conducting a consequential LCA (CLCA).

Results from the study show that the price ceiling imposed on the suppliers of district heating keeps end-user price for heating low, yet, it hinders the large potential for a reduction of the carbon footprint of the district heating system. Scenario nine (with the largest share of recovered excess heat) shows a decrease of emissions from the current 153 kg CO_2-eq. per GJ distributed heat to about 11 kg CO_2-eq per GJ. Furthermore, legal and economic constraints can act as a barrier for companies to initiate investments in excess heat recovery from their processes. That may also partially hinder achieving the ambitions for Aalborg to transition towards low carbon heat sources. Finally, on a more conceptual level, the study invites for a discussion of how a ‘system’ view of ongoing initiatives for heat recovery and opportunities for those, can support Aalborg Portland in reducing emissions associated with cement production.

CHAPTER 6. DARE TO MAKE INVESTMENTS IN INDUSTRIAL SYMBIOSIS? A CONCEPTUAL FRAMEWORK AND RESEARCH AGENDA FOR DEVELOPING TRUST

This chapter includes Paper III, titled: “Dare to make investments in industrial symbiosis? A conceptual framework and research agenda for developing trust” (**Ramsheva, Y.K**., Prosman, E.J., Wæhrens, B.V., 2019)*, published in *Journal of Cleaner Production.*

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Trust is considered essential when engaging in inter-organizational partnerships, as it reduces uncertainties associated with possible upfront investments in industrial symbiosis, as well as the cross-industry nature of the collaboration. Paper II aims to address sub-Q3: ‘*‘How to develop trust when setting up industrial symbiosis partnerships?*’ through a conceptual study merging industrial symbiosis literature and management literature. Management literature is set to hold an abundancy of insights on how trust can develop in buyer-supplier relationships, which can be considered useful to implement in the context of industrial symbiosis.

A conceptual framework is proposed, combining three different notions of trust in the others’:

- **ability**: the belief that the other is able to perform a certain task
- **integrity**: the belief in the other to follow the mutual agreement or contract
- **benevolence**: the belief that the other will not act opportunistically in their own interest if a possibility arises,

This is developed through three complementary trust stages:

- **Calculus-based trust (CBT)**: based on cost estimation of the other party not acting in a trust-worthy manner
- **Knowledge-based trust (KBT)**: based on knowledge of the other party
- **Identification-based trust (IBT)**: based on knowledge of the other party sharing similar goals and thus acting for a common interest and benefit

Those stages are influenced by strategies of:

- **boundary spanners**: gathering information and knowledge about the other's activity and strategic plans
- **common identity**: shared norms and shared goals

The conceptual framework on trust proposed in Paper II can provide new insights for industries on how initial trust challenges can be overcome and how to develop sufficient levels of trust when entering an industrial symbiosis partnership. Yet, authors acknowledge the framework to be rather general and lacking empirical studies supporting the suggested trust strategies. Therefore, Paper II includes a proposal on how future studies could further expand the framework through empirical testing.

CHAPTER 7. THE NEED FOR A 'SYSTEM' PERSPECTIVE IN REALIZING CIRCULAR ECONOMY STRATEGIES

This chapter is divided in two sections. Section 7.1 contains conference Paper IV: "Applying the principles of circular economy in the context of concrete: A review" (**Ramsheva, Y.K.**, 2019)*. The paper was presented at the 19th European Roundtable for Sustainable Consumption and Production and published in the peer-reviewed conference proceedings - *Proceedings of the 19th European Roundtable for Sustainable Consumption and Production. Institute for Sustainability Science and Technology, Universitat Politècnica de Catalunya, Barcelona*, pp. 219–228.

Section 7.2 includes Paper V: "Realizing a circular concrete industry in Denmark through an integrated product, service and system perspective" (**Ramsheva, Y.K.**, Moalem, R.M., Milios, L., 2020)*, which is published in journal *Sustainability*.

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Both papers seek to jointly answer sub-Q4: *How can a 'product', 'service', and 'system' perspective support realizing circular economy strategies?'*, by applying a broader 'system' perspective on the concrete industry value chain.

Through a review of existing academic literature and technical reports, Paper IV highlights potentials and barriers for closing, slowing and narrowing resource loops. Firstly, use of recycled concrete aggregate (RCA) in new concrete, reuse of concrete elements and extend the lifetime of concrete structures are identified as key existing circular economy strategies in the context of the concrete industry. Secondly, four main barriers for realizing those strategies are identified. Barriers are considered the low cost of virgin aggregates, the high emissions associated with transportation of concrete materials and the lack of confidence in using secondary raw materials in construction, which can partially be explained by current legislation and standards not entirely supporting circular economy in the sector. Lastly, the study suggests overcoming those barriers requires collaboration with stakeholders along the whole sector value chain.

The role of inter-organizational collaboration for realizing circular economy in the concrete industry is analysed through Paper V. A conceptual framework on 'product', 'service' and 'system' is proposed and applied in the case of the concrete industry.

Authors suggest circular economy potentials and challenges can be identified through a holistic view on the 'product', 'service', and the 'system', and stakeholder collaboration has a different role in each of these dimensions. A 'product' focus is associated with 'narrowing', 'closing' and 'regenerating' resource flows through more efficient use of concrete. Stakeholder collaboration, even beneficial, is not seen as critical for realizing circular economy potentials. A 'service' perspective incorporates the product as well as associated service activities that address customer's needs. Realizing circular economy in 'service' dimension means implementing strategies for flexible design that can be adopted to existing space needs, using long-lasting concrete materials, designing-for-disassembly, which can 'slow' the end-of-life of concrete buildings. Collaboration between suppliers, service and maintenance responsible has a more crucial role in order for a 'service' to meet the needs of customers. A 'system' perspective demands shifting focus from solely a concrete structure towards the building environment in a given area. In a 'system', stakeholders along the whole value chain are considered interrelated, and realizing circular economy strategies demands establishing collaborative learning platforms and a common set of goals.

7.1. APPLYING THE PRINCIPLES OF CE IN THE CONTEXT OF CONCRETE: A REVIEW

7.2. REALIZING A CIRCULAR CONCRETE INDUSTRY IN DENMARK THROUGH AN INTEGRATED PRODUCT, SERVICE AND SYSTEM PERSPECTIVE

CHAPTER 8. DISCUSSION

This chapter includes a discussion on the role of industrial symbiosis in a low carbon cement industry and the need for a broader 'system' perspective on the whole value chain. Furthermore, reflections on the representativeness of the cement industry case, which this PhD study builds on, are presented.

8.1. THOUGHTS ON THE FUTURE OF CEMENT IN A LOW CARBON ECONOMY

Today, the cement industry is one of the largest industrial CO_2 emitters primarily for two reasons – the combustion of carbon-containing fuels and the release of chemically bound carbon during the process of calcination of the primary raw material input - limestone. Cement faces the challenge of being hard to reuse or upcycle, generating continuous demand for cement due to the current trend of population growth and urbanisation (UN Environment, 2019). Much of the existing research on the cement industry is focused on optimizing CO_2 impacts of fuel combustion, on improving the efficiency of cement kilns, on finding solutions for lowering clinker content in cement, on making new types of durable cement that require less input material (Cembureau, 2020a; Sacchi, 2018; Schneider et al., 2011). Such advancements in the cement production process and the output material have already been undertaken by cement companies, including Aalborg Portland. Nonetheless, the conducted research advocates that for the cement industry to be sustained the long run may require expanding the focus from implementing strategies with production-oriented focus to developing system innovations. A broader 'system' view allows identifying value potentials beyond those of individual businesses, as it builds on a new understanding of developing sustainable solutions for several stakeholders. This finding is further supported by scholars. For example, Braungart et al. (2007) suggests making a shift from increasing resource efficiency through optimisation of current resource flows and reduction of environmental impact, towards resource effectiveness through redesign and transformation of those material flows into regenerative ones.

In the context of the cement industry, industrial symbiosis may be considered a tool improving resource efficiency, as it urges the utilization of resources in the best possible way. A study on waste exchanges through industrial symbiosis by Prosman and Wæhrens (2019) highlights efficiency could be further supported by aligning the quality and properties of the supplied resource with the requirements set by the buyer. Industrial symbiosis exchanges at Aalborg Portland link to the circular economy strategies of 'reduce' and 'recover', and bring value potentials of diverse character – economic, environmental, social, socio-economic and even political (cf. Paper I and II).

Still, a wider view on the value potentials, constraints and prerequisites of industrial symbiosis may have an effect not only on improving resource efficiency and reducing on-site emissions, but also on supporting system innovation and transformation of existing technologies through stakeholder engagement. That idea could be exemplified through the case of the local industrial symbiosis partnership between Aalborg Portland and the utility company of Aalborg. Excess heat from cement production become source of low carbon district heating. It has been estimated that in Europe today, only about 1% of the total excess heat from industry is utilized for district heating purposes (Connolly et al., 2014). Current regulatory and fiscal barriers act as a constraint for new investments for excess heat recovery (cf. Paper II). Yet, a nation-wide study on the 2050 Danish energy vision state that district heat is certainly needed in the future of the Danish energy systems, and a supply of 3 TWh of industrial excess heat for district heating is part of the solution to renewable energy system based on zero emission sources by 2050 (Lund and Mathiesen 2009). Thus, through collaboration between cross-industry stakeholders and investments in additional infrastructure for circulating excess heat would support the objectives for supplying a low carbon source of district heating.

Another academic study worth mentioning in relation to the importance of collaboration in implementing innovative solutions, is Garud and Karnøe (2003) research comparing the wind turbine industry in Denmark and USA. Garud and Karnøe (2003) identify new technologies can either be shaped though joint step-by-step knowledge accumulation of involved actors, or through technology-push. Those are also defined by Garud and Karnøe (2003) as respectively “bricolage” and “breakthrough” tactics. The Danish “bricolage” process proved more successful compared to USA “breakthrough”, and a major impact for that outcome was the collaboration between stakeholders involved in all stages of the value chain that *“through their interactions, are able to gradually transform emerging paths to higher degrees of functionality”* (Garud and Karnøe, 2003). Garud and Karnøe (2003) argument is supported by this thesis and particularly emphasised in Paper V. Interaction between stakeholders along the whole value chain opens up the opportunity to go beyond reduction of resource use on a plant level. Establishing new forms of organization, such as collaborative learning platforms lay the foundation for refining stakeholder dynamics and form common goals. Furthermore, advancing stakeholder experience and knowledge on their joint capabilities to develop sustainable solutions could help them realize the underlying value potentials through *“bricolage approaches”* and mutual effort.

Analysis of carbon capture, utilisation and storage (CCUS) potentials fall out of the scope of this PhD study. Yet, CCUS is a technology increasingly gaining importance for managing CO_2 emission volumes from energy-intensive industrial production, and as such also from cement plants. It seems relevant to reflect on how industrial symbiosis can support CCUS.

Despite continuous efforts to improve cement production process using CO_2-neutral fuels, utilization of excess resources, improving cement properties, etc., demand for cement is only expected to increase. Thus, for the industry to make a carbon neutral future possible may require capturing and utilizing the emissions for Power to X production. Captured CO_2 emissions from cement production has possible application as, for example, fuels such as methanol, methane, Fischer–Tropsch-derived fuels, biofuels, chemicals, even concrete building materials, etc. (Hepburn et al., 2019). The utilization of captured CO_2 emissions represents a new industrial symbiosis potential for Aalborg Portland or any other cement plant. That opportunity supports the grand findings of this dissertation that industrial symbiosis is an effective means for low carbon economy. Yet, a potential big step towards CCUS technology may require a *"bricolage"* method of step-by-step learning process for gradually shaping this technological path, as proposed by Garud and Karnøe (2003).

8.2. REFLECTIONS ON THE REPRESENTATIVENESS OF THE CASE ON THE CEMENT INDUSTRY

This dissertation builds on the premise that findings from the industrial symbiosis at Aalborg Portland can provide lessons of wider relevance, as to whether industrial symbiosis is indeed as an effective means for transitioning into a low carbon economy. This makes it critical to reflect upon the wider representativeness of the case on cement production and the particular role of Aalborg Portland's geographical setting in Northern Denmark.

According to Yin, (2009), one reason to apply a single case study design is if a case could be considered 'extreme' or is particularly distinctive. In many ways, cement production can be considered a rather extreme industry case due to the high-energy intensity of the production process, the hardly avoidable process of the chemically bound carbon released as CO_2, the current low (up)cycling rate of the end product. Looking within the boundaries of the cement production sites, the cement industry is set to realize circular economy principles and strategies through using alternative sources as input fuels, substituting clinker with alternative raw materials, reducing clinker content in cement, exchanging excess resources from the production process. Still, chemically speaking, there exist boundaries to how alternative resources can be utilized during the cement production process without compromising the material properties or how much excess heat, water, or other production-related resources can be captured. That makes cement a somewhat extreme case in comparison to many other industries, where products can potentially be taken back, disassembled and the materials can be reused in new products. Yet, due to the heavy resource flows (in terms of energy, water, wastes, etc.) made possible through inter-organizational exchanges, the cement industry can be considered a good demonstrative case for exploring the potentials of industrial symbiosis.

Furthermore, the geographical and regulatory setting of the cement company under analysis may have a certain contribution to the central role of industrial symbiosis as a successful emission prevention strategy. Reflecting back on Garud and Karnøe (2003) study on the wind turbine industry, regulations and policies are considered key in shaping the emergence and advancement of certain technologies. The Danish cement company Aalborg Portland is situated in a well-regulated (Transparency International, 2020), Northern Europe context, with both EU and national legislation heavily influencing the future of the cement industry (Cembureau, 2020a; European Commission, 2020b). With that setting in place, one should consider whether it would be possible to establish such a large number of industrial symbiosis partnerships in all cement production sites worldwide to the same extend as they are established today in a Danish context.

CHAPTER 9. CONCLUSIONS AND RECOMMENDATIONS

The chapter concludes this PhD dissertation with a summary of the overall research aim and main contributions as well as with proposals for possible future research.

9.1. ADVANCING THE FIELD OF INDUSTRIAL SYMBIOSIS ON FOUR THEMES

This PhD study was set out to explore the following main research question:

What new knowledge can be gained from the cement industry on the role of industrial symbiosis for realizing a low carbon economy?

New knowledge is in this thesis considered as either a contribution to scholarly research or as adding new insights to the practice of setting up, developing or maintaining industrial symbiosis partnerships. The main research question is answered through four sub-questions, which are explored in five academic papers on the following themes of industrial symbiosis: value potentials, constrains, prerequisite and the need to apply a system perspective in realizing circular economy strategies. Aalborg Portland, the single grey and white cement producer in Denmark, was the main source of data for the academic studies. The knowledge gaps outlined in Chapter 2 were addressed through answering the following sub-questions:

sub-Q1: What value potentials does industrial symbiosis offer the cement industry?

It was found that all the twelve industrial symbiosis cases of Aalborg Portland hold economic and resource value potentials (cf. Paper I). Yet, it was found that local industrial symbiosis partnerships also offer value potentials of socio-economic and even political character.

The value potentials of the twelve industrial symbiosis were found to translate into circular economy strategies of resource "reduction" and "recovery". As emphasised in section 2.3, those strategies are not considered with highest priority in comparison to 'repair/maintain' or 'reuse/redistribute' strategies, see figure 2.4. Prioritizing the smaller circular economy loops would require expanding focus beyond the product and towards a system, in which collaboration between stakeholders become even more central.

The study contributes to the current industrial symbiosis literature by diversifying the understanding of value potentials and highlighting the need to expand the analytical scope to the "concrete system" as opposed to merely cement production when realizing circular economy principles and strategies.

sub-Q2: To what extend do legal and economic constraints hinder the full deployment of industrial symbiosis potentials for carbon footprint reductions of the cement industry?

Legal and economic constraints hinder a carbon footprint reduction potential of the district heating network in Aalborg by up to 93% in comparison to present state (cf. Paper II). Assuming that the existing constrains are lifted and the share of excess heat delivered through industrial symbiosis increases from the current 43% up to 90% of the heat supply mix, CO_2-emissions could be reduced from about 153 kg of CO_2-eq. per GJ to about 11 kg of CO_2-eq. per GJ (Sacchi and Ramsheva, 2017). Yet, such a change in the supply mix of the distributed heat for the city of Aalborg could result in more than a 40% price increase in comparison to current heat prices. This relationship between substantial environmental potentials at the expense of high increases in heating prices calls for a political and academic discussion on the role of industrial symbiosis in developing local, sustainable heating sources for a low carbon economy.

sub-Q3: How to develop trust when setting up industrial symbiosis partnerships?

Trust is considered a prerequisite for establishing industrial symbiosis partnerships. The research suggests that trust emerges and progresses from calculus-based trust (CBT) - based on a cost-benefit analysis of an industrial symbiosis partnership, towards knowledge-based trust (KBT) – based on foreseeing the other’s credibility, to identification-based trust (IBT) – based on the motivation to achieve common goals (Ramsheva et al., 2019).

The developed conceptual framework on trust (cf. Paper III) presents a number of strategies for enabling the notions of trust in the ability, integrity and benevolence when setting up industrial symbiosis partnerships. It was found that CBT could be developed through boundary spanners, who could gain an understanding in the other party’s ability, integrity and benevolence. Moving to KBT, boundary spanners also play a central role, yet existing common goals could foresee the other’s integrity and benevolence. IBT could be realized though boundary spanners and common goals, which could possibly predict the ability, integrity and benevolence of the industrial symbiosis partner.

sub-Q4: How can a 'product', 'service', and 'system' perspective support realizing circular economy strategies?

A broader 'product', 'service' and 'system' perspective is applied to the case of the concrete industry (cf. Paper V). It was found that a 'product' focus could bring savings on resource costs, leading to increased resource efficiency in terms of use and reduction of concrete waste amounts. A 'service' focus builds on the value potentials offered by a 'product' perspective and opens up new market prospects for concrete producers to offer supplementary services to users, such as monitoring and renovation of concrete buildings. The 'system' could be viewed as the built environment with cement-based products.

The study shows that a broad 'system' perspective on the value chain of concrete unlocks the smaller circular economy loops by looking beyond the bounds of individual stakeholders. Such a broad perspective calls for the establishment of learning platforms based on stakeholder collaboration and common goals that can result in effective resource management and utilization (cf. Paper IV and V). The development of sustainable solutions through a 'system' focus could address the current and future user needs, and be a step closer to a low carbon economy.

9.2. KNOWLEDGE CONTRIBUTIONS ON THE ROLE OF INDUSTRIAL SYMBIOSIS

Drawing conclusions across the five studies, this thesis responds to the main research question by new knowledge to scholarly literature and practice on industrial symbiosis. This is done partly through research on industrial symbioses with substantial emission reductions, partly by studies on better understanding the constraints, prerequisites and wider dynamics of developing and maintaining such partnerships:

Firstly, this thesis contributes to the current industrial symbiosis literature by identifying and diversifying value potentials and linking these to circular economy principles and strategies (cf. Paper I).

Secondly, this thesis contributes with empirical data on the extent to which legal and economic constraints may hinder the development of industrial symbiosis partnerships with substantial emission reduction potentials (cf. Paper II).

Thirdly, this thesis contributes with knowledge on how trust strategies could apply to successfully establish industrial symbiosis partnerships (cf. Paper III). For industries, the conceptual framework on trust may be useful to understand the complexity of inter-organizational relationships and the central role that trust may have as a prerequisite for establishing collaborative activities.

Fourthly, this thesis contributes with a ‘product’, ‘service’, ‘system’ framework for realizing circular economy strategies (cf. Paper IV and V). Through a case study on the concrete sector, it was found that especially a broad ‘system’ perspective supports realizing circular economy strategies through stakeholder collaboration across the value chain.

Overall, this thesis contributes to the academic literature and field of industrial symbiosis by further diversifying the understanding of value potentials, by assessing legal and economic constraints, by conceptualizing trust as a prerequisite, and by both conceptualizing and exemplifying the need for collaboration across the value chain on a ‘system’ level. Focus on collaboration between value chain stakeholders could be considered one means to overcome underlying constraints and establish common goals for venturing into a low carbon economy.

9.3. AVENUES FOR FUTURE RESEARCH

Due to the comprehensive scope of industrial symbiosis topic and the broad research questions this thesis raised, a number of topics could still be addressed through future research. A few of those are proposed in this section.

This research is to a large extend based on analysing inter-organizational dynamics in terms of value potentials, constraints, prerequisite, and the role of a ‘system’ focus, in realizing the potentials for carbon neutrality. To advance the obtained findings, attention could turn towards the intra-organizational perspective. The capabilities and activities that organizations need to develop internally could add valuable insights to both academia and practice.

In this research, focus has been placed on the case of the cement industry and on the building industry, when analysing the benefits of a ‘system’ perspective (cf. Paper V). Thus, the attained findings may be subjective to the defined scope. Future research could expand the focus to other contexts. In-depth case studies on other industries could uncover new knowledge on the role of stakeholder collaboration and establishment of shared goals and norms for realizing circular economy strategies.

The ambitions set out by the European Commission (2020a) entitles energy intensive industries, such as cement, to find solutions for reducing emissions and aim at reaching carbon neutrality by 2050. Capture and use of carbon dioxide for diverse application is considered a possible, yet, highly debatable solution for removing CO_2 from the atmosphere and utilizing it for the production of fuels, chemicals, materials, etc. A logical next step is to explore the role of industrial symbiosis partnerships in the implementation and operationalisation of technologies for carbon capture usage and storage (CCUS).

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SUMMARY

Through studying the cement industry, this dissertation aims to further academic knowledge and public awareness on how industries could reach carbon neutrality. The environmental impact of the construction sector is growing due to rising population and urbanisation. Cement is a widely used building material due to its performance, cost, and availability, but its production process is highly energy intensive and emits vast amounts of greenhouse gases. The sector faces major challenges with meeting the climate target of the European Union (EU) on reaching carbon neutrality by 2050. Industrial symbiosis is considered central for transitioning industries towards a low carbon economy. Industrial symbiosis is about establishing partnerships for the exchange of diverse waste, by-products and information between industries. Today, industrial symbiosis between cement producers and other industries contributes to the reduction of waste and greenhouse gas emissions. Such cross-sector partnerships are widely seen as a prime facilitator for circular economy, which as a development strategy has the potential to decarbonize the industry. Thus, understanding the role of industrial symbiosis in the cement industry may help to unveil knowledge on how to transition towards a low carbon economy, in cement production as well as in other industries. Building on the five studies, this research presents a diversified understanding of value potentials, assess legal and economic constraints, conceptualizes trust as a prerequisite, and both conceptualizes and exemplifies the need for collaboration across the value chain on a 'system' level.

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