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Navigating Industrial Symbiosis Complexity

Understanding Actors' Perspectives for Enhanced Collaboration

Harfeldt-Berg, Lovisa

2025

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DOCTORAL DISSERTATION

Doctoral dissertation for the degree of Doctor of Philosophy (PhD) at the Faculty of Engineering at Lund University to be publicly defended on 13th of June at 09.00 in lecture hall V:A in the V-building on John Ericssons väg 1, Lund.

Faculty opponent
Professor Patrik Thollander. Linköping University.

Organization: LUND UNIVERSITY

Document name: Doctoral dissertation **Date of issue:** 2025-06-13

Author(s): Lovisa Harfeldt-Berg **Sponsoring organization:** Swedish Energy Agency

Title and subtitle: Navigating Industrial Symbiosis Complexity - Understanding actors' perspectives for enhanced collaboration

Abstract:

Industrial symbiosis is a collaborative approach that aims to enhance resource efficiency and sustainability by facilitating exchanges between industries and other societal actors. Traditionally, industrial symbiosis focused on optimizing physical resource flows, such as excess energy, waste materials, and by-products. However, over time, the concept has expanded to also include, for example, collaboration regarding infrastructure, logistics, and knowledge exchange, fostering more sustainable and resilient systems. This evolution reflects the growing recognition that industrial symbiosis is not just about improving existing resource flows, but also about creating innovative, long-term solutions to complex environmental and societal challenges. To begin with, this thesis explores how the varying perspectives and conditions of individual actors - such as industries, public actors, associations, academia, and other research institutions - affect collaborations in industrial symbiosis. By examining the factors that drive or hinder participation in these collaborations, including the expected benefits and perceived risks, this research provides valuable insights into the dynamics of industrial symbiosis collaborations. The thesis employs qualitative research methods to identify the challenges and opportunities that arise when different actors with diverse priorities collaborate. Based on the knowledge generated in this thesis, a key outcome is the development of two tools aimed at facilitating the implementation and development of industrial symbiosis initiatives. One tool helps map the distribution of benefits and drawbacks across different impact levels, while the other serves as a guiding framework for evaluating and supporting the implementation process. These tools are designed to improve communication, align objectives, and enhance decision-making among actors, ultimately promoting more effective and sustainable collaborations. The findings highlight that successful industrial symbiosis requires a comprehensive understanding of the complex, dynamic relationships between actors. By acknowledging these differences and fostering better collaboration, industrial symbiosis can help build more resilient and sustainable systems for the future.

Key words: Industrial symbiosis, actor perspectives, qualitative research, influencing factors, benefits, adverse effects, evaluation tools.

Classification system and/or index terms (if any) Supplementary bibliographical information

Language: English **ISSN and key title**: 1102-3651

ISBN (print): 978-91-8104-473-7 **ISBN (electronic)**: 978-91-8104-474-4

Recipient's notes **Number of pages**: 82

Price Security classification

Signature Date: 2025-04-22

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Department of Technology and Society

ISBN (print) 978-91-8104-473-7
ISBN (electronic) 978-91-8104-474-4
ISSN 1102-3651
ISRN LUTFD2/TFEM--25/1051--SE + (1- X)

Printed in Sweden by Media-Tryck, Lund University
Lund 2025

To Arvid and Hedda

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Abstract

Industrial symbiosis is a collaborative approach that aims to enhance resource efficiency and sustainability by facilitating exchanges between industries and other societal actors. Traditionally, industrial symbiosis focused on optimizing physical resource flows, such as excess energy, waste materials, and by-products. However, over time, the concept has expanded to also include, for example, collaboration regarding infrastructure, logistics, and knowledge exchange, fostering more sustainable and resilient systems. This evolution reflects the growing recognition that industrial symbiosis is not just about improving existing resource flows, but also about creating innovative, long-term solutions to complex environmental and societal challenges.

To begin with, this thesis explores how the varying perspectives and conditions of individual actors - such as industries, public actors, associations, academia, and other research institutions - affect collaborations in industrial symbiosis. By examining the factors that drive or hinder participation in these collaborations, including the expected benefits and perceived risks, this research provides valuable insights into the dynamics of industrial symbiosis collaborations. The thesis employs qualitative research methods to identify the challenges and opportunities that arise when different actors with diverse priorities collaborate.

Based on the knowledge generated in this thesis, a key outcome is also the development of two tools aimed at facilitating the implementation and development of industrial symbiosis initiatives. One tool helps map the distribution of benefits and drawbacks across different impact levels, while the other serves as a guiding framework for evaluating and supporting the implementation process. These tools are designed to improve communication, align objectives, and enhance decision-making among actors, ultimately promoting more effective and sustainable collaborations.

The findings highlight that successful industrial symbiosis requires a comprehensive understanding of the complex, dynamic relationships between actors. By acknowledging these differences and fostering better collaboration, industrial symbiosis can help build more resilient and sustainable systems for the future.

Populärvetenskaplig sammanfattning

För att skapa ett hållbart och resurseffektivt samhälle krävs nya, mindre miljöbelastande produktions- och konsumtionsmönster. De nödvändiga förändringarna i industrin och samhället i stort är omfattande. Därför pågår flera initiativ som driver samhället mot ökad resurs- och energieffektivitet. Ett exempel är industriell symbios.

Industriell symbios handlar om hur industrier och andra samhällsaktörer kan samarbeta för att använda resurser mer effektivt och skapa långsiktigt hållbara system. Traditionellt har industriell symbios fokuserat på samarbeten kring fysiska resursflöden, såsom utbyte av överskottsenergi, överblivet material och restprodukter, där en industris överskott eller avfall kan bli en värdefull resurs i en annan industris produktion. De senaste åren har fokus dock skiftat från att industriell symbios främst har handlat om att optimera befintliga resursflöden till att samarbeta för att skapa helt nya, mer hållbara och resilienta system. Industriell symbios omfattar därmed inte bara fysiska resursflöden utan även infrastruktur, logistik och kunskapsutbyte. Genom att samverka kan aktörer tillsammans utveckla innovativa lösningar och bygga robusta, mer hållbara system.

I dessa samarbeten involveras därför inte enbart industriföretag, utan även offentliga aktörer, akademi och andra samhällsaktörer. Denna bredd av deltagare bidrar till att skapa dynamiska och innovativa nätverk, men innebär samtidigt att nätverken blir komplexa. Detta skapar utmaningar när det gäller styrning och samordning. För att industriell symbios ska utvecklas och fungera i praktiken är det avgörande att förstå och beakta de varierande förutsättningar som olika aktörer har för att delta i samarbetet.

Aktörernas engagemang påverkas av en rad faktorer, såsom specifika drivkrafter, potentiella hinder, förväntade nyttor och upplevda risker. Eftersom dessa faktorer kan skilja sig avsevärt åt mellan olika aktörer är det viktigt att skapa en samarbetsmodell som tar hänsyn till dessa olikheter. Denna avhandling undersöker därför hur individuella aktörers olika perspektiv och förutsättningar påverkar samarbeten i industriell symbios samt hur samverkan kan stärkas genom att öka förståelsen för detta. Genom en litteraturstudie och två fallstudier analyserar jag drivkrafter, barriärer samt potentiella nyttor och negativa effekter av dessa samarbeten. Studierna visar att framgångsrik industriell symbios kräver en förståelse för aktörernas skilda förutsättningar och att dessa olikheter beaktas i samarbetet.

Ett centralt resultat i avhandlingen är utvecklingen av verktyg för att facilitera utvecklingen av industriell symbios. Verktygen kan hjälpa deltagare att navigera samarbetet genom att konkretisera olika perspektiv samt skapa en gemensam modell för hur man hanterar olika aspekter av samarbetet. Detta bidrar till att stärka kommunikationen mellan aktörer, identifiera utvecklingsområden och skapa en gemensam grund för diskussion och beslut.

Sammanfattningsvis visar avhandlingen att industriell symbios inte enbart handlar om resursoptimering utan kanske främst om att förstå och hantera komplexa och dynamiska system. Genom att skapa samarbetsmodeller som tar hänsyn till detta kan mer långsiktigt hållbara och effektiva system byggas för framtiden.

List of papers

Paper I

Harfeldt-Berg, L., Broberg, S., & Ericsson, K. (2022). The importance of individual actor characteristics and contextual aspects for promoting industrial symbiosis networks. *Sustainability*. 14(9), 4927. https://doi.org/10.3390/su14094927

Paper II

Harfeldt-Berg, L, and, Harfeldt-Berg, M. (2023) Connecting organizational context to environmental sustainability initiatives and industrial symbiosis: Empirical results and case analysis. *Sustainable Production and Consumption,* 40, 210-219. https://doi.org/10.1016/j.spc.2023.06.023

Paper III

Harfeldt-Berg, L. (2024). Distribution of benefits and adverse effects and their role in industrial symbiosis decision-making – A Swedish case study. *Cleaner Environmental Systems*, 13, 100202. https://doi.org/10.1016/j.cesys.2024.100202

Paper IV

Harfeldt-Berg, L., Löwgren, A., Wallin, E., Sommarin, P. Industrial symbiosis readiness – A matrix tool. Submitted to journal.

Author's contribution to the papers

Paper I

I designed and conducted the literature review, I wrote the original draft and conducted review and editing. Karin Ericsson and Sarah Broberg supported through supervision and valuable comments to the draft.

Paper II

I have been involved in every part of this paper from conceptualization to writing the draft. However, we divided key responsibilities: my co-author was primarily responsible for obtaining and processing suitable survey data in the HPM data material and I was primarily responsible for designing the questionnaire and interview protocols used during the case study. When it came to conducting interviews, transcribing, analyzing the material, and writing the paper, we contributed equally.

Paper III

I am the sole author of this paper.

Paper IV

I was actively involved in every aspect of this paper, although my co-authors and I had different responsibilities when collecting the qualitative data and feedback from stakeholders involved in the testing of the tool developed in this paper. In the data collection process, my primary role was leading the interview study at Händel Eco-Industrial Park. The analyses of the collected data were conducted jointly in internal workshops within the research team. My co-authors and I contributed equally to the development of the tool. I wrote the majority of the paper, incorporating valuable comments and written contributions from my co-authors.

Acknowledgements

As the Beatles once sang, "*I get by with a little help from my friends*". This sentiment has been at the heart of my PhD journey. Throughout this process, I have been fortunate to receive invaluable support, guidance, and encouragement from many incredible people. Completing this thesis would not have been possible without the help of my family, friends, supervisors, and colleagues, who have offered their expertise, shared their wisdom, and provided encouragement at every step. This work is not only a result of my own efforts but also a reflection of the collaborative spirit and generosity that have shaped my time as a PhD student.

To begin with, I would like to express my deepest gratitude towards my supervisors, both past and present. Karin, who has been there from the very beginning, providing support, insightful feedback, and consistent encouragement throughout this entire journey - your guidance has been very appreciated. Hanna, who has contributed significantly to the development of my work, especially in the final stages. Your expertise, feedback, and thoughtful input have been crucial in shaping my last years as a PhD student. Sarah, who made this project possible by being one of the initiators. Thank you for supervision, support, and for sharing your knowledge regarding industrial symbiosis in the beginning when I knew little to nothing about the concept. And Lars, thank you for interesting and rewarding discussions, as well as valuable insights and feedback along the way.

To my PhD colleagues, both at IMES and in FoES, past and present - thank you for sharing this journey with me and for making it so much more enjoyable. From playing Dixit on a sailing boat, to fun conversations in hot tubs on hotel roofs, and boules games filled with competitive spirit and laughter, these moments of fun have been incredibly valuable. I am so impressed by each of you, and it is safe to say that great things will happen while you're in the world.

To my other colleagues at RISE and IMES, for providing a thriving context to work in. Especially to Elin, Annika, and Per for great partnership in developing and writing my fourth and final paper, it would not have been possible without the three of you. And just as important, I also want to express a special thank you to Fredric, Max, Johanna, Rickard, and Shane for invaluable feedback and support throughout various stages of my thesis writing.

To my close circle of friends, both near and far, for always being there cheering me on. You are a constant reminder of the fun things that exist outside work. I am truly grateful for each of you and the role you have played in keeping me sane, grounded, and laughing along the way. A special thanks to my little book circle, engaging me in fun reading at times when the pile of academic papers became too daunting.

To my parents and sister, starting this acknowledgment with a Beatles quote is not chosen at random. Throughout my childhood, the tunes of sixties' music, particularly the timeless songs of the Beatles, the Four Seasons, and the Drifters, were a constant presence in our home. The melodies and lyrics provided a backdrop to many moments of joy and togetherness. Thank you for always being a solid element in my life, both in my childhood and growing up, but also in the very real struggles of adulthood.

Last, but surely not least, to my ever-so-loved family. Arvid and Hedda, you define my proudest moments. Although I am proud of seeing my PhD journey through, it does not come close to how proud you make me every single day. I am so, so proud of being your mom. Magnus, no words can truly capture how grateful I am for your endless support throughout this journey. You have been by my side not only as my husband but also as a co-author, a sounding board, and a source of laughter when I truly just wanted to cry. I couldn't have done this without you, and I wouldn't have wanted to. Thank you for being my partner in life, in research, and in not taking things too seriously, at least not ourselves. This thesis may mark the end of one long journey, but you, and our children, will always be my greatest adventure.

Lovisa Harfeldt-Berg
April, 2025

Abbreviations

BRL – Business Readiness Level

CEAP – Circular Economy Action Plan

CODP – Customer Order Decoupling Point

CORALIS – Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis

ERL – Environmental Readiness Level

FoES – Graduate School in Energy Systems (Forskarskolan Energisystem)

HEIP – Händelö Eco-Industrial Park

HPM – High Performance Manufacturing

ISRLM – Industrial Symbiosis Readiness Level Matrix

LRL – Legal Readiness Level

MTO – Make-to-order

MTS – Make-to-stock

ORL – Organizational Readiness Level

SCS – Sotenäs Center of Symbiosis

SMRC – Sotenäs Marine Recycling Center

SRL – Societal Readiness Level

TIRL – Technology and Integration Readiness Level

WFD – Waste Framework Directive

1 Introduction

Waste… what a nuisance!? The word itself carries multiple meanings, yet in almost every context, it invokes a negative connotation. Whether it is the waste of time, the waste of money, or the waste of resources, the term consistently signals a loss of value. In all cases, waste is a reminder of something lost or underutilized, something that could have been turned into something valuable but, instead, became a burden. Whether tangible or intangible, waste represents a gap in potential. The very concept of waste typically stirs frustration as it often symbolizes excess, inefficiency, and the failure to optimize. As society becomes increasingly aware of the environmental and economic consequences of waste, the term takes on an even heavier weight, tied to concerns about sustainability, climate change, and resource scarcity. Waste, then, isn't just a nuisance - it's a symbol of the need for improved systems, processes, and different mindsets.

Waste is an ever-growing problem as the global production and consumption of goods continues to increase (UNEP, 2024). Every product produced comes with significant footprints in terms of emissions, water use, and significant amounts of wasted resources. In 2008, the EU adopted the Waste Framework Directive (WFD), seeking to establish clearer definitions and guidelines for waste management including key concepts such as waste, recycling, and resource recovery from waste (Directive, 2008/98/EC.). In 2018, the WFD was supplemented with an amendment to further define and regulate waste and its related concepts (Directive, 2018/851). In this amendment industrial symbiosis is highlighted as a key component in how industries can increase circularity through close collaborations on resource recovery between different industrial or societal actors. In addition, the Circular Economy Action Plan (CEAP), first adopted by the European Commission in 2015 and updated in 2020 (European Commission, 2015, European Commission, 2020), emphasizes industrial symbiosis as a promising strategy for transitioning from linear production and consumption models to more circular resource pathways.

Industrial symbiosis is traditionally defined as a collaborative initiative between conventionally independent industrial actors, aiming to enhance efficiency by optimizing the flow of resources between them (Chertow, 2000). However, over the past decades, the concept of industrial symbiosis has evolved and expanded (Lombardi and Laybourn, 2012). Rather than being viewed solely as a physical network that enhances resource efficiency within existing structures, industrial symbiosis can also be understood as a broader collaborative framework, one that actively challenges conventional systems and drives the transition toward more sustainable alternatives (Lombardi and Laybourn, 2012). In this sense, industrial symbiosis collaborations are not limited to industrial actors alone but also involve a diverse range of stakeholders, including municipalities, facilitating organizations, associations, policymakers, and research institutions.

When managed effectively, industrial symbiosis holds the potential to deliver significant economic, environmental, and social benefits through, for example, cost savings and additional revenue streams, emission and pollution reduction, new job opportunities and innovative force (Cui et al., 2018, Dong et al., 2017, Fraccascia et al., 2021, Mirata et al., 2024, Sun et al., 2017). Through the adoption of industrial symbiosis, industries and society can repurpose wasted resources, transforming them from being viewed as waste into valuable assets, thereby, in some sense, redefining the concept of waste itself.

However, despite its potential in theory, the adoption of industrial symbiosis initiatives in practice has been slow, and its full benefits remain largely unrealized. Moser and Rodin (2021) call this shortfall "the industrial symbiosis gap", which highlights the difference between what is feasible and what is realized, and various challenges contribute to this slow pace of implementation (Domenech et al., 2019, Kosmol and Otto, 2020, Neves et al., 2019b). Challenges can sometimes arise from an unwillingness to collaborate due to distrust between partners (Bacudio et al., 2016). Other times, they stem from technical or economic issues, and in some cases, there is insufficient regulatory or political support for these initiatives (Aid et al., 2017, Golev et al., 2015, Patricio et al., 2018, Päivärinne et al., 2015, Sakr et al., 2011). While the main objective of industrial symbiosis is to collaborate regarding underutilized resources and inefficiencies, improper planning or poor execution can result in unintended negative consequences, such as lock-in effects or inefficient resource use (Janipour et al., 2022, Walls and Paquin, 2015, Wolf et al., 2005). The complexity industrial symbiosis entails makes organizing and planning collaborations challenging and the coordination of resources, technology, and strategic goals can be difficult to align. This, in turn, can lead to inefficiencies or disruptions in collaboration. Since successful industrial symbiosis depends on strong partnerships, collaboration is a fundamental prerequisite (Cervo et al., 2019, Katana et al., 2024, Taddeo et al., 2012).

Many challenges posed to industrial symbiosis are related to the fact that these networks consist of multiple, essentially different individual actors. Actors differ in size, resources, industry affiliation, strategic vision, and ownership structure (Aid et al., 2017, Fraccascia et al., 2020, Henriques et al., 2022, Madsen et al., 2015). Each individual actor brings a unique set of preferences that shape its strategies and decisions (Klerkx and Aarts, 2013, Kokoulina et al., 2019, Scott, 2000, Wilkinson and Klaes, 2012), which makes industrial symbiosis collaborations inherently complex (Kosmol and Esswein, 2018). The heterogeneous nature of industrial symbiosis networks creates a dynamic environment shaped by the individual actors and their unique context (Corder et al., 2014). To fully realize the potential of industrial symbiosis, it is essential to understand each actor and their unique contextual setting - including aspects such as what type of resource to be exchanged, their geographic location, sector affiliation, regulatory and political environment, financial pre-conditions, and ownership structure, among others. The individual actor perspective is however a rare sighting in academic literature and industrial symbiosis research (Ji et al., 2020, Walls and Paquin, 2015). Up until this point, most research has focused on industrial symbiosis from a network perspective, not considering the role of the individual actors shaping the system.

My own interest in industrial symbiosis lies in understanding the interconnected nature of these networks while also recognizing the distinct components that comprise the system. This dual focus is, to me, what makes industrial symbiosis both intriguing and complex. The inherent complexity of industrial symbiosis, characterized by the diversity of actors involved, requires a detailed exploration of the dynamics that shape these collaborations. Therefore, in this thesis I intend to explore the actor perspective in industrial symbiosis, examining the factors that influence the interplay and functionality of these collaborative efforts. By emphasizing the importance of trust, effective communication, and aligned objectives among partners, this research sets out to illuminate how various elements affect decision-making processes for different actors. By understanding how different elements influence each actor’s decisions, this research provides practical insights for building stronger partnerships and successfully implementing industrial symbiosis initiatives.

1.1 Objectives and research questions

When I first started my PhD journey, I thought that my research topic was given to me paper in hand. Obviously, it turned out a little more complex than that. At the outset of my PhD studies, I thought my contribution would be to identify and monetize effects of industrial symbiosis networks. However, as I delved into the literature, what intrigued me the most was the complexity inherent in industrial symbiosis networks.

This curiosity led me to question how to reconcile the diverse interests of multiple different actors into a cohesive collaboration that ideally benefits all, both the actors involved and society at large.

As my journey progressed, two overarching research objectives crystalized, serving as the guiding principles for this thesis. To achieve these objectives, supporting questions for each objective were formulated.

Objective 1

To better understand the role of individual actor perspectives and contextual aspects in industrial symbiosis, and how individual differences affect the dynamics and complexity of its implementation.

- How do contextual aspects impact the factors that influence actors' participation in industrial symbiosis?
- How do the individual actors' perceptions of benefits and adverse effects of industrial symbiosis influence the decision to participate in industrial symbiosis?

Objective 2

To facilitate the implementation and development of industrial symbiosis through provision of tools to guide and assess its development and implementation.

- How can we better understand the distribution of benefits and adverse effects from industrial symbiosis initiatives across actors, the industrial symbiosis network, and society?
- How can the implementation of industrial symbiosis networks be facilitated by accounting for their complexity and the diverse characteristics of participating actors?

Achieving the two research objectives in this thesis will 1) help shed light on the role of individual actors in industrial symbiosis and how their individual differences add to the complexity these networks entail, and 2) help actors navigate complex collaborations through tools provided for guidance and assessment. This in turn can narrow the gap between potential and realized implementation of industrial symbiosis.

Table 1 gives an overview of the appended papers and how they relate to each objective. For each paper, the table presents the connections to the research objectives and an overview of the methods and the primary research focus.

Table 1. Overview of the appended papers.

	Paper I	Paper II	Paper III	Paper IV
Objectives addressed	1	1	1, 2	2
Methods	Systematic Literature Review	Mixed methods approach Case study and survey-based study including: - Statistical analyses - Questionnaire - Interviews - Qualitative data analyses	Case study research Embedded single case study - Questionnaire - Interviews - Qualitative data analyses - Tool development	Tool development through co-design - Literature review - Interviews - Workshops - Testing and validation
Data	Literature	Survey-based quantitative data Qualitative data from interviews and questionnaire	Qualitative data from interviews and questionnaire	Literature Qualitative data from interviews and workshops
Specific research aims	To explore whether and how the indiviudal actor perspective on factors that drive, inhibit and enable industrial symbiosis is acknowledged in present literature.	To investigate how drivers and barriers may differ depending on organizational context and how these factors may differ between general sustainability initiatives and a specific industrial symbiosis initiative.	To explore differences between individual actors in a specific industrial symbiosis network regarding their experiences of benefits and adverse effects generated by the industrial symbiosis and to create a framework for impact assessment.	To develop a tool to assess the readiness level of an industrial symbiosis network and a guide to facilitate its development.
Main findings	Perceptions of drivers, barriers, and enablers depend on actor characteristics and the context. These differences influence: - Business opportunities and risks - Inequalities in the network - Regulatory and political factors	Drivers and barriers to sustainability initiatives vary based on organizational context, in this study distinguished by the customer order decoupling point (CODP). This pattern was not observed in the case study, suggesting that further research involving more actors and larger resource flows would be valuable.	Actors perceive varying types and levels of benefits and adverse effects. Benefits primarily drive decisions to engage in industrial symbiosis collaborations. Adverse effects are less considered than the potential benefits. An Impact Assessment Matrix helps map the distribution of these effects.	A tool for guidance and assessment of industrial symbiosis. The tool assists in both guiding industrial symbiosis development and evaluating its readiness. The results provide a basis for discussion among actors in collaboration to identify activities to develop further and align strategies and common goals.

1.2 Scope and delimitations

As is true for all forms of research, there are some delimitations associated with the work presented in this thesis. Firstly, I would like to address how the concept of industrial symbiosis has been understood in this thesis. In the literature, industrial symbiosis is referred to in various ways, concepts such as eco-industrial parks, industrial ecosystems, industrial and urban symbiosis, and virtual industrial symbiosis are used interchangeably. In this thesis, however, the term "industrial symbiosis" will be used consistently as the primary reference. One can also find different definitions of industrial symbiosis and it is possible to define it as a strictly industrial collaboration. However, I have used the concept in a wider, more encompassing way, including collaborations across a variety of actors and societal contexts. I do this because in practice, many industrial symbiosis collaborations rely on support from local governments, other actors in the public sector, associations, financiers, and investors. Without these non-industry actors doing their part, the application of industrial symbiosis collaborations would be even more limited. For example, in a Swedish context, industrial symbiosis often constitutes a multi-actor collaboration where the roles of non-industrial participants, such as municipalities and facilitating organizations, are important. These non-industrial actors often serve as catalysts and coordinators, bridging gaps between industries and fostering an environment favorable to collaboration. They may provide resources, policy support, infrastructure, and land for establishing new businesses, ensuring that diverse stakeholders can participate effectively in collaboration. Therefore, I find it too restrictive to merely study the industrial players involved in industrial symbiosis networks.

Secondly, this thesis work has primarily been empirically driven and a large part of the work is based on data collected from Swedish case studies. This limits the extent to which the results can be extrapolated. That being said, the research presented in the thesis has international representation in the form of collaborations with industrial symbiosis networks on continental Europe, participating in the CORALIS[1] project.

Finally, a third limitation which is also associated with the case studies has to do with the method itself. Since I have primarily used qualitative analysis techniques, the results presented in the thesis should not be considered objective measurements of what is

[1] CORALIS - Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis (CORALIS), which has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 958337.

studied. In general, this type of method does not allow one to make claims of causal relationships or absolute “truths” (Flyvbjerg, 2006). However, this is not the point of the research conducted either, but it is nonetheless worth mentioning. The research presented in this thesis instead aims to broaden the understanding of the interplay between different industrial symbiosis actors by exemplifying when and how the complex and dynamic nature of industrial symbiosis matters.

1.3 Thesis outline

The following chapters of this thesis are structured as follows: Chapter 2 provides an introduction to industrial symbiosis, tracing its evolution since the term was first introduced. Chapter 2 also presents and explains key related concepts that are central to this thesis. In Chapter 3, I detail my research approach and provide a reflection on the selected methods. Chapters 4 and 5 address the overarching research objectives outlined in Section 1.1. Specifically, Chapter 4 focuses on the role of individual actors, their differences, and how these factors influence the dynamics and complexity of implementing industrial symbiosis. Building on the insights from Chapter 4, Chapter 5 presents frameworks for guidance and assessment to support industrial symbiosis implementation. Chapter 6 provides some concluding remarks and main take-aways from this thesis work.

2 Industrial symbiosis and related concepts

This chapter provides an overview of industrial symbiosis, tracing the evolution of its definition over time and presenting the specific definition that informs and frames my work. It highlights the dynamic nature of industrial symbiosis as a concept, evolving from its initial focus on material and energy exchanges between industries to encompass broader environmental, social, and economic dimensions.

In this chapter I also briefly examine how industrial symbiosis is situated within the broader European policy context, demonstrating some examples where policies and strategies support and encourage such initiatives, pointing to its importance in a European context. Furthermore, I explain the industrial symbiosis gap and briefly highlight some factors influencing the implementation of industrial symbiosis.

Finally, I emphasize the critical role of the human dimension in industrial symbiosis, addressing how collaboration, trust, and shared values among actors significantly influence the success and scalability of such initiatives. By highlighting the interplay of human behavior and organizational priorities, I aim to underscore the multifaceted nature of industrial symbiosis beyond its technical and logistical components.

2.1 Industrial symbiosis

Industrial symbiosis was first developed as a key concept within the broader field of industrial ecology. To begin with, the first definitions of industrial symbiosis were rather industry oriented. For example, Frosch and Gallopoulos (1989), first described the underlying concept of industrial symbiosis as an *"industrial ecosystem"* in which *"the consumption of energy and materials is optimized, waste generation is minimized and the effluents of one process … serve as the raw material for another process"*, focusing very much on the industrial aspect of it. On the same note, in 2000, Chertow defined industrial symbiosis as *"…engaging traditionally separate industries*[2] *in a cooperative approach to competitive advantage involving physical exchange of materials, energy, water, and by-products."* (Chertow, 2000). Later on, in 2007, Chertow developed a *"3-2 heuristics"* which states that an industrial symbiosis network must entail at least *three* entities exchanging at least *two* resources (Chertow, 2007). Other authors have used similar definitions while relaxing the *"3-2 heuristics"* by arguing that a minimum of two industries exchanging materials, heat, water, and/or by-products can be defined as industrial symbiosis (Liu et al., 2015).

In 2012, Lombardi and Laybourn expanded the definition of industrial symbiosis, highlighting the critical role of collaboration and the synergistic opportunities it offers (Lombardi and Laybourn, 2012). Their expanded definition broadens the focus beyond traditional industry actors to include non-industry participants such as academia, facilitators, and other stakeholders.

This thesis draws on this broader definition, understanding industrial symbiosis as a collaborative framework rather than being confined to only a physical network focused on resource efficiency. Even though resource efficiency and optimization through physical exchanges are important components, collaborative efforts through industrial symbiosis can also actively challenge existing structures, foster innovation, and drive the transition toward more sustainable societal and industrial systems.

This expanded perspective, I believe, also highlights both the interdependencies within the system and the unique roles played by individual actors. The interplay between different actors, perspectives, drivers and barriers, makes industrial symbiosis both intriguing and complex, requiring a holistic approach to its study and implementation. This inclusive perspective underscores the importance of diverse partnerships in driving sustainable development through collaborative efforts and is further reinforced by recent literature emphasizing the need to adopt a societal viewpoint on industrial symbiosis (Domenech et al., 2019, Sommer, 2020).

The broader understanding of industrial symbiosis forms the foundation of this thesis. This perspective is crucial for the research presented here, as it builds on the perspectives of a wide range of actors, including both industrial companies, municipalities, publicly owned organizations, facilitators, and others. Each of these participants plays a unique role in fostering effective industrial symbiosis collaborations.

[2] My own emphasis.

2.2 Industrial symbiosis in an EU policy context

As the EU intensifies its focus on achieving a circular and low-carbon economy, industrial symbiosis is expected to play an important role (Corsini et al., 2024, Sommer, 2020). The EU has established various funding mechanisms and initiatives to promote industrial symbiosis adoption. Programs such as Horizon Europe, LIFE, and the European Regional Development Fund provide financial and technical support for industrial symbiosis projects. These initiatives aim to foster innovation, enhance cross-border collaboration, and scale up successful industrial symbiosis models across the EU.

As mentioned in the introduction of this thesis, the CEAP explicitly highlights industrial symbiosis as a key strategy for fostering resource efficiency and closing material loops (European Commission, 2020). By encouraging the exchange of by-products, energy, and resources between industries, industrial symbiosis is identified as a means to transition from a linear to a circular economy (Corsini et al., 2024, Sommer, 2020). The CEAP underscores the importance of industrial symbiosis in reducing dependency on virgin materials, lowering greenhouse gas emissions, and promoting sustainable industrial practices (European Commission, 2020).

Industrial symbiosis also plays an important role in helping member states meet climate targets under the European Green Deal (Karagkounis, 2020). By optimizing resource use and minimizing waste, industrial symbiosis holds the potential to reduce emissions associated with production and disposal processes (Zhang and Wang, 2014, Yedla and Park, 2017)). For example, the exchange of energy or heat in industrial symbiosis networks can support decarbonization by replacing fossil fuels with renewable or waste-derived energy sources. These synergies align with the EU's broader goals of achieving net-zero emissions by 2050 (Regulation (EU) 2021/1119).

There are also several EU directives, directly or indirectly, supporting industrial symbiosis initiatives in different ways. For instance, the EU WFD and related policies emphasize waste prevention, reuse, and recycling, all of which are central to industrial symbiosis (Directive, 2018/851, Directive, 2008/98/EC.). Industrial symbiosis networks provide practical pathways for industries to comply with these directives by converting waste streams into valuable inputs for other processes. Another EU directive, the EU Landfill Directive, originally adopted in 1999 and amended in 2018 (Council Directive 1999/31/EC, Directive (EU) 2018/850), aims to minimize landfill waste by requiring member states to reduce landfilling as much as possible. Since one of the drivers of industrial symbiosis is the diversion of waste from landfills and the reduction of waste disposal (Giurco et al., 2011, Neves et al., 2019a, van Beers et al., 2007), the directive serves as an important incentive for industrial symbiosis. By encouraging industries to find alternative uses for by-products and waste materials, the EU Landfill Directive supports the creation of resource-sharing networks and promotes collaboration among industries, municipalities, and other actors in society.

Furthermore, various regional and national initiatives have been established to promote industrial symbiosis by fostering collaboration, resource efficiency, and sustainable industrial practices. For example, in Sweden, the government recognized industrial symbiosis as a key strategy for advancing sustainable initiatives in industry in its 2020 research proposition (Government Bill 2020/21:60). Regional strategies and development plans in Swedish municipalities often promote industrial symbiosis as a means of boosting local economies while advancing sustainability (Karlberg et al., 2024). Municipalities and regional governments play crucial roles in facilitating industrial symbiosis by aligning infrastructure, regulations, and incentives with industrial collaboration goals, therefore, early involvement by municipalities or regional authorities in industrial symbiosis planning is essential (Södergren and Palm, 2021).

2.3 Industrial symbiosis gap and key influencing factors

The industrial symbiosis gap refers to the disconnect between what is feasible in theory and what is actually implemented across industries and society (Moser and Rodin, 2021). Although industrial symbiosis has been demonstrated to reduce waste, improve resource efficiency, and generate economic and environmental benefits, its adoption remains limited in practice (Neves et al., 2019a, Rodin and Moser, 2021). This implementation gap underscores the challenges in transforming theoretical ideation and pilot projects into widespread and sustainable applications.

Several factors contribute to the industrial symbiosis gap. A lack of awareness and knowledge about industrial symbiosis opportunities is a major barrier (Ceglia et al., 2017, Madsen et al., 2015, Patricio et al., 2018, Päivärinne et al., 2015). Many industries are either unaware of its benefits (Ceglia et al., 2017, Patricio et al., 2018), or lack the expertise and tools to identify partners and develop relationships with other organizations (Madsen et al., 2015, Patricio et al., 2018, Yu et al., 2014). These challenges are accompanied by financial considerations (Heeres et al., 2004, Päivärinne et al., 2015, Siskos and Van Wassenhove, 2017), and companies being dependent on traditional business models (Aid et al., 2017, Yu et al., 2014). Furthermore, technological and infrastructural readiness is key for industrial symbiosis implementation (Bacudio et al., 2016). Especially important is the ability to integrate different processes, ensuring resource qualities are aligned and technologies are made compatible with one another. A lack of integration of technology and infrastructure between collaborating parties will inhibit collaboration (Aid et al., 2017).

Policy and regulatory hurdles also play an important role in the industrial symbiosis gap (Domenech et al., 2019, Lybaek et al., 2021, Taddeo et al., 2012). Ambiguities in waste classification and other legislative requirements can create uncertainty, making it difficult for organizations to navigate the legal landscape of resource exchange (Lybaek et al., 2021, Salmi et al., 2012). In addition, social dynamics between actors is another factor influencing collaboration (Ceglia et al., 2017, Lybaek et al., 2021). Coordination and trust issues between potential collaborators add another layer of complexity. Establishing effective industrial symbiosis often involves aligning the goals and processes of diverse stakeholders (Janipour et al., 2022), which can be challenging due to misaligned interests, poor communication, or lack of trust (Bacudio et al., 2016, Päivärinne et al., 2015).

Given the complex nature of industrial symbiosis, there are factors of multiple different domains that influence collaboration. How these factors influence industrial symbiosis, whether as drivers, barriers, or enablers, can differ widely across organizations, depending on their specific capacities, and contextual circumstances. Therefore, narrowing the industrial symbiosis gap requires a multifaceted approach that also acknowledges the context-specific challenges posed to individual actors.

2.4 The human dimension in industrial symbiosis

The human dimension in industrial symbiosis highlights the critical role of individuals, relationships, and collaboration in driving successful industrial symbiosis exchanges. While much of the focus in industrial symbiosis has traditionally been on material flows, technological innovation, and economic efficiency, the human element in industrial symbiosis underscores how trust, communication, joint problem-solving, and shared values are pivotal to building and maintaining these networks (Agudo et al., 2023, Ceglia et al., 2017, Doménech and Davies, 2011, Madsen et al., 2015, Päivärinne et al., 2015).

If there is lack of willingness to engage in collaboration amongst actors, it is not certain that industrial symbiosis will be initiated even though the technology exists, and a physical exchange is feasible. There are several examples of networks where exchanges were feasible from a technological and economic point of view, but collaboration did not take place because of organizational, institutional, and human factors (Lombardi, 2017, Noori et al., 2020). It has been shown that a vital factor for engaging in collaboration is trust among the participating actors (Corder et al., 2014, Taddeo et al., 2012, Yu et al., 2014). If there is a lack of trust, collaboration is likely to fail (Aid et al., 2017, Bacudio et al., 2016, Morales and Diemer, 2019, Päivärinne et al., 2015).

Doménech and Davies (2011) explored the role of embeddedness in industrial symbiosis and under what conditions trust and cooperation are developed. Their analysis pointed to the importance of a common vision, a successful former experience of cooperation and professional relationships, where personal and emotional ties also play a key role. Multiple studies address the human dimension as both the driving and limiting factor when initiating collaboration in industrial symbiosis networks (Bacudio et al., 2016, Doménech and Davies, 2011, Kokoulina et al., 2019, Kosmol and Esswein, 2018, Morales and Diemer, 2019) pointing towards the importance of addressing its role in industrial symbiosis collaborations.

Based on the literature on industrial symbiosis it is clear that such initiatives rely heavily on decisions made by humans. Exploring and understanding the interaction between actors and their respective context, is essential in industrial symbiosis development (Doménech and Davies, 2011).

3 Research approach and process

This chapter elaborates on the overall research approach and reflects on the methodological choices made throughout the conducted research. It aims to provide transparency regarding the rationale behind these decisions, how they were implemented, and the implications they may have had for the resulting findings and conclusions.

3.1 Research approach and point of departure

During my PhD journey, I have adopted an interpretative approach in my research. This approach is particularly well-suited to qualitative studies due to its focus on understanding subjective experiences within specific contexts (Berryman, 2019, Weber, 2004). Rooted in the interpretivist paradigm, this perspective views reality as subjective and socially constructed, shaped by individuals' unique environments and interactions (Berryman, 2019, Sovacool et al., 2018, Weber, 2004). Through this lens, I have explored the nuanced interplay between individual perceptions and contextual dynamics that influence the success and sustainability of industrial symbiosis partnerships.

This approach enables a detailed examination of the complex, context-dependent phenomena that define industrial symbiosis networks. Specifically, it facilitates an in-depth understanding of the socio-cultural, economic, and environmental factors that shape actors' motivations, challenges, and decision-making processes. By interpreting these dynamics, I have aimed to uncover how they affect individual actors' roles, engagement, and collaboration within industrial symbiosis partnerships.

Furthermore, my thesis seeks to contribute to increase the implementation rate of industrial symbiosis by offering insights into how actor dynamics can be assessed, facilitated and aligned. By expanding knowledge of the contextual and subjective factors driving industrial symbiosis collaboration, this work provides valuable guidance for fostering effective and sustainable partnerships.

3.1.1 PhD education and research environment

Given the nature of my employment, I have had the opportunity to work in many different research environments. As an industrial PhD student at RISE Research Institutes of Sweden, I have been working in various projects, all in one way or another related to industrial symbiosis, resource efficiency, and circular systems thinking.

Complementing my employment at RISE, I have had the opportunity to be part of the division of Environmental and Energy Systems Studies at Lund University, Faculty of Engineering. This research environment has been highly enriching, broadening my understanding of how various societal, industrial, institutional, and political perspectives are deeply interconnected. Engaging with this environment has allowed me to see how these perspectives influence one another, shaping complex systems and driving both challenges and opportunities within collaborative settings. By examining these interdependencies, I have gained a more holistic view of how policies, industry practices, social factors, and institutional structures collectively impact outcomes in areas such as sustainability, innovation, and policy development. This broadened perspective has been invaluable, enhancing both my analytical skills and my ability to approach problems with a more integrated and interdisciplinary mindset.

Additionally, my PhD project is financed by the Swedish Energy Agency and furthermore part of the Research School in Energy Systems (FoES). FoES has given me the opportunity to draw on yet another research environment, both in terms of courses and joint meetings with the whole research school, including both senior and junior researchers. Being part of FoES stipulated interdisciplinary collaborations, why this has been central to parts of my thesis work. Through my involvement in FoES I have also been part of the PhD project *Smart Symbiosis – Collaboration for common resource flows* together with two other PhD students. This collaboration has been rewarding in so many ways, both in terms of intense discussions and collaborations regarding case studies and joint course work, but mostly in terms of collegial support.

3.2 Research process and methods

This section outlines the research process and methods used in the appended papers. An overview of the research process is illustrated in Figure 1 and briefly described in the following sections.

At the outset of my research, I conducted a systematic literature review to familiarize myself with the field of industrial symbiosis. This review focused on exploring how previous studies addressed the actor perspective in industrial symbiosis collaborations, particularly regarding the factors influencing participation. The insights from this review laid the foundation for the subsequent three papers. In Papers II and III, I conducted case study research at the Sotenäs industrial symbiosis site, using an exploratory approach to investigate how actors perceive drivers, barriers, benefits, and adverse effects related to industrial symbiosis. Paper II emphasized drivers, barriers, and business performance outcomes, while Paper III examined the broader benefits and adverse effects experienced by participants. In Paper IV, my co-authors and I developed a tool for assessing and guiding industrial symbiosis collaborations. This effort employed a collaborative and iterative approach, incorporating feedback and suggestions from different industrial symbiosis stakeholders throughout the development process to ensure the tool's relevance and applicability.

This thesis predominantly employs qualitative methods, including a systematic literature review and case study research based on data gathered through questionnaires and interviews. Additionally, it draws on close collaboration with industrial symbiosis stakeholders and interdisciplinary partnerships with colleagues from related research areas. Each method is described in short in this thesis, and in detail within its respective paper.

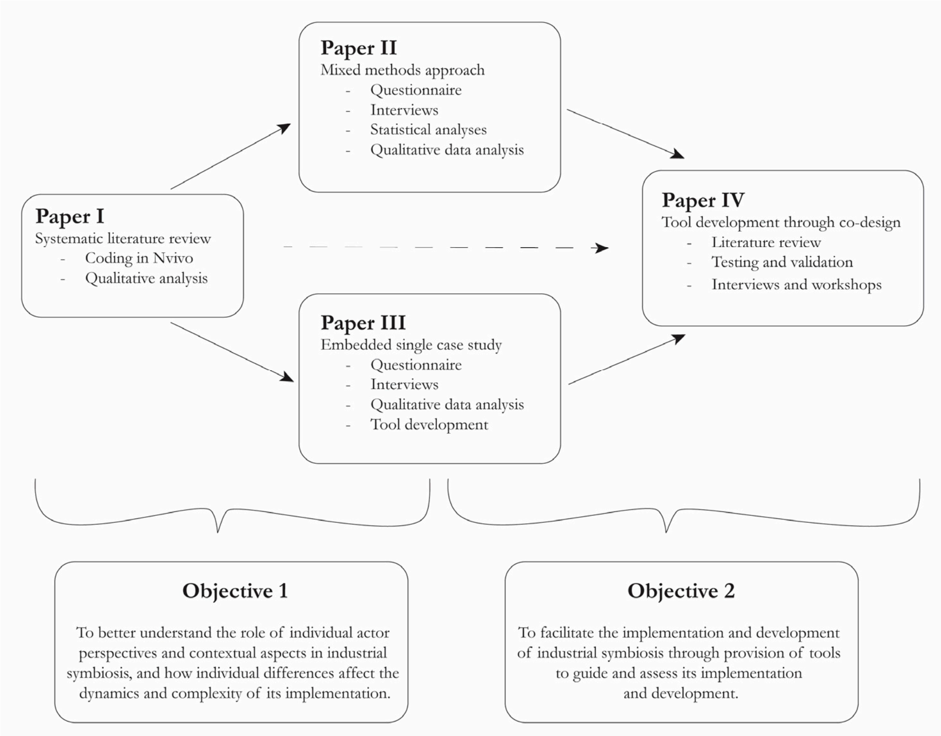

Figure 1. Research process.

3.2.1 Systematic literature review

The literature review in my first paper laid the foundation for my entire research journey, providing insights that, to a great extent, influenced all subsequent papers. This approach aligns well with Watson and Webster (2020) who state that the primary contributions of a literature review should be to synthesize existing knowledge within a specific research field and to advance theoretical directions to support future research. To ensure transparency and replicability, I conducted a systematic literature review. The selection and coding process is detailed in Paper I. The aims of the literature review were, first, to identify drivers, barriers, and enablers that influence actors' decisions to engage in industrial symbiosis, and secondly, to examine how the perception of these factors may vary according to individual actor characteristics and specific contextual conditions. By setting the course for my PhD work early on, the review not only organized and synthesized prior findings but also helped chart a clear path for advancing the field in general, and my own research in particular.

By consolidating findings from multiple studies, I was able to provide a holistic view of factors influencing industrial symbiosis and in particular highlight how this may differ depending on the context in which the industrial symbiosis is situated. This implied that I could gather insights that might not be apparent from just examining individual studies. This approach may come at the expense of deep contextual analysis or critical interpretation of individual studies, which can limit a nuanced understanding of complex issues. However, the aim of this study was not to focus on that aspect, but rather to offer a holistic synthesis and understanding of the existing body of literature.

3.2.2 Case study research – Embedded single case study at Sotenäs Center of Symbiosis

To begin with, case study research is particularly well-suited for exploring issues where the goal is to understand complexity and the context-specific nature of a subject, producing concrete, context-dependent knowledge (Flyvbjerg, 2006). Unlike methodologies aimed at broad generalizations, case studies prioritize deep, detailed understanding of specific instances, providing insights that are particularly valuable within their unique settings (Yin, 2018). Although case studies cannot establish causal relationships, and one should be careful with broad generalizations, they offer a rich source of learning and context-sensitive understanding (Flyvbjerg, 2006, Gerring, 2004, Yin, 2018).

In papers II and III, an embedded single case study design was adopted, hence, the study focused on an overarching single case unit with multiple embedded units of analysis. Sotenäs industrial symbiosis network was chosen as the case of study due to its well-established network and the municipality's extensive experience working on related initiatives over several years. The Sotenäs network consists of several different initiatives, and, while interconnected, there are two distinct networks within the broader industrial symbiosis network. These are depicted in Figure 2 (Note: this is the structure of the network at the time of the study). The first distinct network, centered around the food processing industries and the biogas plant in Sotenäs (indicated by green arrows in Figure 2), has been studied in prior research (Martin, 2015, Martin and Harris, 2018, Mirata, 2018). In contrast, the second network, focused on the Sotenäs Marine Recycling Center (SMRC, indicated by the orange arrows in Figure 2), has received comparatively less attention. This gap in exploration provided a valuable opportunity for deeper investigation, making the SMRC-focused network the focal point of this study. For more information regarding the six case participants, see Paper II and III.

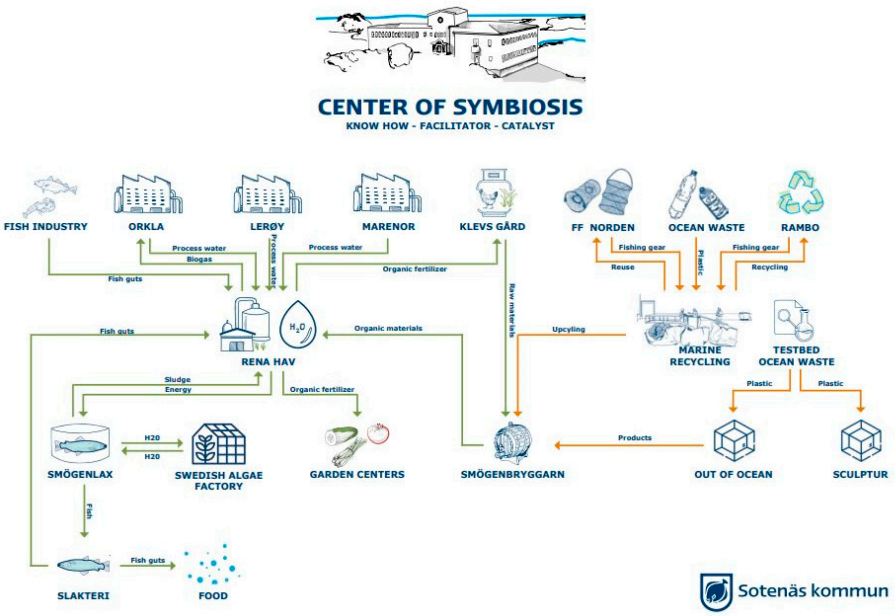

Figure 2. Map of the physical flows within the Sotenäs Symbiosis, used with permission from Sotenäs Center of Symbiosis (SCS) (SCS, 2022), also depicted in Paper II and III. This study focuses on the part of the IS network that is centered around the Sotenäs Marine Recycling Center (SMRC), indicated by the orange arrows. Note: The actors presented as part of the testbed are not part of the study.

In the Sotenäs case study, we used an interpretive and exploratory approach to examine differences in how actors perceive drivers, barriers, benefits, and adverse effects associated with industrial symbiosis. Paper II focused on drivers, barriers, and business performance outcomes, while Paper III examined the broader benefits and adverse effects, based on data collected for both papers simultaneously. For clarity, this study makes a distinction between barriers and adverse effects and defines barriers as factors that hinder collaboration, while adverse effects are negative effects generated by the collaboration. The presence of potential adverse effects can in turn be a barrier, but this study argues that they are not inherently the same. If adverse effects are acknowledged from the start, they can be included in risk assessments and thereby avoided or compensated for.

The qualitative case data was gathered through a two-step process combining questionnaires and semi-structured interviews. The questionnaire, distributed to six participating organizations, aimed to provide an initial understanding of the organizations, their perspectives on the industrial symbiosis network, and the perceived benefits and challenges of participation. Semi-structured interviews were then conducted both on-site in Sotenäs and digitally, offering deeper insights into the factors influencing participation decisions and the effects generated by the industrial symbiosis network. Both the construction of the questionnaire and the interview protocols were informed by 1) the literature review conducted in Paper I, 2) complementary literature focusing on benefits and adverse effects, and 3) the High Performance Manufacturing (HPM) survey feeding in quantitative data to Paper II (explained further below). In addition, the interview protocols were adapted to each case participant based on their answers in the pre-distributed questionnaire.

Paper II used a mixed methods approach comparing the results from the embedded single case study with statistical analyses based on data collected in the fourth round of the HPM survey project. The HPM data was collected and finalized in 2018 and encompass survey responses from 330 production plants in 14 different countries located in Asia, Europe, North- and South America, and the Middle East. The production plants cover three different manufacturing industries including electronics, automotive suppliers, and machinery (Harfeldt-Berg, 2024). The data collected concern strategy, improvement activities, and performance outcomes of manufacturing and supply chain operations. The data used for this study was restricted to general initiatives related to environmental sustainability. The focus of the statistical analyses was to explore differences in experienced drivers, barriers and business outcomes, given general sustainability initiative activities performed by the studied industries, based on organizational context.

Organizational context in Paper II was determined by the organization's customer order decoupling point (CODP) position. The CODP can be defined as the point in a supply chain or service process where operations shift from being driven by forecasts to being tailored to a specific customer order. It marks the transition from standardized production or service preparation to customization based on actual customer demand. The two most archetypical CODP positions are make-to-order (MTO) and make-to-stock (MTS). MTO is order-based and the operational environment is defined by flexibility, while MTS is forecast-based and the operational environment is associated with stability and predictability (Harfeldt-Berg and Olhager, 2024, Naylor et al., 1999, Olhager, 2003, Sharman, 1984). Based on the questions asked in the HPM survey material it was possible to define the manufacturing companies' CODP position. In line with this, the CODP positions of the case participants in the Sotenäs network were also determined based on their questionnaire responses. Results from the two different data types were then compared to see if there were any similar or diverging patterns between the survey-based material and the case study.

Finally, the qualitative data from the questionnaires and interviews were analyzed systematically by identifying keywords relevant to the research focus of Paper II and Paper III, respectively. Segments of the interview transcripts containing these keywords were extracted and then further analyzed, with a focus on interpreting the underlying meaning of the statements. In Paper II we focused on whether and how drivers, barriers, and business outcomes differed between the actors based on their CODP position, and in Paper III the primary focus was to explore discrepancies between the actors based on the effects they reported, and in what ways these impacted their decision to participate in industrial symbiosis. The interview material also informed the distributional mapping of effects in the Impact Assessment Matrix developed in Paper III (further explained in section 3.2.3)

One important dimension of the methods employed in Paper II is the adoption of a mixed methods approach, which typically combines quantitative and qualitative data sources (Creswell and Clark, 2007). While the results from these two sources were not directly comparable in a traditional sense, this integration provided complementary insights that enriched the overall analysis and yielded valuable methodological lessons. The approach also provided practical learnings about conducting mixed methods research, such as how to align data analysis of different data sources and interpretation of the findings. While both the quantitative and qualitative data offered unique insights, their integration posed challenges. The results were not directly comparable, limiting the ability to draw unified conclusions. These learnings can inform future studies aiming to navigate the challenges of methodological integration.

3.2.3 Tool development and design

In Paper III and IV, two different assessment tools were developed. Paper III contributes with an Impact Assessment Matrix which maps the distribution of effects generated by an existing industrial symbiosis collaboration based on impact level, time frame, and if the effect has economic, social, or environmental implications. In Paper IV we developed the Industrial Symbiosis Readiness Level Matrix (ISRLM) tool which adopts a holistic perspective on industrial symbiosis development by offering a tool for guidance and assessment.

The Impact Assessment Matrix developed in Paper III is primarily based on a combination of previous research (Chertow et al., 2019, Nehler and Rasmussen, 2016) while also drawing on conclusions in additional literature (Martin and Harris, 2018, Wadström et al., 2021). The tool was then applied on the data collected during the case study in Sotenäs, where the participating actors had stated perceived benefits and adverse effects of their ongoing collaboration. Based on qualitative analyses of the actors' own reasoning regarding the benefits and adverse effects during the interviews, the distributional mapping of the effects was conducted using the Impact Assessment Matrix. The results of the mapping will be briefly described in Section 5.1 and are further detailed in Paper III.

In paper IV, we adopted a collaborative approach to developing the ISRLM tool. Co-design in research and methods development refers to an approach where multiple actors, such as researchers, practitioners, and intended end-users, work together to develop, for example, research frameworks, methodologies, or tools (Poderi et al., 2020, Sanders and Stappers, 2008, Storni, 2015, Zamenopoulos and Alexiou, 2018). This collaborative process emphasizes drawing on shared knowledge and iterative feedback to ensure that the developed methods are context-relevant, practical, and effective in addressing the practical challenges that are being addressed. Key aspects of collaborative design in research are co-creation of knowledge, iterations of feedback from involved stakeholders, ensuring contextual relevance, creating a sense of inclusion and ownership, and adopting an interdisciplinary approach drawing on insights from experts within different fields (Zamenopoulos and Alexiou, 2018).

According to Lange et al. (2017) the complexity and dynamic nature of industrial symbiosis could be better understood by using a co-design approach. By developing a practical, guiding and evaluating tool through co-design within ongoing industrial symbiosis collaborations, this approach can create general guiding principles for future initiatives in different settings.

The process of developing the ISRLM tool was an iterative one where several stages of literature review and case testing were performed. The collaborative part of this study was conducted in collaboration with different industrial symbiosis case participants, both fully established networks as well as actors with the intention to initiate industrial symbiosis. These case participants were both situated in Sweden and on continental Europe. A detailed list of the case participants is presented in Paper IV along with a detailed description of the three rounds of testing.

After each round of case testing, internal workshops were conducted to analyze the data or feedback collected such that the usability and accuracy of the ISRLM tool could be improved. Literature was also reviewed continuously to further validate the content and ensure its relevance. This structured and iterative approach to data collection, analysis, and case testing ensured that the ISRLM tool was rigorously developed, continuously improved, and adapted to real-world industrial symbiosis contexts, allowing for a robust and accurate reflection of the dynamics within industrial symbiosis collaborations.

Although the co-design process of developing the ISRLM tool rendered fruitful insights and contributions from the different stakeholders involved, it also came with a couple of challenges. One difficulty was to determine which suggestions to incorporate, as the input from the stakeholders was sometimes diverse and contradictory. While some of the stakeholders emphasized the importance of usability and simplicity, others recognized the value in a more complex and detailed tool. These diverging opinions were to some extent dependent on the actors' experience of industrial symbiosis and how far into to the process of developing collaboration they were. To the best of our ability, we developed a tool that makes it possible to maintain a simple and holistic approach to industrial symbiosis evaluation while also, if needed, allowing for a more detailed analysis. This will be further elaborated on in Chapter 5.

3.2.4 Reflection on interdisciplinary collaboration

Interdisciplinary research is particularly valuable for challenges like industrial symbiosis, where interconnected factors such as economics, environmental issues, societal challenges, and technology converge. In paper II and IV I had the opportunity to collaborate with colleagues within multiple different disciplines, ranging from energy engineering to statistics.

I find that the most fulfilling aspect of working in interdisciplinary projects is the creativity and solidity that is created when different disciplines are paired to investigate a certain research topic. I think being able to discuss the project and draw on each other's different experiences and knowledge has been very rewarding for the progress of the papers I have written in collaboration with colleagues in other disciplines, both in terms of developing the actual study but also in progressing with the writing.

Another valuable aspect of these interdisciplinary collaborations has been stepping out of my comfort zone to engage with methods and research approaches that I was not entirely familiar with. For example, in Paper II, we used a large data set to perform statistical analyses, and even though I did not conduct the actual testing in the statistical software we used, I got to revisit and refresh my former statistical knowledge by interpreting and analyzing the results we retrieved.

Furthermore, in Paper IV, I worked with both colleagues from different disciplines, and practitioners to develop the ISRLM tool. The ISRLM tool itself consists of multiple different perspectives, why it was a necessity to include multiple different disciplines to secure a solid knowledge base spanning, to some extent, all perspectives covered in the ISRLM tool. I think the iterative process we adopted, along with the broad knowledge base covered by different colleagues and other collaboration parties, created a robust and applicable tool for industrial symbiosis practitioners. This would clearly not have been possible solely based on the individual knowledge of any of the involved researchers.

4 The importance of acknowledging actor differences in industrial symbiosis collaborations

This chapter will address objective 1, to better understand the role of individual actor perspectives and contextual aspects in industrial symbiosis, and how individual differences affect the dynamics and complexity of its implementation. This chapter draws on results and conclusions from Paper I, II and III, respectively.

4.1 Contextual aspects and actor perspectives in industrial symbiosis

4.1.1 Contextual aspects influencing collaboration

Research on factors influencing industrial symbiosis collaborations has progressed substantially, leading to a variety of labels for these factors, such as drivers, incentives, enablers, facilitating factors, barriers, inhibitors, and challenges. Among these, the terms *drivers*, *barriers*, and *enablers* are the most commonly used (Corder et al., 2014, Fraccascia et al., 2020, Fraccascia, 2018, Henriques et al., 2021, Moser and Rodin, 2021, Neves et al., 2019b), and therefore formed the focus of Paper I. In short, drivers are factors that motivate actors to participate in industrial symbiosis, barriers regard factors that inhibit collaboration, and enablers constitute factors that enhance the likelihood of successful implementation.

Research regarding these factors has predominantly focused on the network level or general dynamics of industrial symbiosis, often overlooking the perspective of individual actors and context specific circumstances (Ji et al., 2020, Walls and Paquin, 2015). While the actor-specific perspective remains underexplored, existing studies frequently emphasize the importance of considering the unique context of individual actors when analyzing factors that shape collaboration (Costa and Ferrão, 2010, Henriques et al., 2021, Lybaek et al., 2021, Rweyendela and Mwegoha, 2020, van Beers et al., 2009).

Therefore, the literature review (Paper I) conducted early on in my PhD studies served as an initial exploration of the industrial symbiosis field, focusing on whether and how the individual actor perspective had been reflected in the existing literature with regards to drivers, barriers, and enablers. This review essentially laid the groundwork for the three upcoming papers II-IV and expanded my understanding of the complexity of industrial symbiosis collaborations.

To begin with, the literature review identified numerous drivers, barriers, and enablers. For the full list, refer to Paper I. Based on the analysis of the reviewed literature it was possible to synthesize these influencing factors into six overarching categories. The six categories were also used, though to some extent further refined, when developing the ISRLM tool in Paper IV.

- Legal and political factors
- Economic and market-related factors
- Organizational and informational factors
- Techno-physical and geographical factors
- Community-related factors
- Environmental sustainability-related factors

The findings demonstrate that drivers, barriers, and enablers of industrial symbiosis collaboration vary substantially across different contexts. The analysis of the literature also shows that actors' perceptions of the factors categorized above are shaped by the following six characteristics:

- Sectoral affiliation and type of resource exchanged
- Company size and internal resources
- Actors' roles and responsibilities
- Geographic context
- Level of dependence, investment, and benefits
- Strategic vision

Furthermore, the literature revealed that these six characteristics are closely interconnected with, and affected by, 1) how actors perceive business opportunities/risk,

2) inequalities within the network, and 3) the political and legal context actors must navigate. Together, these highly affect actors' willingness and ability to engage in industrial symbiosis. These connections are presented in Table 2.

Table 2. Recurring core concerns identified in relation to actor characteristics and contextual aspects. Table reconstructed from Paper I.

Recurring core concerns	Actor characteristics and contextual aspect
Perceived business opportunity/business risk	- Sector affiliation and type of excess resource - Company size and internal resources - Actors' roles and responsibilities - Level of dependence, investment, and benefits
Inequalities within the network	- Company size and internal resources - Actors' roles and responsibilities - Level of dependence, investment, and benefits - Strategic vision
Regulatory and political setting	- Sector affiliation and type of excess resource - Geographic context

To exemplify how these are interconnected I will give a few examples. Perception of business opportunity/risk often concerns the financial viability of the resource exchange. Based on the analysis in Paper I it is clear that the financial viability of an industrial symbiosis collaboration is closely tied to key factors such as the type of resource being exchanged, the existence of demand for that resource, and the size of the resource flow. Resource type and demand determine whether the resource has a marketable value, while the flow size establishes whether there is sufficient quantity of the resource to make the exchange worthwhile. Based on the literature it is also evident that actors' roles, company size, the level of actors' dependence on the exchange, and the distribution of benefits further influence actors' risk tolerance.

Furthermore, inequalities within the network arise from disparities in power, investment, and benefit distribution, driven by differences in actor size, contributions, and roles. Therefore, addressing these imbalances is crucial for equitable collaboration. Lastly, regulatory and political contexts vary across sectors and geographical areas, affecting legal compatibility for resource exchanges. These dynamic conditions underscore the need for tailored strategies to facilitate collaboration, mitigate risks, and navigate legal frameworks for successful industrial symbiosis collaboration.

4.1.2 The customer order decoupling point as a proxy for organizational context

Intrigued by the results in Paper I, I wanted to explore how an organization's context could potentially affect what type of drivers, barriers, and business outcomes are experienced by different industrial symbiosis actors. Therefore, in Paper II, my colleague and I are testing one aspect of organizational context using the CODP as a proxy. The CODP is known to affect an organization's context of operation (Harfeldt-Berg and Olhager, 2024), and can be used to distinguish between order-based and forecast-based operations (Naylor et al., 1999). The positioning of the CODP is primarily governed by the stability and predictability of the organization's environment. As mentioned in section 3.2.2, the CODP configuration MTS is forecast-based and associated with the greatest stability and predictability while MTO is associated with order-based operations where flexibility is one of the key elements (Harfeldt-Berg and Olhager, 2024, Naylor et al., 1999, Olhager, 2003, Sharman, 1984).

Paper II statistically analyzed differences in drivers, barriers, and business outcomes between the two CODP configurations in the HPM survey data. Additionally, it qualitatively compared variations among case study participants in Sotenäs based on their reported CODP.

The results show that there are some statistically significant differences between the MTS- and MTO-based configurations in the HPM material. According to our statistical analyses, MTS companies are more driven by legal requirements than MTO companies. MTS companies also seem to be more management-driven when implementing environmental sustainability initiatives compared to MTO companies, suggesting a more top-down approach. In contrast, MTO plants face greater challenges with organizational support but tend to benefit more from sustainability efforts, particularly in regulatory performance and overall business performance. While business performance improvements are moderate overall, they are more pronounced in MTO settings. However, when analyzing our qualitative data, we could not see the same pattern in the case study. Even though there are differences between how the case participants in Sotenäs have reported drivers, barriers, and business outcomes related to industrial symbiosis, we could not attribute those differences to their CODP position.

Given the results presented in Paper II, we could not establish that one of the two analyzed CODP positions was better suited for industrial symbiosis collaborations.

However, stability, large production volumes, and predictability are critical enablers for industrial symbiosis, as highlighted by several studies (Aid et al., 2017, Ji et al., 2020, Liu et al., 2015, Päivärinne et al., 2015). This notion is also consistent with my own analysis of the relationship between perceived business opportunity/risk and size of the resource flow emphasized in Paper I. The factors just mentioned align closely with the characteristics of MTS environments, which allow organizations to predict resource needs and estimate surplus materials available for exchange. In contrast, the unpredictability of MTO operations makes it difficult to forecast both resource requirements and by-product availability, creating challenges for industrial symbiosis collaboration. On the other hand, flexibility has also been reported as an enabler of industrial symbiosis (Mathews and Tan, 2011, Rosado and Kalmykova, 2019), indicating that the opposite relationship might be true. While MTS environments seem more suitable for industrial symbiosis due to their stable resource flows, they are vulnerable to fluctuations in production volumes, which could lead to inefficiencies and hesitation to invest in uncertain collaborations. The inherent flexibility of MTO environments could potentially better accommodate the dynamic changes often associated with industrial symbiosis.

One can find multiple perspectives on MTS- and MTO operations in the literature, suggesting that either one might be suitable for industrial symbiosis (Aid et al., 2017, Ji et al., 2020, Mathews and Tan, 2011, Päivärinne et al., 2015, Rosado and Kalmykova, 2019), but the findings from the Sotenäs case study, involving small businesses handling limited resource volumes, did not conclusively favor one CODP configuration over the other for industrial symbiosis. Future studies exploring larger industrial players with higher resource volumes could yield more definitive insights into how CODP positioning impacts industrial symbiosis suitability.

4.1.3 Different perspectives on benefits and adverse effects in industrial symbiosis and its role in decision-making

This section mainly draws on Paper III, where benefits and adverse effects in industrial symbiosis are explored in a case study at the Sotenäs industrial symbiosis network. The study also explores how the perception of effects impacts their decision on participating in industrial symbiosis. The benefits and adverse effects are categorized into economic, social, and environmental effects. The full lists of reported benefits and adverse effects can be found in Paper III.

The findings from Paper III reveal significant variations in how different actors perceive the benefits and adverse effects of industrial symbiosis, highlighting distinct differences in priorities. Environmental benefits emerged as the dominant factor influencing decisions to engage in collaboration. Conversely, adverse effects received comparatively less attention, suggesting they might be downplayed or simply not considered. However, the most prevalent adverse effects were related to economic concerns.

Based on both the questionnaire responses and in-depth interviews, Paper III highlights notable differences in how actors perceive the benefits of industrial symbiosis, with variations across economic, social, and environmental advantages. While some actors primarily experienced economic benefits, the majority found greater value in social or environmental outcomes. For instance, certain actors identified multiple economic advantages, whereas others reported only a few but instead emphasized significant social and environmental benefits. This variation suggests that the perceived benefits of industrial symbiosis depend on the actors' roles, priorities, and engagement within the network.

The interviews also reveal varied perspectives among actors regarding adverse effects in industrial symbiosis collaborations. While the questionnaire responses mentioned few adverse effects, deeper discussions during the interviews uncovered several challenges, including increased production costs, higher logistics expenses, and greater administrative burdens. Interestingly, some of the actors did not explicitly consider these adverse effects in their decision-making processes related to industrial symbiosis. This could indicate that, rather than being unaware of these challenges, they may place less emphasis on them, either because they have found ways to manage or mitigate them or because they view them as secondary to the overall benefits of collaboration. Additionally, it is possible that these effects are reframed within a long-term perspective, making them appear less pressing in the immediate decision-making process. This suggests adoption of a long-term perspective, where short-term difficulties are accepted in favor of long-term benefits.

Conversely, other actors were more hesitant to engage in industrial symbiosis collaboration if high immediate costs were involved. For instance, one actor avoided initiatives that were costly due to economic constraints and prioritization of customer expectations, underscoring how financial limitations can restrict the pursuit of sustainability initiatives. Another actor expressed a willingness to incur short-term costs if benefits materialized quickly but struggled with committing to long-term investments due to financial pressures and market uncertainties. These differing perspectives highlight the varying levels of risk tolerance among actors and the difference in influence of economic considerations on their participation in industrial symbiosis.

Another factor possibly influencing the perception of adverse effects may be participation bias. Since the interviewed actors are already engaged in the industrial symbiosis network, they may have encountered and successfully navigated potential challenges, making them less likely to view them as significant drawbacks. Alternatively, their continued participation might suggest that the challenges they faced were not severe enough to deter involvement in the first place. These insights highlight the complexity of assessing adverse effects in industrial symbiosis and suggest that actors' perspectives are shaped by their level of engagement, their ability to adapt, and their overarching strategic priorities.

Finally, Paper III identifies differences in how actors balance benefits and costs. While some actors prioritize long-term benefits, and accept higher initial costs as investments in sustainable outcomes, others are constrained by financial pressures and market demands, leading them to favor short-term gains or avoid costly environmental measures altogether. These actor-specific differences underscore the importance of incorporating individual actors' perspectives to better understand the actors' different decision-making processes to facilitate the development of industrial symbiosis.

4.2 Discussion on the role of contextual aspects and actor perspectives in industrial symbiosis

This chapter addresses the first objective of this thesis, emphasizing the importance of recognizing the individual actor perspective in industrial symbiosis collaborations. Findings from Papers I through III demonstrate that acknowledging and, in some cases, aligning the perspectives of individual actors is crucial for turning collaborations into reality. Individual actors play critical roles in the success of industrial symbiosis efforts, as their decisions directly influence the sustainability and viability of the network (Paper I and III). These actors bring unique perspectives shaped by their organizational goals, size, and sectoral affiliations (Aid et al., 2017; Henriques et al., 2021; Madsen et al., 2015). Such characteristics influence how they perceive collaboration opportunities, their motivations for participating, the benefits they expect to gain, and the risks they might be exposed to.

The case study findings in Papers II and III reveal that actors have differing perceptions of both business opportunities and risks, reinforcing the literature review findings in Paper I. Some actors approach industrial symbiosis with a long-term, strategic mindset, prioritizing overarching sustainability goals despite facing increased costs, administrative burdens, or logistical challenges. These actors tend to view industrial symbiosis as an investment in future sustainability, where short-term difficulties are necessary trade-offs for achieving broader environmental and societal benefits (Papers II and III). Their commitment often stems from a strong internal sustainability agenda or a belief in the long-term value of resource efficiency and circularity. For instance, one participant explicitly acknowledged that participation in the network required considerable time and financial resources but saw these as necessary steps toward ensuring a sustainable local environment (Papers II and III). This highlights how some actors are willing to absorb initial costs or inefficiencies as part of a broader sustainability-driven vision.

However, the study also highlights actors who have to adopt a more pragmatic, financially focused approach. These actors evaluate industrial symbiosis, at least to some extent, through the lens of immediate financial benefits. Their decisions are influenced by a careful assessment of upfront costs, expected returns, and the tangible benefits that can be realized quickly. For instance, one participant explained how they avoided committing to long-term investments in the collaboration due to uncertainty in their sales figures. Another actor expressed that they would be willing to invest in long-term sustainability if short-term gains could be realized, however, the uncertainty surrounding the timing of these returns made them hesitant.

The variation in how actors prioritize short-term versus long-term objectives underscores the necessity for flexible industrial symbiosis models that accommodate diverse perspectives. Initiatives that acknowledge varying financial capacities, risk tolerances, and strategic priorities are more likely to attract a broad range of participants. For example, some actors in the network have been able to mitigate the risks of collaboration by adopting an incremental approach, making small, manageable investments in sustainable practices that align with both their financial constraints and environmental goals. The findings also suggest that actors' ability to contextualize potential adverse effects within their broader strategic goals plays a key role in shaping their willingness to engage in industrial symbiosis. While some actors view challenges as obstacles that hinder progress, others see them as necessary hurdles that ultimately contribute to the success of the collaboration. This illustrates the delicate balance between short-term financial objectives and long-term sustainability goals in industrial symbiosis participation. It also adds another dimension to the findings of Paper I, illustrating that perceptions of business opportunities and risks are closely tied to an actor's strategic vision and their approach to balancing immediate priorities with long-term goals.

Furthermore, the findings illustrate that the willingness of some actors to contextualize adverse effects and view them as part of the learning and adaptation process is crucial in shaping positive outcomes. For example, one actor noted that while the collaboration led to higher logistical costs in the early stages, these costs were offset by the creation of new customer relationships and increased market visibility, which led to better financial outcomes in the long run. In this sense, some actors have reframed the perceived negative effects within a broader context of growth and opportunity, demonstrating a flexible mindset required for successful industrial symbiosis collaboration.

However, not all actors are equally positioned to bear the costs of industrial symbiosis participation. Notably, actors with external project funding expressed less concern about challenges like administrative burdens or upfront investments, as funding allowed them to take a longer-term perspective on sustainability. In contrast, more business-driven organizations in the case study were limited by financial constraints and the need to meet customer demands and performance targets. This highlights how external funding can reduce resistance by easing financial pressure and enabling participation. It also emphasizes the crucial role of facilitators in mediating individual actors' immediate business needs and the collective long-term goals of the network. Effective facilitation can help create an environment where the benefits of collaboration are equitably distributed, ensuring that industrial symbiosis remains viable for a diverse set of stakeholders.

The differing mindsets and strategic visions among actors also influence the overall implementation of industrial symbiosis initiatives. Visionary actors often serve as catalysts for development, driving the agenda forward with ambitious sustainability goals while more pragmatic actors tend to focus on immediate operational concerns, weighing benefits against potential risks and costs. These differing approaches can create both friction and complementarity within a network. On one hand, a mismatch in strategic vision may slow progress, particularly when risk-averse actors hesitate to commit without clear short-term gains. On the other hand, the balance between visionary ambition and pragmatic caution can lead to more grounded, resilient outcomes, where bold ideas are moderated by practical implementation strategies. Striking a balance between these perspectives is essential for long-term success. Misalignment in expectations can lead to stagnation or reluctance to commit, whereas well-facilitated alignment can strengthen collaboration and increase the likelihood of sustained participation.

Ultimately, these findings reinforce the need for industrial symbiosis networks to be adaptable and inclusive, recognizing that actors will have different motivations, risk aversion, and constraints. By fostering open communication, aligning expectations, and ensuring that participation remains viable for a range of stakeholders, industrial symbiosis initiatives can become more resilient and scalable. The success of such collaborations hinges on their ability to integrate diverse perspectives while maintaining a shared commitment to long-term sustainability. Facilitators, policymakers, and network leaders must actively engage with actors to help bridge the gap between short-term challenges and long-term rewards, ensuring that the collaboration remains sustainable and beneficial for all involved.

5 Industrial symbiosis development – Guidance and assessment

This chapter addresses the second objective of this thesis: to facilitate the implementation and development of industrial symbiosis through the provision of tools to guide and assess its development. It draws on results and conclusions from Papers III and IV. Chapter 5 builds on the knowledge generated in Chapter 4, which informs the design and content of the tools by providing insights into actor perspectives, factors that influence collaboration, and effects that may be generated from it. Despite the growing number of available tools and frameworks, a notable gap remains in offering integrated guidance that links assessment outcomes with concrete actions for industrial symbiosis development (Chrispim et al., 2023, Dai et al., 2022). Therefore, this part of the thesis intends to support the implementation, development, and assessment of industrial symbiosis through practical tools. The first tool, presented in section 5.1, is the Impact Assessment Matrix, which offers a structured approach to mapping the distribution of benefits and adverse effects within industrial symbiosis networks. The second tool, introduced in section 5.2, is the ISRLM tool, designed to facilitate industrial symbiosis implementation by providing a holistic approach to guidance and evaluation throughout the development process.

5.1 Impact Assessment Matrix

The following sections will present the Impact Assessment Matrix developed in paper III. One of the objectives of paper III was to visualize the distribution of benefits and adverse effects among the actors, the network, and society, and a timeline indicating when they were expected to be realized. To add an extra dimension to the analysis, the benefits and adverse effects were also identified as economic, social, or environmental. The Impact Assessment Matrix is primarily developed drawing on a combination of previous literature (Chertow et al., 2019, Martin and Harris, 2018, Nehler and Rasmussen, 2016, Wadström et al., 2021).

5.1.1 Results from the Sotenäs case study

The Impact Assessment Matrix is presented in Figures 3 and 4 where the results from the Sotenäs case study are mapped (Paper III). The benefits and adverse effects were mapped into the matrix, giving a visualization of how the effects were distributed among actors, the network, and society, and how they are distributed over time. For clarity, I have made a distinction between effect and impact, where the term effect refers to the consequence (positive or negative) resulting from the collaboration, whereas the term impact refers to how the effects impact actors, the network, or society. The benefits and adverse effects presented in the matrices were reported by the actors of the Sotenäs case study. Based on their reasoning, benefits and adverse effects were mapped and distributed into each respective matrix. Below, I will shortly comment on the results presented in Figures 3 and 4. A detailed discussion on the distribution of effects can be found in Paper III.

The distribution of effects in the matrices highlights substantial differences between actors and the varying levels at which these effects manifest. It shows that it is not only the individual actors, or even the network, that are impacted by the collaboration. The reported effects spread to a higher societal level as well. For instance, positive marketing has been identified as a benefit across all impact levels and time frames within the industrial symbiosis collaboration. Some actors reported immediate positive marketing outcomes at the actor level, such as enhanced visibility and reputation directly benefiting their operations. Others emphasized the long-term societal advantages of promoting the region as an innovative, thriving hub for industrial symbiosis. This broader marketing effect could attract new businesses to establish operations in Sotenäs, thereby expanding the network and creating additional regional benefits, including job opportunities and new revenue streams. These findings highlight the multifaceted impact of positive marketing, which spans both short-term organizational gains and long-term regional growth.

Looking at the matrices, some ambiguities emerge in how actors perceive certain outcomes, for example lock-in effects. Lock-in effects are a well-documented concern in industrial symbiosis (Janipour et al., 2022, Mirata et al., 2024, Morales and Diemer, 2019, Walls and Paquin, 2015), arising when companies become highly dependent on one another. While such interdependence can promote stability, efficiency, and innovation, it may also reduce adaptability, making it harder to respond to market shifts or adopt new technologies. If a key partner withdraws, the disruption can impact the entire network.

In this case, some actors viewed lock-in effects positively, emphasizing regional business stability and long-term job creation. Others saw them as adverse, pointing to the risks of over-dependence. These contrasting views highlight the dual nature of lock-in effects and their complex role in collaborative networks. As such, it's important to address interdependence and shared goals early on, through strategic dialogue, to ensure resilience and flexibility in the development of industrial symbiosis.

Discrepancies are also evident in how actors perceive social relations within the collaboration. While some report improved partnerships and stronger social ties as benefits, another actor report disimproved relations due to failed collaborations (Paper III). Such divergent views can pose challenges for trust and future collaborations if not addressed. A shared strategic vision, as emphasized in Paper I and other related literature (Aid et al., 2017, Janipour et al., 2022, Noori et al., 2020, Päivärinne et al., 2015), is critical for successful industrial symbiosis initiatives.

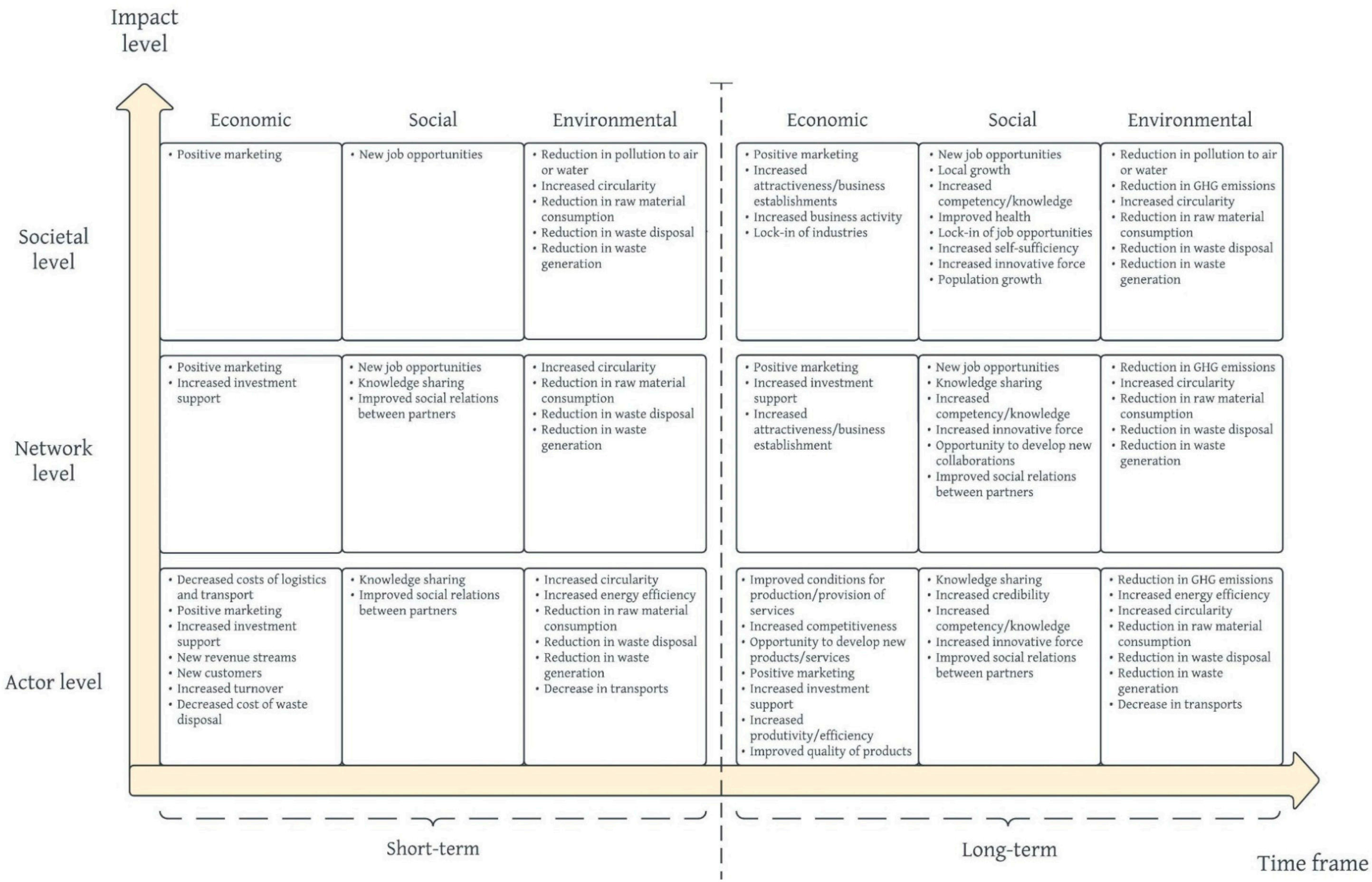

Figure 3. Impact Assessment Matrix – distribution of benefits. Figure as depicted in Paper III.

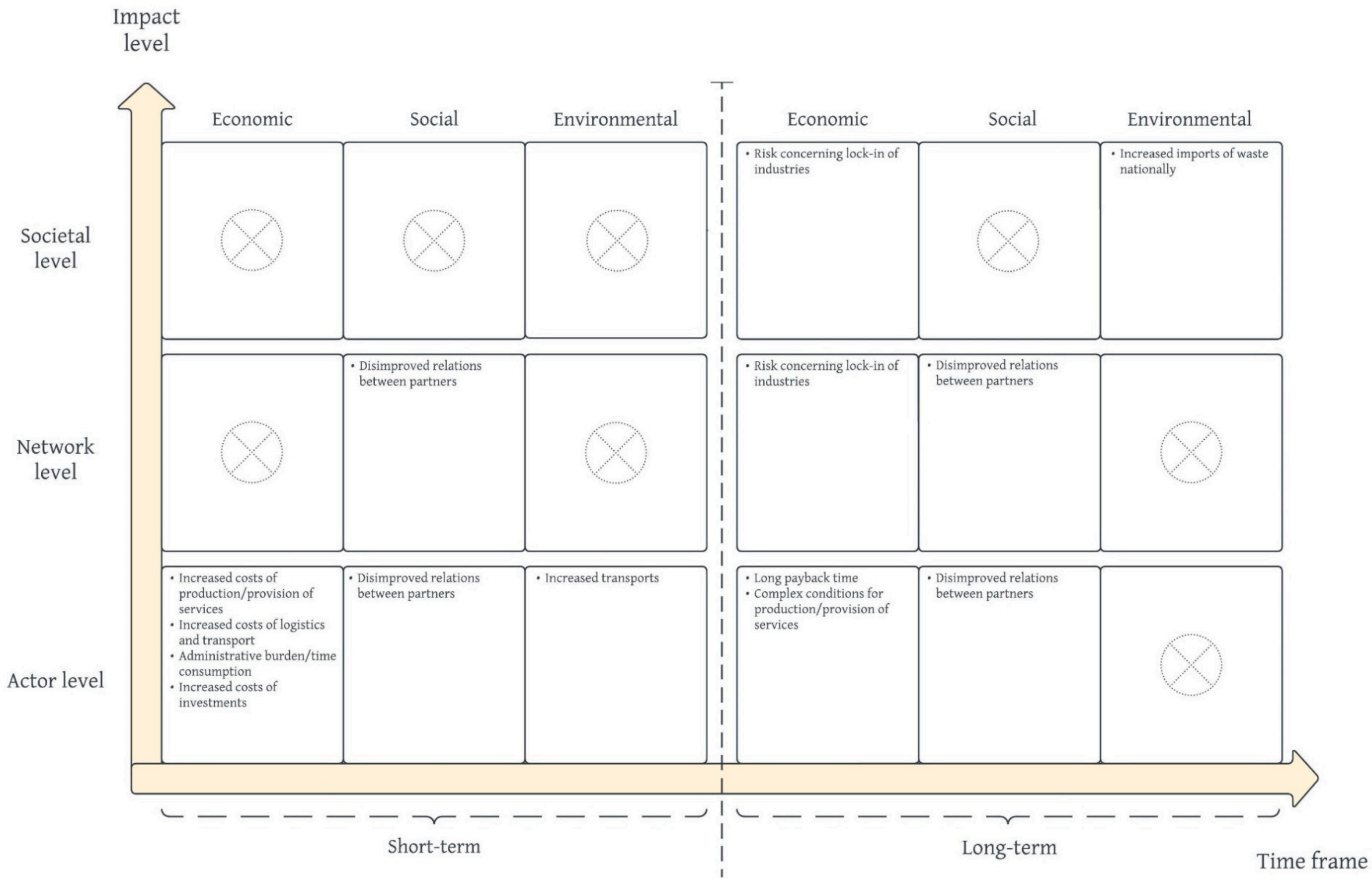

Figure 4. Impact Assessment Matrix – distribution of adverse effects. Figure as depicted in Paper III.

5.1.2 Implications of the Impact Assessment Matrix

The primary aim of implementing the Impact Assessment Matrix within an established network was to tap into the firsthand experiences of the involved stakeholders. This approach allowed for an exploration of how impacts are distributed among the case participants and society, drawing on actual outcomes rather than estimated projections typical of planned networks. Furthermore, there is substantial value in utilizing the matrix within the evolving context of the Sotenäs network. Given its ongoing development, mapping out the benefits and drawbacks serves as a valuable tool for enhancing existing and future exchanges. As an industrial symbiosis network continuously evolves, it is advisable to revisit this type of mapping regularly throughout the collaboration.

The Impact Assessment Matrix can showcase both the distribution of benefits and adverse effects, as well as potential discrepancies between actors, such as in the Sotenäs case. The findings demonstrate that industrial symbiosis is multifaceted, with varying perceptions of effects among actors. Hence, the Impact Assessment Matrix can serve as a basis for discussions on how the actors perceive different effects and help align them in their view on the distribution.

The knowledge that come from applying the matrix can also point to whether governmental subsidies, or other incentivizing measures are justified to increase the implementation rate of industrial symbiosis. The Impact Assessment Matrix presented here gives an overview of how to assess the distribution of benefits and adverse effects among the different levels of interest in industrial symbiosis. It also showcases that there is no clear-cut division regarding the outcomes of collaboration. To develop this even further, future research can address the measurability of benefits and adverse effects and offer an even more granular distribution among actors.

5.2 Industrial symbiosis readiness level – A matrix-tool

5.2.1 The ISRLM tool

In paper IV, we develop the ISRLM tool with the aim to capture the complexity of industrial symbiosis implementation and to guide the user throughout the development process. The ISRLM tool has served, not only as a guiding and assessment tool for practitioners, but as a process for myself to understand the intricate and complex nature of industrial symbiosis collaborations.

The ISRLM tool is based on the technology readiness level assessment concepts first developed by NASA (Mankins, 1995). The ISRLM tool has been developed through an iterative process of both literature reviews, drawing on multiple different applications of the readiness level concept (Bruno et al., 2020, Kobos et al., 2018, Olechowski et al., 2020, Yasseri and Bahai, 2020), combined with co-design, engaging multiple stakeholders in the development process.

The ISRLM tool is divided into two different matrices, where the network level is addressed in one of the matrices and single resource exchanges are assessed in the other, as shown in Tables 3 and 4, respectively. The network level is assessed from three different perspectives, organization (ORL), society (SRL) and environment (ERL), whereas single resource exchanges are assessed from four perspectives corresponding to technology and integration (TIRL), business (BRL), legal aspects (LRL), and environment (ERL). Environmental performance is evaluated at both levels to capture the progress of environmental performance, not only from a single resource exchange but also from the greater systemic perspective. This implies that there are six distinct categories.

Furthermore, the ISRLM tool holds nine readiness levels corresponding to six different categories to be guided and/or evaluated. Hence, each category is assessed on a readiness scale from 1 to 9, where level 1 represents the least mature state and level 9 indicates a high maturity. The nine readiness levels further correspond to four different development phases as depicted in Tables 3 and 4.

A set of activities has been identified for each category and readiness level with the aim to support the progression and development of the industrial symbiosis collaboration. While the complete list of activities is provided in the Supplementary materials appended to Paper IV, where the ISRLM tool is fully outlined, the following section offers an overview. Tables 3 and 4 synthesize these activities, offering a summary for each readiness level across the categories within each matrix. For further elaborations on the development process and the details of the tool itself, refer to Paper IV.

Table 3. ISRLM for evaluation at the industrial symbiosis network level.

Phase	RL	Organization	Society	Environment
Full-scale operation	9	Full-scale operation where actors seek to ensure long-term sustainability, and evaluate existing and new partnerships.		
	8	Operation at full-scale has just commenced. Monitor impacts on society and the environment.		
Preparing for full-scale operation	7	Establish joint agreements regarding responsibilities, management, and procedures for monitoring performance. Adapt the IS network based on (potential) societal concerns.		
	6	Develop long-term plan for leadership, governance and monitoring, alongside validation of impacts on society and the public's acceptance.		
Testing	5	Analyze social and environmental added values, and identify potential means for secure data and information sharing.		
	4	Align actor strategies and create a shared vision, build long-term relationships and mutual benefit, establish internal communication, assessing public impact, and collect data based on KPIs.		
Ideation	3	Engage key actors, assess management needs, define responsibilities, share information with societal stakeholders, and identify key performance indicators (KPI) to monitor environmental impact and efficiency.		
	2	Establish contacts between potential partners, identify societal stakeholders and preliminary impacts on the environment.		
	1	Describe the the IS network by identifying possible key actors, skills, and impacts.		

Table 4. ISRLM for evaluation of single resource exchange.

<table>
<tr><th>Phase</th><th>RL</th><th>Technology and integration</th><th>Business</th><th>Legal</th><th>Environment</th></tr>
<tr><td rowspan="2">Full-scale operation</td><td>9</td><td colspan="4">Operation at full scale with adaptable technology, sustainable business models, compliance with legal standards, and continuous evaluation of environmental impact and value creation.</td></tr>
<tr><td>8</td><td colspan="4">Ensure that essential infrastructure is in place, follow-up on sustainable business performance metrics, legal compliance, KPI monitoring and ongoing environmental impact evaluation.</td></tr>
<tr><td rowspan="2">Preparing for full-scale operation</td><td>7</td><td colspan="4">Build large-scale infrastructure and simulate operations. Negotiate fair pricing by including social and environmental values. Secure legal compliance, and establish monitoring of environmental performance.</td></tr>
<tr><td>6</td><td colspan="4">Build prototype demonstration. Evaluate long-term financial sustainability through risk and pricing analysis. Plan how to monitor long-term environmental performance.</td></tr>
<tr><td rowspan="2">Testing</td><td>5</td><td colspan="4">Validate technology in real environments and ensure compatibility with recipient needs and infrastructure. Refine business models, align legal requirements, and update environmental impact analysis based on local data.</td></tr>
<tr><td>4</td><td colspan="4">Test technology and system integration at small-scale. Refine business model, assess legal compliance, collect data based on KPIs, and discuss the distribution of economic and environmental benefits among partners.</td></tr>
<tr><td rowspan="3">Ideation</td><td>3</td><td colspan="4">Prioritize scenarios based on techno-economic and risk assessments, refine the business model and map regulatory frameworks, while identifying key performance indicators (KPI) for business and environmental performance.</td></tr>
<tr><td>2</td><td colspan="4">Compile data for scenario analysis, identify technical solutions and related risks, establish supplier-recipient contacts, investigate market potential, legal constraints and environmental impacts.</td></tr>
<tr><td>1</td><td colspan="4">Map residual resources and potential users and identify value-creating opportunities. Investigate legal requirements, determine ownership, and describe environmental impacts to inform scenarios for cooperation.</td></tr>
</table>

5.2.2 Results and interpretation

The results from the readiness level assessments are illustrated in spider diagrams to create an accessible visualization of actors' readiness, potential alignments and discrepancies. Figures 5 and 6, showcase a fictive example of an industrial symbiosis network, illustrating how results can be depicted and interpreted. In figure 5, the full industrial symbiosis network is assessed based on ORL, SRL, and ERL. In this fictive case, one can see that there are some misalignments, especially for the ORL. If this were a real case, this misalignment could potentially create collaborative challenges as actors view the organizational aspects differently.

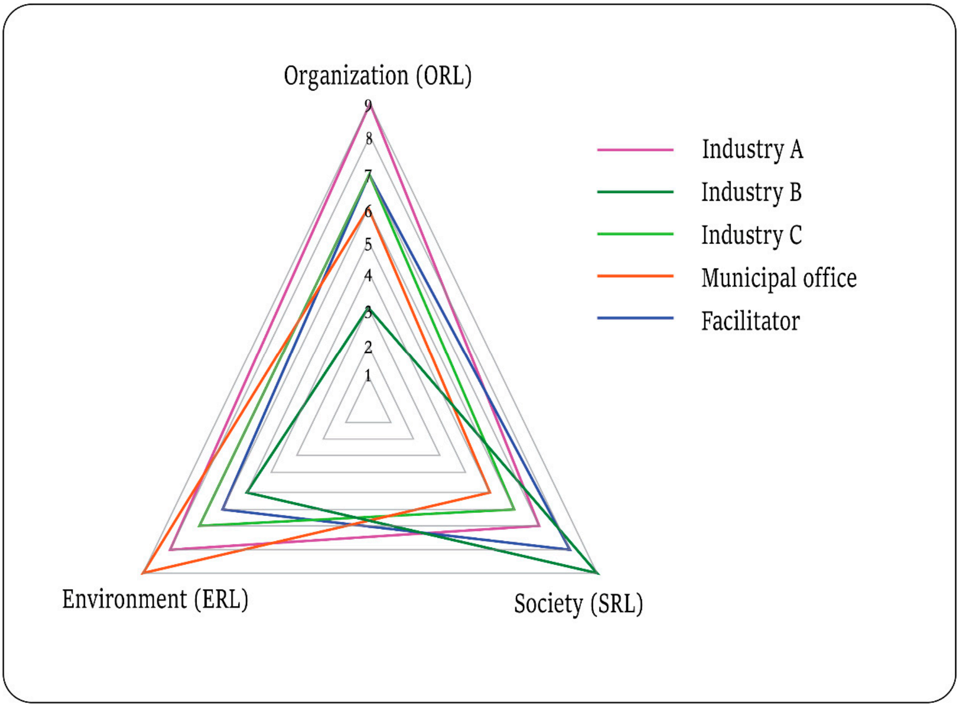

Figure 5. Visual illustration of a fictive evaluation of the entire network by Industry A, B, C, the municipality, and facilitator

Furthermore, Figure 6 presents a fictional example of a resource exchange between Industry A and Industry B, where a divergence in business readiness points to possible disagreements over contract terms - an issue that could be crucial to resolve. The spider diagrams, paired with the recommended activities from the ISRLM tool, provide a structured basis for constructive discussions. These visualizations help participants identify discrepancies, refine organizational strategies, and work collaboratively toward a shared vision for the partnership.

In addition to the matrices and graphical summaries, the ISRLM tool includes an action plan that could help outline specific steps, responsibilities, and milestones for advancing the collaboration. To sustain progress, actors are encouraged to periodically revisit their assessments and update the action plan. This iterative process ensures that momentum is maintained, emerging challenges are addressed, and collective efforts remain aligned with the network's objectives.

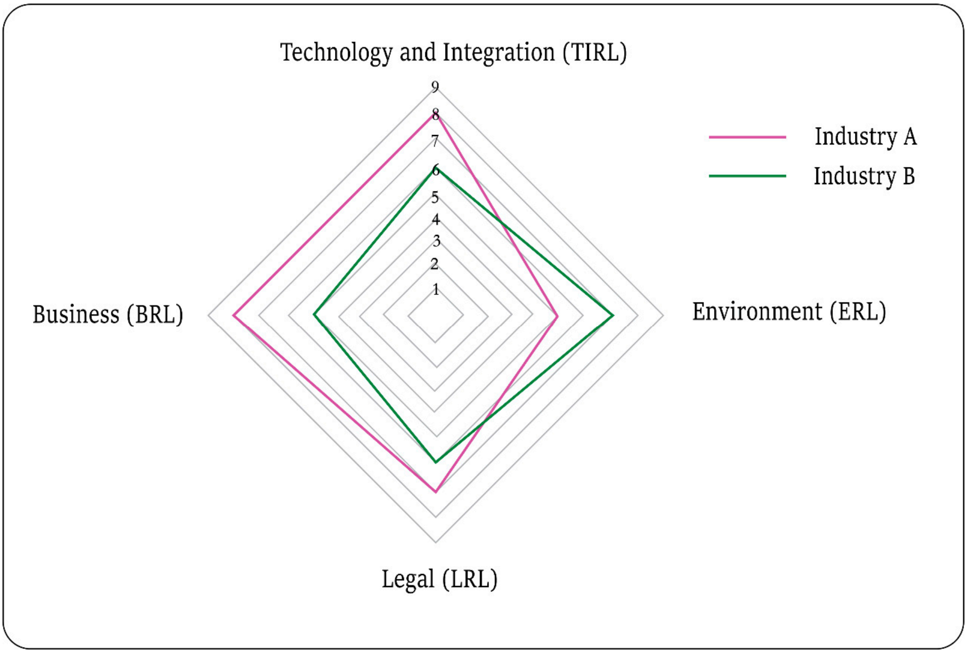

Figure 6. Visual illustration of a fictive evaluation of a single resource exchange between Industry A and B.

5.2.3 Insights from actors

The ISRLM tool was developed through a collaborative and iterative process to ensure its relevance, applicability, and usability in existing industrial symbiosis networks. By engaging diverse stakeholders such as industry representatives, researchers, and facilitators - the tool was refined to address critical challenges in indsutrial symbiosis implementation while balancing theoretical underpinnings with practical usability. Workshops, interviews, and feedback loops were integral to this process, allowing stakeholders to contribute to shaping the tool into a resource that is both user-friendly and actionable.

The actors recognized the ISRLM tool for its ability to simplify complex aspects of industrial symbiosis, offering clear guidance for both initiating new partnerships and enhancing existing ones. The tool was appreciated by actors to to facilitate structured discussions, foster communication, identifying gaps, and aligning efforts throughout an industrial symbiosis network's development. Its dual focus, separating assessments of the network and the single resource exchanges, captures critical nuances, supporting a deeper understanding of specific collaboration dynamics.

The actors also appreciated the tools graphical representation of readiness levels. They viewed the tool as something they could use as a diagnostic framework, where they could pinpoint issues, engage new participants, and navigate the complex process of industrial symbiosis developement. Despite this overall recognition of the tool's utility, the perceived value of its use was influenced by its timing within the industrial symbiosis development process. While some actors found it particularly beneficial as a starting point, others believed it was more effective later, once the collaboration had become more clearly defined.

Looking ahead, continuous application of the ISRLM tool across diverse industrial symbiosis settings could further enrich its methodology. Over time, the ISRLM tool could evolve into a living document, incorporating best practices and insights to guide industrial symbiosis networks in fostering collaboration, innovation, and sustainable growth.

5.3 Discussion on the utility, applicability and implications of the tools

Chapter 5 draws on the knowledge generated by Papers I-III, alongside Chapter 4 in this thesis. Based on this knowledge, this chapter introduced tools to guide and assess implementation of industrial symbiosis. The Impact Assessment Matrix and the ISRLM tool developed in Papers III and IV, respectively, can work synergistically to facilitate industrial symbiosis implementation.

Viewed from a systems perspective, industrial symbiosis is not merely a collection of two-sided exchanges, but a dynamic, multi-actor collaboration embedded within broader socio-economic, political, and environmental systems. Even though I argue that acknowledging and understanding the individual actor perspective is important, successful implementation of industrial symbiosis requires tools that not only assess individual actors or isolated transactions but also consider how these interact across time, sectors, and different societal domains.

The ISRLM tool addresses this need by assessing the systemic readiness of actors and networks across multiple dimensions. It helps identify gaps and misalignments, fosters cross-actor learning, and provides a structured basis for action planning. By surfacing disparities in readiness, the tool supports network-level coordination, enabling actors to make sense of their interdependencies and plan collectively for capacity-building, sequencing of efforts, and resource allocation.

The Impact Assessment Matrix can complement the ISRLM tool by extending the analysis to include the outcomes and impacts of industrial symbiosis collaborations. The Impact Assessment Matrix provides a framework for systematically assessing environmental, economic, and social effects, enabling actors to evaluate the tangible and intangible benefits and adverse effects of their participation, as well as illustrate their distribution. By identifying and illuminating the distribution of potential and/or realized effects of industrial symbiosis, the Impact Assessment Matrix ensures that stakeholders reflect on the broader implications of their actions, beyond their own organization.

Furthermore, the ISRLM tool plays a key role in visualizing the alignment of readiness among different industrial symbiosis actors. By clarifying where alignment exists and where disparities in readiness may cause friction, this visualization helps actors prioritize areas for development and supports transparent, collaborative discussions. This tool does not only enable more effective planning and execution of industrial symbiosis networks, but also fosters a mutual understanding of each actor's position, motivations, and constraints, helping to build a shared vision and reduce potential conflicts, something inherently important in industrial symbiosis collaborations (Behera et al., 2012, Janipour et al., 2022, Kokoulina et al., 2019, Noori et al., 2020). Furthermore, both the ISRLM tool and the Impact Assessment Matrix encourages regular reassessments, thereby they can continuously be used to evaluate the progress and impact of improvements. This iterative process ensures that both readiness and effects are continuously evaluated.

By using the Impact Assessment Matrix alongside the ISRLM tool, practitioners can prioritize actions identified in the readiness assessment based on their potential effects.

For example, initiatives that show high readiness and significant positive effects can be fast-tracked. Additionally, both tools promote reflexivity by encouraging regular reassessment. They invite actors to revisit assumptions, track progress, and respond to shifting conditions. This feedback-driven approach helps build system resilience, ensuring that industrial symbiosis networks remain adaptable in the face of regulatory changes, market dynamics, or environmental pressures.

From a systems innovation perspective, these tools also help bridge micro-level decision-making with meso- and macro-level outcomes. By supporting shared visioning, clarifying motivations and constraints, and illuminating trade-offs, they foster collective knowledge and coordinated action. This is particularly important in industrial symbiosis, where the success of one actor often depends on the actions of others, and where long-term partnership relies on mutual understanding and trust.

Moreover, future development of the ISRLM tool and Impact Assessment Matrix could benefit from integration with complementary methodologies, such as regional data analysis for identifying synergies or performance indicators for tracking industrial symbiosis performance (Behzad et al., 2024, Cagno et al., 2023, Kosmol et al., 2021, Marinelli et al., 2021, Patricio et al., 2022). This holistic approach would enable the tools to address both the identification of opportunities and the ongoing evaluation of industrial symbiosis networks, fostering sustainable and equitable development.

Together, the ISRLM tool and Impact Assessment Matrix allow for a dual focus: ensuring that actors have the necessary tools to form a sound collaboration and evaluate the resulting effects. They enable a comprehensive assessment, ensuring both preparedness and effectiveness in achieving desired outcomes. Integrating the two tools allows for an approach to industrial symbiosis which enhances more informed decision-making, highlights synergies and trade-offs, and enables industrial symbiosis networks to progress sustainably and equitably.

6 Concluding remarks

Two primary objectives have driven the research and contributions made in this thesis. The first was to integrate and acknowledge actor-specific perspectives into the overall understanding of industrial symbiosis, recognizing the diversity of actors and how these differences influence collaboration. The second objective was to facilitate the implementation and development of industrial symbiosis through provision of tools to guide and assess its development. By using these objectives as the guiding principles for this thesis, my research has explored actor and context specific characteristics in industrial symbiosis, demonstrating how these impact actors' perception and stance in industrial symbiosis participation. It also shows how this knowledge can contribute to the facilitation of industrial symbiosis implementation. The following sections present the key findings and conclusions derived from the research conducted in this thesis, while also exploring potential avenues for future research related to industrial symbiosis collaborations.

To address the first objective, the findings in this thesis highlight several critical factors influencing the formation and success of industrial symbiosis networks, emphasizing the complexity and contextual nature of these collaborations. A key takeaway is that industrial symbiosis formation is highly dependent on a range of factors, including the specific characteristics and contexts of participating actors. Each actor, whether due to their size, ownership structure, resource flows, or geographic location, brings a unique perspective that shapes their experience of driving and inhibiting factors, as well as the positive and negative effects rendered by the collaboration. In Paper I, II and III, I show that perceptions of these factors vary substantially between actors, influencing both the value they assign to the collaboration, and the cost and level of risk they are willing to accept.

One key insight, aligned with the first objective, is that recognizing these differences is essential to understanding how actors contribute to, or complicate, the collaborative process. The varied perceptions on factors influencing participation and the effects generated from it, illuminates the potential for both opportunity and risks in industrial symbiosis partnerships. What I find in, Paper I and III, suggests that differences among actors in, for example, funding, company size, sector, and role within the network can create power imbalances, trust issues, and unequal distribution of benefits, which, if left unaddressed, may hinder the network's stability and growth.

On that note, another important insight is that the distribution of benefits and adverse effects ought to be better examined, as these are not confined to individual participants but extends to the broader network and even society. In this research, particularly in Paper III, I examine this distribution to illustrate how industrial symbiosis effects go beyond immediate participants, influencing the network level and societal outcomes. The Impact Assessment Matrix serves as an initial step in evaluating the distribution of effects from industrial symbiosis collaborations. The Impact Assessment Matrix can serve as support in negotiations and reaching agreements between industrial symbiosis partners, contributing to the second objective of this thesis. However, additional efforts to quantify and potentially monetize these effects could further motivate financial support and incentives for the continued implementation of such initiatives. Developing improved methods for assessing and distributing the benefits and adverse effects of industrial symbiosis initiatives represents a potential future research trajectory. Enhancing the measurability and granularity of these outcomes, particularly in terms of their distribution across individual actors, would allow for more informed decision-making and equitable collaboration.

The inherent complexity of industrial symbiosis networks emphasized in this thesis poses evident challenges. Collaboration across diverse actors, each with its own goals, can make alignment difficult. This complexity underlines the need for clear guidance and accessible frameworks for practitioners and facilitators to navigate and manage industrial symbiosis collaborations more effectively. To this end, I contributed to the development of the ISRLM tool in Paper IV. In line with the second objective, the ISRLM tool provides a practical framework to guide actors through the complex process of industrial symbiosis implementation, from ideation to full-scale operation. Developed iteratively with direct feedback and suggestions from industrial symbiosis participants, the ISRLM tool integrates several key perspectives, and renders a holistic approach to evaluation and guidance.

Future development of the ISRLM tool and Impact Assessment Matrix could be strengthened through integration with complementary methodologies. These might include regional data analysis to identify new synergy opportunities, and performance indicators to monitor and track the development of industrial symbiosis over time. Together, such advancements would enable a more dynamic, data-driven, and context-sensitive approach to fostering sustainable and resilient industrial symbiosis collaborations. Furthermore, there is a need to test and validate the ISRLM tool and the Impact Assessment Matrix in a variety of contextual settings, including different geographical regions, industrial sectors, value chain structures, and regulatory environments. Such comparative studies would help assess the generalizability of the tools and support the refinement of their design and application.

Further attention should also be given to the roles, capabilities, and organizational positioning of facilitators. As key actors in enabling collaboration and mediating between diverse stakeholders, facilitators have significant influence on network formation, governance, and long-term resilience. Understanding how different facilitator models function in practice could provide valuable insights into what makes industrial symbiosis more adaptive and effective.

Another potential avenue for future research could be to explore how lock-in effects in industrial symbiosis evolve over time, shifting from beneficial to potentially detrimental. In some regards, lock-in can enhance stability, trust, and commitment, supporting long-term collaboration and shared investments. However, as networks mature, high interdependence may reduce flexibility, hinder innovation, or amplify systemic risk if a key partner leaves the collaboration. Studying the dual nature of lock-in effects can offer valuable insights. Future research could also explore strategies to manage or mitigate negative lock-in, such as models for system adaptation, scenario planning, or built-in flexibility. Understanding these dynamics is key to designing resilient industrial symbiosis collaborations. Future studies focusing on how collaborative structures can remain resilient while allowing for change would contribute to more robust industrial symbiosis frameworks.

In summary, this thesis represents a step toward bridging the industrial symbiosis gap. In my research, I advance knowledge on industrial symbiosis implementation by addressing both the unique influences of individual actors and the need for structured guidance in its development. By exploring the interplay between actor-specific dynamics, and by providing the tools for comprehensive evaluation, these findings contribute to the broader goals of sustainable resource use and effective cross-sector collaboration. As industrial symbiosis continues to evolve, these insights and tools will be valuable for both practitioners, facilitators, and researchers striving to create resilient, mutually beneficial, and environmentally sustainable industrial symbiosis collaborations.

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INDUSTRIAL SYMBIOSIS is a collaborative strategy aimed at enhancing resource efficiency and sustainability through exchanges between industries and other societal actors. While it initially focused on optimizing physical flows, such as excess energy, waste, and by-products, the concept has since evolved to include collaboration around infrastructure, logistics, and knowledge sharing. This broader view highlights industrial symbiosis as a means to develop innovative, long-term solutions for complex industrial and societal systems. Even if industrial symbiosis has great potential, it has not yet been widely implemented across society. This thesis examines how the diverse perspectives and conditions of individual actors influence the development of industrial symbiosis collaborations, and provides tools to navigate its complexity.

Printed by Media-Tryck, Lund 2025 NORDIC SWAN ECOLABEL 3041 0903

LUND UNIVERSITY

Faculty of Engineering
Department of Technology and Society

ISBN 978-91-8104-473-7
ISSN 1102-3651