Aalborg University

Department of Planning
Rendsburggade 14
DK-9000 Aalborg
EMSS4

Quantifying the Environmental Performance of Industrial Symbiosis Networks

A Case Study of Industrial Symbiosis North in Aalborg

Master's Thesis

Quantifying the Environmental Performance of Industrial Symbiosis Networks

A Case Study of Industrial Symbiosis North in Aalborg

Master's Thesis

January 7, 2022

By Asbjørn Uldbjerg Bundgaard, Jesper Kokborg Lassen, and Nichlas Lange Dalsgaard

4th Semester, Environmental Management & Sustainability Science

Aalborg University, Department of Planning, Rendsburggade 14, DK-9000 Aalborg Denmark

http://en.plan.aau.dk

Frontpage by Center for Logistics & Collaboration (2022)

AALBORG UNIVERSITY
STUDENT REPORT

Department of Planning
Rendsburggade 14, 9000 Aalborg
DK-9000 Aalborg
http://en.plan.aau.dk

Title:
Quantifying the Environmental Performance of Industrial Symbiosis Networks

Theme:
Master's Thesis

Project Period:
Spring semester 2022

Project Group:
EMSS4

Participants:
Asbjørn Uldbjerg Bundgaard
Jesper Kokborg Lassen
Nichlas Lange Dalsgaard

Supervisor:
Søren Løkke

Copies: 1

Page Numbers: 134

Date of Completion:
January 7, 2022

Abstract:

Background: With increasing pressure on companies to minimize environmental impacts, this study develops an applicable approach to quantify environmental impacts for industrial symbiosis (IS) networks, with the purpose of supporting decision-making for symbiotic flows, in addition to assisting in the maturing of the network.
Methods: A case study of Industrial Symbiosis North is carried out to develop a life cycle assessment (LCA) model based on the case context and a literature review of preexisting literature.
Results: Results showed it possible to represent the environmental impacts for three taxonomic levels (i) Networks (ii) Entities (iii) Flows. The LCA results are bound by limited data quality and a narrow system boundary. Therefore, further improving adjustments to the model were identified along with implementation steps.
Conclusion: Quantifying environmental impacts at taxonomic levels proves beneficial for creating value propositions for companies within the IS network. By doing so, the facilitating organization expands its role for the network in regards to supporting sustainable development in a broader sense. Applying LCA in IS networks is therefore seen as a vital step for maturing both the facilitating organizations and the IS networks.

Preface

This study was written by Asbjørn Uldbjerg Bundgaard, Jesper Kokborg Lassen, and Nichlas Lange Dalsgaard during 10th semester of the program, *Environmental Management and Sustainability Science*, at Aalborg University (AAU). The study was conducted in the period 01-02-2022 to 03-06-2022. The aim of the study is to investigate how the quantification of environmental performance through utilization of life-cycle assessment (LCA) can assist in maturing Industrial Symbiosis (IS) networks, based on a case study on the emerging Industrial Symbiosis North (ISN). Moreover, the learnings of the case are connected to the overarching perspectives and considerations of key stakeholders within the field of IS network development with the intent of posing a set of recommendations for both ISN and the general development of IS networks. For this reason the key audience of this research is the general stakeholders partaking in IS networks, although complexity of LCA modeling might reduce the applicability to a limited set of practitioners namely LCA specialists. We would personally like to acknowledge Søren Løkke for his valuable supervision and guidance of this study in addition to Lucia Mortensen and Leoine Schlueter (Port of Aalborg A/S) for their dedication and time spent in facilitating data and knowledge. Lastly, we would like to recognize interviewee Per Møller (Kalundborg Symbiosis) for sharing his valuable experience regarding IS networks.

Reading instructions

References in the report follow the Chicago referencing style. For this reason, figures and tables are referred to by their respective chapter followed by the sequential number within that chapter. Moreover, a list of abbreviations used and their meaning can be found on the following page. Site-specific company data and interview transcription can be found in the Appendix. Additionally, an excel-file containing the LCI inventory and Integrated Matrix Augmentation System (IMAS) are found within the supplementary digital appendix. Attached to this are 3 CSV files containing the data for the symbiotic networks scenarios. A comprehensive guide on how to import these file into SimaPro are found within Appendix A.1. **Note:** Importing the CSV files will require setting up a custom unit for the adjusted monetary unit utilized (See attached guide).

Asbjørn Uldbjerg Bundgaard
Asbjørn Uldbjerg Bundgaard
abundg17@student.aau.dk

Jesper Kokborg Lassen
Jesper Kokborg Lassen
jlasse17@student.aau.dk

Nichlas Dalsgaard Lange
Nichlas Lange Dalsgaard
ndalsg17@student.aau.dk

Resumé

Dette specialeprojekt omhandler kvantificering af miljøpåvirkninger for Industrielle symbioser. Industrielle symbioser er netværk af uafhængige virksomheder, som udveksler affaldsressourcer og biprodukter til anvendelse i produktionen for andre virksomheder. Specifikt er projektets fokus på anvendelse af aktivitetsdata i industrinetværk med formål om at skabe anvendelig information om miljøeffekter for symbiotiske udvekslinger. Denne information er betragtet som værende kritisk i beslutningstagningen for hvorvidt en eksisterende såvel som ny udveksling er miljømæssigt forsvarlig. Kompetencer til at kunne skabe information for vurdering af miljøeffekter af udvekslinger ses som et nødvendigt skridt for Industrielle symbiosers modningsproces, hvor eksisterende symbioser er udfordret af en økonomisk styring i identifikationen af nye udvekslinger.

Projektet tager udgangspunkt i et case studie af Industriel Symbiose Nord (ISN) anlagt i Nord Jylland. ISN er faciliteret af Center of Logistik og Samarbejde (PARD) som udvikler symbiosen gennem projekter støttet af Den Europæiske Fond for Regionaludvikling. Det eksisterende symbiotiske netværk, ISN, kan potentielt udvides med en række nye virksomheder og symbiotiske udvekslinger som er identificeret under projektet GRØN. For at kunne kvantificere miljøeffekterne af denne udvidelse undersøge projektet først den eksisterende erfaring gennem et scoping review af litteratur på området. Formålet er at udlede terminologien anvendt samt udlede en metodisk fremgangsmåde for kvantificering af miljøeffekterne ISN. Den valgte metode tager udgangspunkt i en kvantificeringsmodel baseret på livscyklusvurdering (LCA) som er blevet sammensat af mangler ved eksisterende studier og herved kan beskrives med følgende karakteristikker:

- Modellen anvender multi-dimensionelle funktionelle enheder til at vurderer miljøeffekterne på tre taksonomiske niveauer (netværk, entitet og flow).
- Modellen tager udgangspunkt i et integrated matrix augmentation system (IMAS), med inddragelse af IO-data fra hybriddatabasen Exiobase 3 til at overkomme problematikker angående datakvalitet og -tilgængelighed.
- Modellen inddrager en konsekvens tilgang til at evaluere hvordan produktsystemet vil respondere på et skift i efterspørgsel.

Projektet har været succesfuld i at opbygge en livscyklusvurderingmodel der formår at skabe værdi proposition for både virksomheder, og netværket, ved at muliggøre kvantificering af miljøeffekter på alle taksonomiske netværksniveauer. Kvantificeringen er således bidrage til at forankre facilitatorens rolle i netværket, hvilket medfører en øget mulighed for at fremme den bæredygtige omstilling. Herved anses kvantificeringsmodellen som et essentielt værktøj i at facilitere modningen af IS-netværk, og facilitatoren.

Abbreviations

BaU: Business-as-Usual
CE: Circular Economy
CHP: Combined Heat and Power
CSRS: Current Symbiotic Reference Scenario
DM: Dry Matter
ENS: Expanded Network Scenario
EMS: Environmental Management System
FU: Functional Unit
GHG: Greenhouse Gas
GRØN: Green Resource Ecosystems North Jutland
GWP: Global Warming Potential
HSRS: Hypothetical Symbiotic Reference Scenario
ICT: Information and Communication Technologies
IMAS: Integrated Matrix Augmentation System
IoT: Internet of Things
IS: Industrial Symbiosis
ISN: Industrial Symbiosis North
ISO: International Standard Organization
KPI: Key Performance Indicator
KS: Kalundborg Symbiosis
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
MEUR2003: Million Euro 2003
MEUR2011: Million Euro 2011
MEUR2018: Million Euro 2018
NPS: Nordjylland Power Station
PARD: Port of Aalborg Research and Development
PEF: Product Environmental Footprint
$PM_{2.5\text{-}eq}$: Particulate Matter 2.5-equivalent
QALY: Quality Adjusted Life Years
RF: Reference Flow
SME: Small and Medium Enterprises

Table of Contents

List of Figures

List of Tables

Introduction

Companies are increasingly being held responsible for their environmental impacts, which incentivizes the identification and implementation of reduction measures (The European Commission 2020). To achieve reduction measures, the concept of industrial symbiosis (IS) has emerged as a branching concept of circular economy and is considered a potent tool for future industry development (Lybæk et al. 2021). The primary objective of IS is to facilitate symbiotic resource exchanges within a network of different companies, to reduce the strain on the environment through optimizing resource utilization by selling or sharing secondary resources such as waste and bi-products (Chertow 2007). However, assessing the symbiotic exchanges is considered a challenge due to a general lack of standards, assisting tools, and competencies in assessing the environmental potential of new symbiotic exchanges (Ormazabal et al. 2018). In this regard, challenges for effectively and accurately providing information on environmental impacts of IS exchanges impede stakeholder engagement and maturity of IS network (Zheng and Jia 2017). Therefore, methods for quantifying the environmental performance and improvement potentials in IS networks are needed.

In the North Denmark Region, Port of Aalborg Research and Development (PARD) is responsible for the network, Industrial Symbiosis North (ISN), as a facilitator with the purpose of identifying new symbiotic exchanges and maturing the collective of enterprises (Center for Logistics & Collaboration 2022). The implementation of several new IS exchanges through the GRØN Project is one such example (Network for Sustainable Business Development 2021). However, limited knowledge regarding the environmental performance and improvement potential of the project is currently present within the institution.

This study will utilize life cycle assessment (LCA) to develop a model for continuous evaluation of the performance and decision-support in expanding and optimizing IS networks. The LCA model takes inspiration from pre-existing experience within the field of research and applies it to the case of ISN to gain insights into utilizing environmental quantification as a means of maturing IS networks. In addition to this, the model addresses the challenges concerning data quality and availability to provide multiple value propositions for the companies included in the network.

Background

Chapter 1

Case Contextualization

This chapter outlines the main reasons why the quantification of environmental performance in IS networks is essential for maturing the networks. First, the topic's relevance is described by emphasizing the present issue of resource depletion in relation to the concept of industrial symbioses and its challenges. Furthermore, the case of Industrial Symbiosis North (ISN) is contextualized as a foundation for further analysis regarding quantification methods.

1.1 Industrial Symbiosis

The depletion of natural resources is a central challenge of the twenty-first century and is resulting in an intensification of competition among affected resource users (Prediger et al. 2013). Between the 1980s and 2009, the global material consumption has increased by 95%, and resources are increasingly becoming more costly (Kalaitzi et al. 2018). Moreover, the global use of natural resources has accelerated carbon emissions along with the production of waste which has increased in line with the growing extraction of natural resources (Schandl et al. 2016). This trend has led to the phenomenon of resource scarcity, which refers to the observed shortage of natural resources while still having a global dependency on the same resources (Dawson et al. 2017).

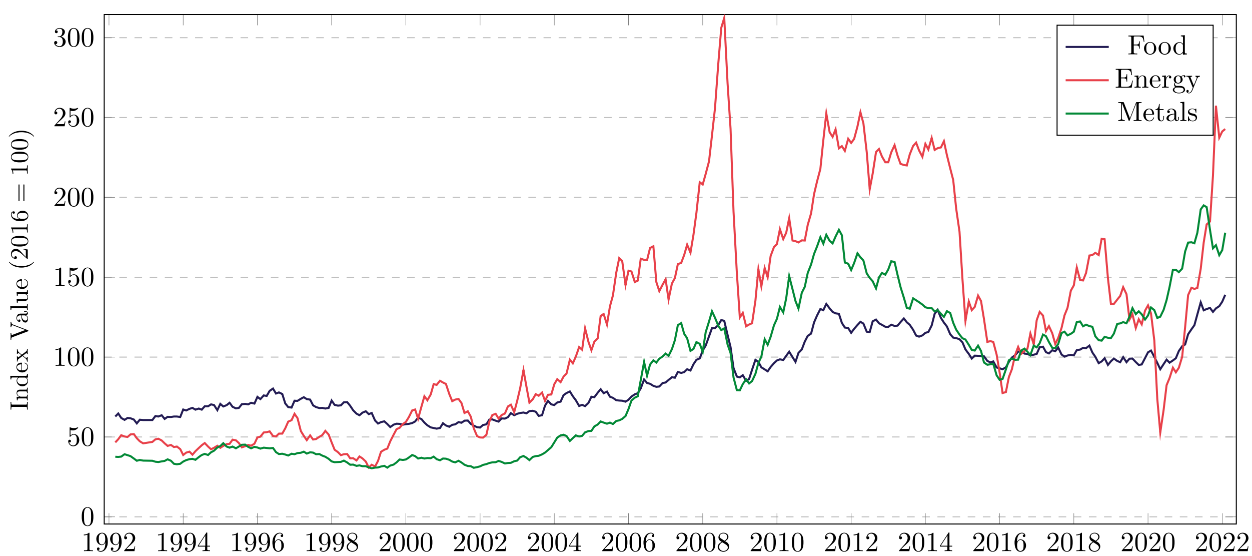


Figure 1.1: Global primary commodity prices from 1992-2022 for food, energy, and metals. Data extracted from International Monetary Fund (2022)

As illustrated by Figure 1.1 resource prices have significantly increased and become more volatile over the last 30 years as a consequence of demand International Monetary Fund (2022). Meeting the future resource demand, therefore, implies a shift in practices towards sustainable resource consumption, which, according to the United Nations, requires not compromising the ability of future generations to meet their own needs (United Nations 1987). In this regard, sustainability is commonly seen in terms of three dimensions: (i) social, (ii) economic, and (iii) environmental (Kuhlman and Farrington 2010).

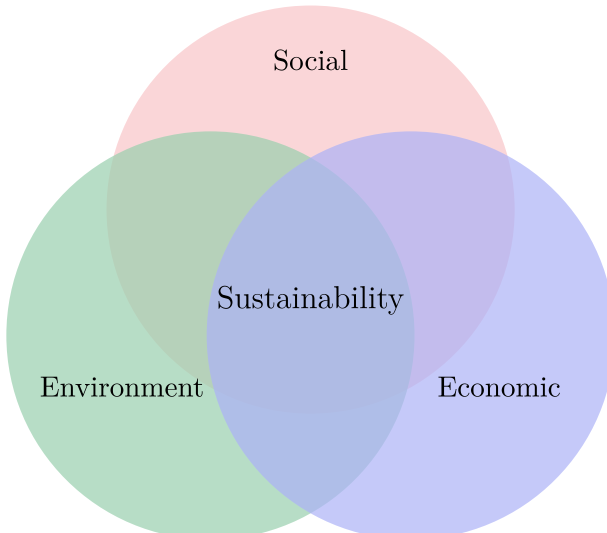


Figure 1.2: Relationship between the economic, environmental, and societal dimension (Purvis et al. 2018)

To prevent resource scarcity and transition towards sustainable resource consumption, scientists, policymakers, and engineers are working with the challenge of implementing the concepts of industrial ecology (IE) (Kapur and Graedel 2004). IE involves a system thinking approach to transition the industry into a more circular practice. To optimize resource utilization, the concept of industrial symbiosis (IS) occurred as part of IE (Lybæk et al. 2021). IS is an analog to the biological systems, where symbiosis refers to the interdependence between species in eco-systems (Lybæk et al. 2021). IS' role in the context of preventing resource depletion is that of minimizing the extraction of new resources by utilizing waste- and bi-products in an optimized way by sharing it within an industry network (Chertow 2007). In this regard, IS is defined by Chertow (2000) as:

> "The engagement of traditionally separate industries in a collaborative approach to physically exchange materials, energy, water, and/or by-products to gain competitive advantages"
>
> (2000, p. 313)

The development of new symbiotic exchanges has previously been primarily driven by financial incentives (Fraccascia and Yazan 2018). However, as enterprises are increasingly held responsible for their environmental performance through policy developments, the competitive advantages of IS have shifted from exclusively economic to additionally including an environmental dimension (See Figure 1.2). The most recent strategy of the EU, *The European Green Deal*, has the objective of achieving regional net zero emissions of greenhouse gasses by 2050 and decoupling economic growth from resource usage. Moreover, the policy initiative constitutes an ever-increasing emphasis on industries' responsibilities regarding the environment and sustainability (The European Commission 2020). In this respect, quantification of the environmental performance and improvement potentials poses a valuable opportunity for gaining further competitive advantages while supporting sustainable development. Consequently, there is an inherent need for expertise and knowledge regarding the topic of maturing IS networks through environmental quantification.

Furthermore, it should be recognized that the emergence and development of IS networks can manifest through distinct arrangement approachesGhali et al. (2016). Because of these differences, IS networks can be divided into three development categories as presented by Table 1.1.

	Self-Organizing	**Planned**	**Facilitated**
Corresponding Diffusion Systems	**Decentralized**	**Centralized**	**Hybrid**
Direction of diffusion	Among the firms (that could be considered as potential adopters of IS knowledge, positive attitude and practice) through their horizontal networks.	One-way direction from the promoting agency to firms in the context of planned IS, the promoting agency (usually governmental agency) acts as the central planner.	Among firms through the coordination of the promoting agency, as well as from the promoting agency. In the context of facilitated IS, the promoting agency is usually a third-party organization who acts as facilitator.
Source of innovations	Innovations come from the firms who are also the potential adopters.	Innovations come from R&D, introduced by the promoting agency (central planner).	Innovations come from the firms themselves as well as the R&D introduced by the promoting agency (facilitator).
Who decide the innovation	The firms themselves	Top administrators and technical subject-matter experts (in the context of planned IS, represented by the central planner).	The firms themselves. In addition, top administrators might be involved in the introduction of some very promising innovations (coordinated by the facilitator).
Degree of centralization in innovation-decision	Sharing of control among the firms themselves; or client control by the opinion leaders in the firms.	Overall controlled by the top administrators and technical subject-matter experts (represented by the central planner).	Sharing of control among the firms themselves; or client control by the opinion leaders. Alternatively, decisions on some promising innovations might follow the centralized model.

Table 1.1: IS Network models according to Zheng and Jia (2017) based on diffusion of innovation by Rogers (2003)

In the self-organized category, the exchanges between entities emerge spontaneously, often by a mutual profit-driven interest in the resource exchange without awareness of the environmental potential inherently present (Chertow 2007). As opposed to the self-organized category, the planned category has the primary intention of creating IS networks, often manifesting as a planned and zoned eco-industrial park (Heeres et al. 2004). The planned approach typically builds upon specific goals managed and facilitated through a government agency (Chertow 2007). Lastly, the facilitated category is a hybrid solution between the self-organized and planned category, in which an external third-party facilitator is tasked with promoting and facilitating the communication between prospecting companies identified for the IS. This hybrid approach utilizes the facilitator in the initial tasks of identifying potential resource flows, matching partners together, and facilitating the dialogue as a neutral third party (Zhang et al. 2017). Consequently, each of the three categories has its challenges in how they facilitate an IS. In relation to this, quantification of environmental performance is seen as a valuable tool in decision-making – particularly concerning planned and facilitated networks.

When quantifying environmental performance, the scope of the network is a central element in question as it will determine the boundaries of the system. It should be recognized that several sectors traditionally have business practices with exchanges of by- and waste products, such as in the chemical industry (OECD 1965). Therefore, one may question the preliminary scope when applying the IS terminology. IS revolves around existing industries that are materially open and currently rely on non-renewable resources (Kapur and Graedel 2004). In this regard, IS can be distinguished from regular exchanges between enterprises by fulfilling two criteria.

1. At least three different entities must be involved in the symbiosis, of which none are primarily engaged in recycling-oriented businesses.
2. Industries should, as a minimum, exchange two different resources.

(Chertow 2007, p. 12)

When these two criteria are fulfilled, it is by the definition of Chertow (2007) fair to recognize the system as having more complex circular relationships rather than the traditional linear connections. There are, however, several additional challenges concerning the development of IS networks.

1.2 Challenges of IS Development

While the driving forces behind IS network development are typically determined by which model it emerges from, as illustrated by Table 1.1 – so are the challenges present in both the emergence and the subsequent preservation of the network. The following section will briefly highlight some of these challenges.

Non-technical Challenges A great deal of problems occurring in the development of IS networks is ascribed as non-technical (Ormazabal et al. 2018). Companies are primarily reliant on their capability to identify by-products, waste, or other material resource flows suitable for IS network integration (Bessant 2008). Consequently, the identification and initiation of material resource exchanges are particularly a problem in small and medium enterprises (SMEs), an essential set of stakeholders to include in the realization of IS networks, and a more circular economy in general. For instance, SMEs account for

70% of industrial pollution, 40-45% of all industrial air emissions, water consumption, and energy consumption in the EU, as well as 60-70% of industrial waste production in France (Ormazabal et al. 2018). Conversely, SMEs are in large part reactive to environmental regulation and initiatives (Pigosso et al. 2018). This reactiveness contrasts larger corporations who are more proactive, with the required resources available and often supported by environmental policies or directives dictated by their internally developed corporate social responsibilities policies (Ormazabal et al. 2018).

In cases where SMEs successfully manage to identify material flows, the actual implementation process may be extinguished or outright fail due to non-technical challenges, such as an organization's lack of vision or dedication to the realization and development of the IS (Ormazabal et al. 2018; Pigosso et al. 2018). Furthermore, the failure of facilitating trust between prospecting IS participants is often credited as to why a symbiosis fails to develop, which is why the adaptation of third-party facilitators is seen as a critical driving factor for the successful development of an IS network (Zheng and Jia 2017). These facilitators inherit the vital role of creating trust and facilitating sharing of information that has the potential of being sensitive in a way that does not compromise the integrity of business models. Subsequently, the failure to share information and activity data is credited as one of the primary causes of why IS networks fail to manifest or maintain themselves, as this failure is often grounded in reluctance or a direct lack of trust in collaboration with stakeholders (Fraccascia and Yazan 2018).

Technical Challenges As previously detailed, symbiotic exchanges are often layered in a degree of economic incentives. These symbiotic flows require consistent or otherwise manageable resource flows in the supply and demand relationship between prospective or otherwise already participating stakeholders of an IS network (Fraccascia and Yazan 2018). If a prospecting IS participant chooses to adopt an alternative resource as a substitute for raw materials in their production, the company supplying this alternative will need to provide a series of assurances and guarantees to the recipient. The supplier has to: (i). Consistently meet the desired demand of the recipient. (ii). Reduce perturbations, i.e., events that affect the feasibility conditions of the exchange (Fraccascia et al. 2017). For example, the supplier can not change production methods in a way that might affect the recipient of the alternative resource, as this could potentially disrupt their business by a sudden lack of the required resources. Consequently, perturbations as such are often why prospecting symbioses fail to emerge in the IS Network or why companies exit an already established symbiosis (Mirata 2004).

Additionally, while resource exchanges in an IS network are often rationalized and grounded by economic incentives, at least in the self-organized model, planned and hybrid models conversely base themselves on increased environmental drivers (Pigosso et al. 2018). However, quantifying and assessing the actual environmental performance tied with the resources exchanged are considered to be a significant challenge for companies wanting to be knowledgeable as to how the exchange affects their environmental impacts (Mattila et al. 2010b). Moreover, the availability and quality of activity data prevents accurate representation of the environmental potentials and minimizes the applicability of the results in decision making (Ormazabal et al. 2018). This is both for the individual exchanges in the symbiosis and on a more systemic scale (Martin et al. 2015b). As such, the prospect of engaging in an IS network is often to develop some variation of a green business model, and failing to provide presentable and quantifiable environmental savings deters some companies from engaging in an IS network (Ormazabal et al. 2018). Furthermore, the uncertainty of who in the supplier-recipient relationship is environmentally credited for the emissions in the exchange waste of waste products is uncertain and currently lacks standardized reporting methodology (Mattila et al. 2010b).

1.3 Industrial Symbiosis Networks in Denmark

This section introduces the case-specific IS network, Industrial Symbiosis North (ISN), as well as a best-case scenario in the form of Kalundborg Symbiosis, as a means to compare how the two differ. This concerns both the function at present and the future potential that is envisioned.

1.3.1 Industrial Symbiosis North (ISN)

The North Denmark Region has, since 2016, facilitated the strategic partnership Environment^{++} between Aalborg Municipality, Aalborg Utilities, Reno-Nord I/S, Aalborg University, and Port of Aalborg who has been working toward the creation of sustainable synergies and -business models. (Kørnøv et al. 2020). Central to this is that environmental planning becomes an essential competitive parameter in maintaining current enterprises and attracting additional companies and jobs to the region. In this regard Environment^{++} comprises of four strategic tracks.

Track A: Strategic framework for value-producing growth
Track B: Strategic stakeholder involvement
Track C: Resource-optimization and synergies
Track D: Green business models

It is within these tracks that the knowledge hub, Port of Aalborg Research and Development (PARD), functions as a binding agent between enterprises connected to large and medium-sized Danish commercial ports and the affiliated business areas (Center for Logistics & Collaboration 2022). This entails supporting the connection between university-based research and business environments to improve the competitiveness of enterprises operating within the said area. Industrial Symbiosis North (ISN) is one such initiative, founded on the strategic tracks of Environment^{++} and includes several companies within Aalborg East and the surrounding region.

The flows consist primarily of waste exchanges and integration of surplus production heat into the municipal district heating system. However, it should be recognized that the vast majority of the prominent symbiosis exceed the Environment^{++} project and have naturally developed based on economic incentives since the mid-70s (Schlüter and Milani 2018) and have since steadily expanded. Grønne Ressource-Økosystemer Nordjylland [1] (GRØN) is an ongoing development project, similar to Environment^{++}, aimed at facilitating symbiotic exchanges among 100 participating small and medium-sized enterprises (SMEs) (Network for Sustainable Business Development 2021). Once the project period

1. Green Resource Ecosystems North Jutland

is over, the intention is to merge the newly established exchanges with the broader IS network of ISN. The timeline presented in Figure 1.3 presents the major events present throughout the development of ISN.

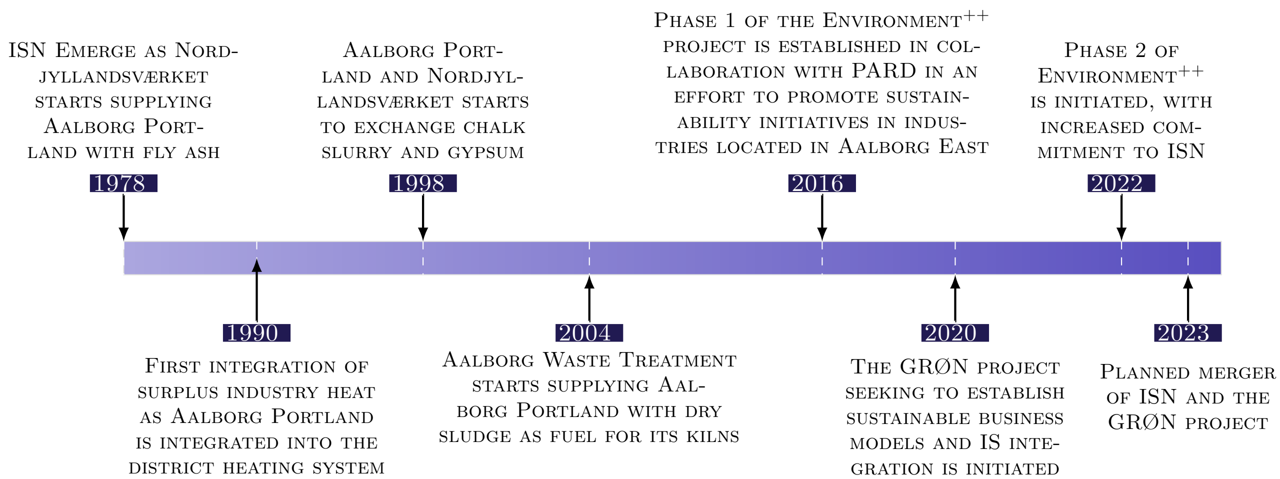


Figure 1.3: Timeline of substantial events during development of Industrial Symbiosis North

Another essential point is that the majority of the resource exchanges preceding Environment^{++} are an integral and established part of the supply chain. For instance, exchanges concerning fly ash, gypsum, sand, and chalk slurry have, in the case of ISN, existed for more than 30 years. This has resulted in companies not seeing these symbiotic exchanges as substitutions for otherwise virgin material but as a fundamental part of their supply chain. Conversely, this has meant that the majority of the companies facilitating present exchanges are either not aware of the symbiotic nature of the exchange or fail to articulate it despite acknowledging it.

Lastly, no facilitating institution has ever been part of ISN pre-dating PARD, meaning that there is neither a cultivated identity nor active collaboration behind ISN. Therefore, it should be understood that the current iteration of ISN is but a future vision driven by PARD and select stakeholders surrounding it and is, thus, neither tangible nor actively practiced.

1.3.2 IS landscape in Denmark

Other ÍS networks are constantly emerging, with the most established being the Kalundborg Symbiosis (KS), which is a partnership between thirteen public and private companies exchanging more than twenty-five different symbiotic flows (Kalundborg Symbiosis 2022). The network initially emerged as a self-organized collaboration and has been attributed to be the first documented industrial symbiosis, with its initial emergence occurring in 1961, followed by academic discovery in 1989 (Chertow 2007). The Kalundborg case has since established itself as the most prominent and best-case example of an industrial symbiosis (Chertow 2007). The successful collaboration behind the symbiosis can largely be attributed to the fact that none of the members consider each other as competitors, resulting in relatively uncomplicated network administration.

Another essential point is the active cultivation of identity, which has been occurring since 1996 when KS transitioned from a self-organized to a facilitated IS network (See Table 1.1). This facilitator was not limited in supporting the expansion and maintenance of the IS but also sought to promote and act as inspiration for others seeking to replicate symbiotic exchanges as a business model (Kalundborg Symbiosis 2022). This identity was further entrenched in 2010 when the consortium joined together in an association financed by membership, with support from Kalundborg Municipality. The goal of this association was to have all of the companies actively partaking in the continued development of KS, further strengthening their business competitiveness by centralizing IS and sustainability as part of their core business models. The timeline in Figure 1.4 presents the major events present throughout the development of KS.

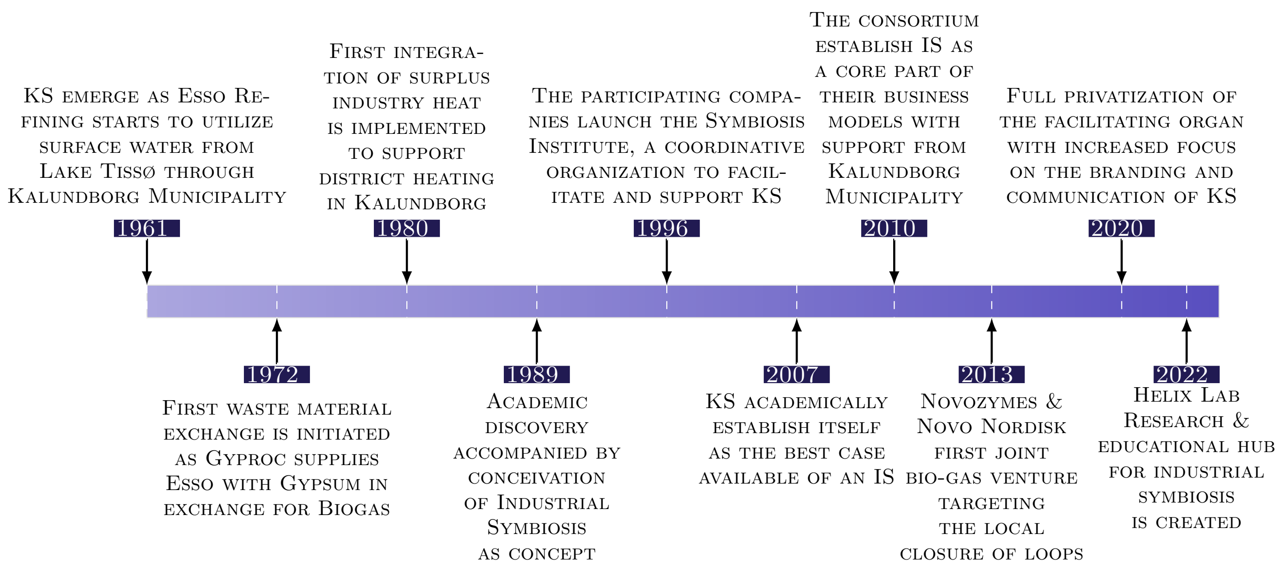


Figure 1.4: Timeline of substantial events during development of the Kalundborg Symbiosis

It is thus evident that KS differs from ISN in terms of network maturity despite somewhat emerging simultaneously. It could be argued that this difference is grounded on how KS received early academic attention within its lifespan, thereby making it easier to garner support and foster an identity around it. In contrast, ISN has been overlooked academically and therefore first seen active support in recent years where IS development has become a contemporary topic. Moreover, aspiring IS networks at a similar stage of maturity to ISN are located around Denmark. These are supported by recently emerged associations like the Danish Symbiosis Center, a national knowledge hub and advocate of IS, which tries to facilitate communication and experiences between the emerging and established IS networks (Danish Symbiosis Center 2022). However, so far, a lack of quantifying the environmental improvement potential of IS networks in Denmark, both emerging and established, are seen as a challenge that deters potential stakeholders from engaging (Ormazabal et al. 2018). Thereby, the ambition to quantify the environmental performance, and subsequent improvement potential, is the possibility to increase incitement for companies to join an IS network as the actual effect of the exchange suddenly becomes tangible and new opportunities arise in regards to communication and branding. Such initiative could be seen as KS recently sought to quantify the environmental performance of the network, which in 2020 resulted in a mass flow analysis (MFA) which estimated that the resource exchanges facilitated through the symbiosis reduced carbon emission by 586.000 tons of CO_2-eq annually (Kalundborg Symbiosis 2022). However, MFA does not assess the actual environmental performance as it is limited to mapping the resource flows going in and out of the network. An underlying consensus regarding that IS should contribute to environmental improvement has therefore resulted in a shift towards life cycle assessment (LCA) (Martin 2013). As a consequence, additional knowledge regarding the methodology of quantifying environmental performance to mature IS networks is thus required.

1.4 Research Question

In conclusion, the case contextualization suggests that there exist an inherent need for companies to partake in sustainable development. Industrial symbiosis (IS) has been identified as a concept applicable in supporting this transition. However, IS networks are prone to a series of challenges such as the quantification of environmental performance, and accessibility of activity data within the network. Consequently, overcoming these challenges will mature and strengthen the value proposition of the IS network.

By assessing the environmental performance of the current symbiotic exchanges present in ISN, and the prospective environmental improvement potential inherent in the GRØN project, this study sets out to explicate how life cycle assessment can support and facilitate the establishment and maturity of IS networks. Based on this, the following research question is posed.

Research Question:

How can activity data from industries be applied to track and assess the systemic environmental improvement potential of resource flows with the objective of maturing industrial symbiosis networks?

The answering of the RQ will take starting point in ISN as the case network. Sub-questions are posed to establish a systematic approach and assist in answering the research question. They are intended as a guideline for investigating the case and will be explained further with the research design as described in Chapter 2

Question 1: How can the principles of life cycle thinking be applied in quantifying the environmental improvement potentials of industrial symbiosis networks?

Question 2: How can activity data be utilized to quantify the environmental improvement potential of the Industrial Symbiosis North (ISN) network in practice?

Question 3: What are the opportunities and barriers in quantifying systemic environmental improvement potential, and how can these be overcome?

Theories and Methods

Chapter 2

Research Design and Methodology

Based on the research question and sub-question of Section 1.4, the following chapter will outline the applied research framework and course of action. Foremost to the research design is the framework utilized in structuring the project. In this respect, the ensuing chapter will describe the process of planning an investigation to quantify the environmental performance and improvement potential of IS networks. Furthermore, the chapter will detail the methodological approaches by elaborating on each sub-question with the chosen theories and methods applied to answer each of the questions.

2.1 Research Framework

As described by Farthing (2016), the core of designing research is establishing a strategy for transitioning from a series of unanswered questions to the end of a process with a final set of answers. The framework illustrated by Figure 2.1 connects the pre-established sub-questions to the conclusion of the research question through a series of interlinked processes. The research framework should be understood as progressing both laterally and horizontally by connecting the interlinked processes. Moreover, the framework is split into six horizontal parts, where each represents a central element of the design. The six aspects can be described as such:

Sub-questions: The questions posed guide the study in answering the research question.
Scientific Approach: The applied philosophy of science shapes the perspectives of the study.
Methodology: The methods used for collecting data in the particular area under study.
Theory: The application of theories supporting the study.
Units of Analysis: The processes of examining collected data in answering the research question.
Conclusion: The answer to the research question which the study seeks to answer.

(Bundgaard 2022)

As detailed in the case contextualization of Section 1.3.1, the study is carried out in cooperation with Port of Aalborg Research and Development (PARD). This project will hence seek to contribute to the continued development of Industrial Symbiosis North (ISN) by investigating how quantification of environmental performance and improvement potential can be realized. By analyzing the case of the ISN network, this study aims to expand the existing body of literature concerning the quantification of IS networks. This study thus aligns with the perception that practical and concrete (context-dependent) knowledge is equally valuable compared to general theoretical (context-independent) knowledge (Flyvbjerg 2006). Here, the classification model of Yin (2009) is used as inspiration for the structural design one may utilize in a case study.

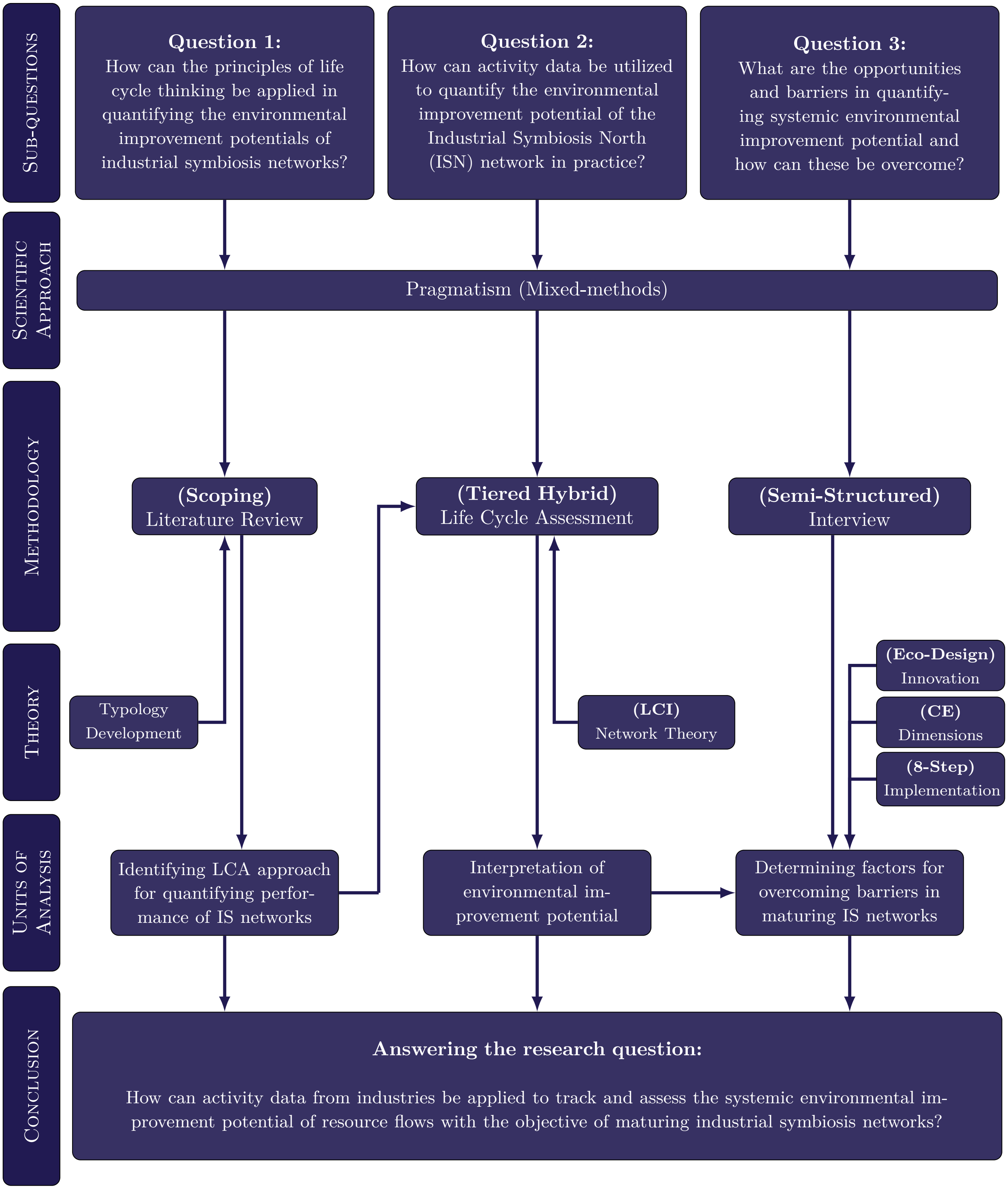


Figure 2.1: Research Framework - The project visualized as a set of processes within an established framework

2.1.1 Application of Theory

The scientific approach of this study is best described as pragmatism. Although an inductive research process is utilized in synthesizing a collective body of data into a general series of principles and learnings (Saunders et al. 2013; Wilson 2014), the focus is shifted towards incorporating operational decisions into the production of actionable knowledge (Kelly and Cordeiro 2020). Consequently, the collaboration between theory and methods to create a practical solution is central to the study. For this reason, the case study is structured as single-embedded with multiple units of analysis applicable to the examination of the research question. As illustrated by Figure 2.1, each sub-question builds upon the previous in establishing a straightforward course of action for maturing IS networks. The same logic applies to the choice of methodology, which can be described as utilizing mixed methods, i.e., both quantitative (Life cycle assessment) and qualitative (semi-structured interviews) (Biesta 2015).

The use of theories overall serves a variety of purposes, and will be introduced as it is applied throughout the project. Table 2.1 presents the variance of theories and their application in this study following the classification scheme by Kørnøv (2015) based on the explicit literary use of the term *theory*,

Ch.	Theory	Use of Theory	Application	Source
1	Diffusion of Innovation	Non-attached theory	Establishing legitimacy surrounding the context of IS emergence and its challenges	(Rogers 2003)
2	Pragmatism	Theory informing	Informing the design of the research	(Kelly and Cordeiro 2020)
2	Case Classification	Theory informing	Informing the design of the case study	(Yin 2009)
3	Typology Building	Theory informing	Development of typologies in the literature review	(O'Raghallaigh et al. 2010)
5	Network Theory	Theory informing	Structure for the construction of life cycle inventory (LCI)	(Kuczenski 2015)
8	Dimensions of Circular Economy	Theory interpretation & discussion	Adding perspective to the application of the LCA model	(Bocken et al. 2016)
8	Innovation of Eco-Design	Theory interpretation & discussion	Visualizing the implication of innovation at different taxonomic levels	(Brezet 1997)
8	Implementation Theory	Theory interpretation & discussion	Applying an 8-step model of organizational change to PARD	(Kotter 2012)

Table 2.1: Differentiation of theories applied in the study (Adapted from Kørnøv (2015)).

2.1.2 Single-Embedded Case Study

The case study methodology is chosen with inspiration from the characterization of case studies by Yin (2009) as illustrated in Figure 2.2. Case studies focus on contemporary events, which is the instance concerning the expansion of ISN. As described in Section 1.3.2 ISN is at a stage of transitioning into a facilitated symbiosis (See Table 1.1) and is therefore facing several new challenges. Hence, there is a unique opportunity to gain insight into the companies involved in ISN and cooperate with a facilitating institution that already has the know-how of the existing networks in the region. Additionally, these learnings will pertain to the companies involved with ISN and the GRØN project in obtaining new knowledge on how to quantify and apply data in maturing ISN and aspiring IS networks in general.

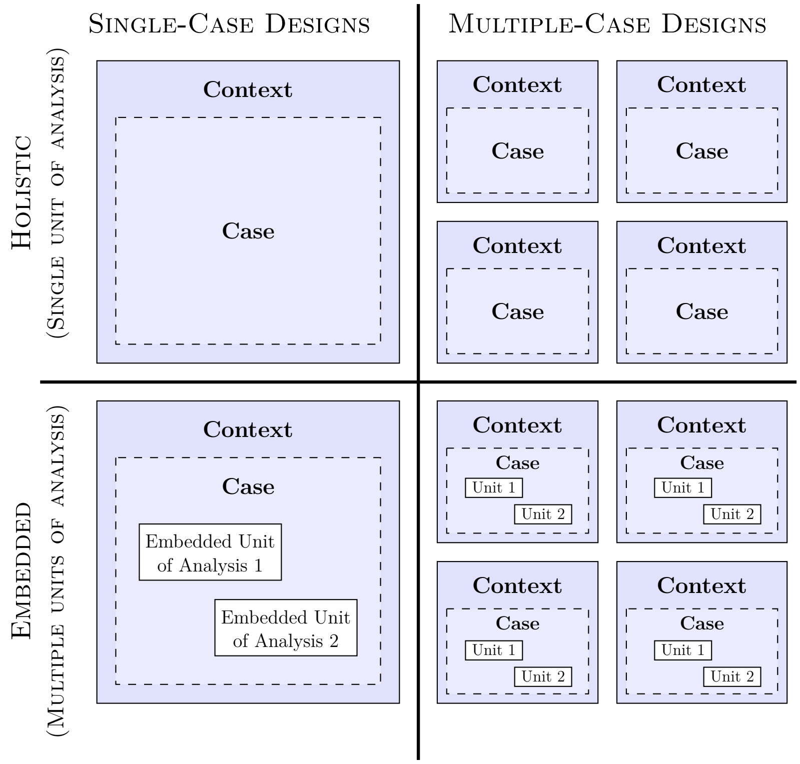


Figure 2.2: Classification of four types of case study designs (Adapted from Yin (2009)).

ISN represents the pre-existing symbiotic network identified in North Denmark Region, whereas the GRØN project represents new potential symbiotic exchanges (See Section 1.3.1). The study will examine the expansion of ISN as an embedded (multiple units of analysis) single-case. This choice can be attributed to two main rationales: (i) The IS network represents the state and situation of many symbiotic networks as it is self-organized and in the process of anchoring principles of industrial ecology (IE) into the existing business practice. (ii) Examining the research question entails multiple units of analysis, which is why embedded case studies typically include both qualitative and quantitative methodologies (Yin 2009). This is best illustrated by the three sub-questions highlighting the elements analyzed to answer the research question in Figure 2.1. The following sections will describe each sub-question.

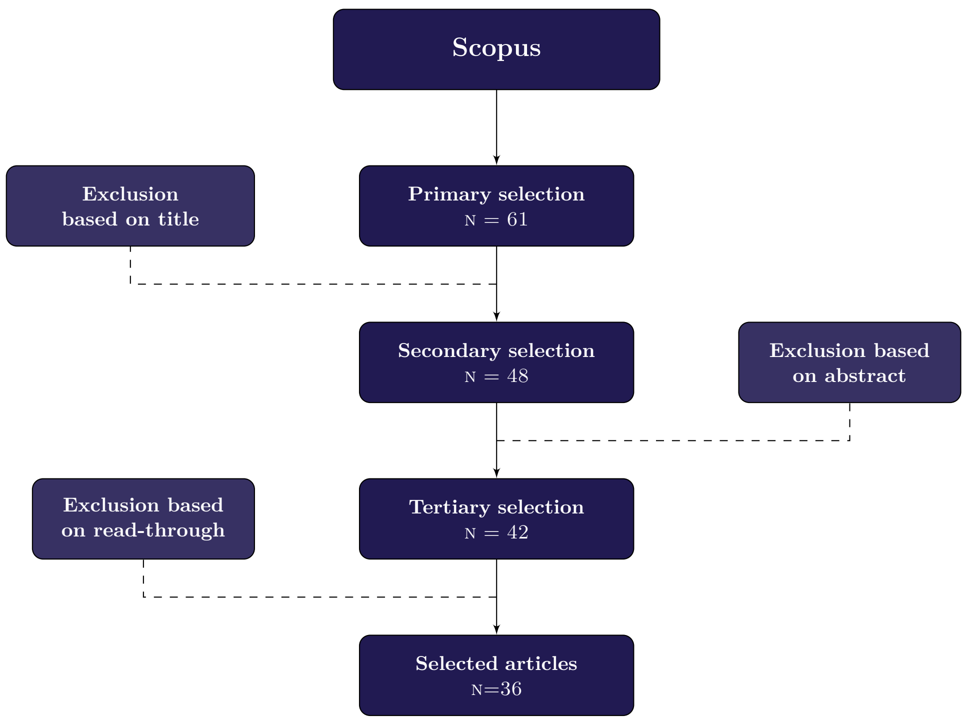
2.2 Sub-Question 1 - Scoping Review

If IS networks are to successfully incorporate tools aimed at holistic quantification of environmental performance, it is first relevant to examine the existing corpus of scientific literature. The following sub-question is therefore posed:

> **Question 1:** How can the principles of life cycle thinking be applied in quantifying the environmental improvement potentials of industrial symbiosis networks?

A scoping review is performed to examine the pre-existing state-of-the-art surrounding quantification of the environmental performance of IS networks. The scoping review takes inspiration from the method presented by (Munn et al. 2018) to ensure the study does not replicate existing research and reveals potential thematic gaps in the literature.

Scopus's literary database is utilized to identify an exhaustive corpus of scientific literature. A search protocol is applied to ensure a systematic collection of literature to cover the relevant field of expertise and prevent biases. In this regard, literature is sourced from a database through a specific, predetermined string of terms considered relevant to the study. The identified literature is subsequently filtered based on its perceived relevance through a three-step screening process as illustrated by Figure 2.3. The selection of literature is further elaborated on in Chapter 3.



Year: 2010-2022
String: TITLE(INDUSTRIAL SYMBIOSIS) OR TITLE(INDUSTRIAL SYMBIOSES) OR TITLE(INDUSTRIAL EXCHANGES) AND TITLE-ABS-KEY(LCA) OR TITLE-ABS-KEY(LIFE CYCLE ASSESSMENT) OR TITLE-ABS-KEY(LIFE CYCLE THINKING) OR TITLE-ABS-KEY(LIFE CYCLE MANAGEMENT) OR TITLE-ABS-KEY(QUANTIFICATION)

Figure 2.3: Selection of literature applied in the scoping review

Based on the selection of literature, the objective of Chapter 3 is to investigate how the principles of life cycle thinking can be applied in quantifying the environmental impacts and potentials of IS networks. While life cycle assessment (LCA) is the most commonly applied methodology, studies utilizing alternative approaches (e.g., GHG-protocol or LCSA[1]) are not excluded based on their means of quantification. On the contrary, it should be recognized that material flow analysis (MFA) does not quantify the environmental performance since no classification and characterization is applied in assessing the impact, and studies based on this methodology are therefore omitted from the review. To analyze the body of literature, a set of typologies are developed to classify the conceptual landscape of studies. The

1. Life Cycle Sustainability Assessment

typologies thus function as categories of activities (O'Raghallaigh et al. 2010). In this respect, inspiration is drawn from existing research on IS networks. The following four typologies are used (See Section 3.1.1 for a detailed description):

1) **Studied Scenarios:** Examines the different purposes for conducting an LCA on an IS network by differentiating between three types of studied scenarios. The classification is based on previous research by Mattila et al. (2012).
2) **Reference- and Alternative Scenarios:** Cross-references the temporal aspect of secondary scenarios (current/hypothetical) with the presence of IS exchanges (symbiotic/non-symbiotic) in the LCA model applied. The two dimensions are based on a previous critical literature review by Aissani et al. (2019).
3) **LCA Methodologies:** Categorizes the application of LCA methodologies on a spectrum ranging from process-based LCA to input-output analysis. The spectrum is adapted from the work of (Crawford et al. 2018).
4) **IS Taxonomy:** Distinguishes between the varying levels of perspective (network, entity, flow) that can be applied in quantifying the environmental performance of IS network. The taxonomy levels are based on a previous classification by Kerdlap, Low, Tan, et al. (2020).

The expected outcome of the literature review is a selection of methodological choices for how to quantify the environmental improvement potential of the expanded ISN network. These learnings will be positioned within the existing body of literature and thus serve as a foundation for an improved LCA model.

2.3 Sub-question 2 - Life Cycle Assessment

Following the scoping review in Section 3.3, sub-question 2 is posed to gain practical experience with quantifying environmental impacts with the application of the improved LCA model:

> **Question 2:** How can activity data be utilized to quantify the environmental improvement potential of the Industrial Symbiosis North (ISN) network in practice?

This part of the analysis takes inspiration from network theory to construct the life cycle inventory (LCI). Kuczenski (2015) highlights that the design decisions made for the LCI and database application are highly influential on the results implying that no generalizations are functionally made for how to construct an LCI in network analysis. Therefore the LCI structure applied are informed by the methodological considerations identified through the literature review and case context. The hybrid input-output (IO) database, Exiobase 3, is chosen for background data. Further argumentation for choosing Exiobase can be found in the analysis Section 3.3. The selection of background data is based on the value of hybrid IO databases to model comprehensive LCAs of varying data quality, which is to be expected in an IS network with multiple entities. Applying IO-data is seen as a trade-off, consequently leading to less exposure for truncation error and stronger exposure to aggregation error (Berners-Lee et al. 2011).

There is currently no standard for systemic accounting of environmental impacts in IS networks. However, ISO 14040:2006 poses a general framework for LCA (ISO 2006a, 2006b). To ensure a systematic approach to account for the environmental potential of ISN and the GRØN project, the LCA study will follow the 4 phases prescribed in ISO 14040:2006 as shown on Figure 2.4.

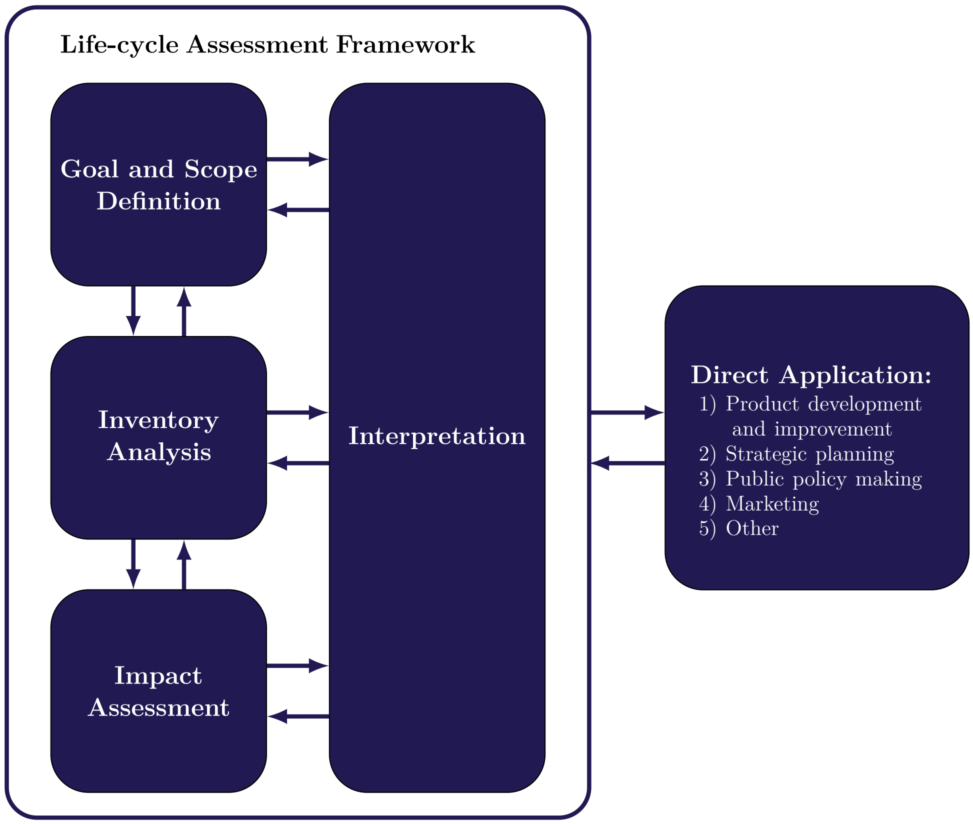


Figure 2.4: General phases of a life-cycle assessment, as prescribed in 14040:2006 by ISO (2006a, p. 8)

The identified terminology from the literature review is applied in the framework, as this most accurately determines the methodological choices. These choices are disclosed in the scoping review Section 3.3. Data needed for the LCI is collected through reports on PARD's previous work with the ISN network and ongoing data collection of the GRØN network, also administrated by PARD. Other site-specific data is acquired through annual environmental- and financial reports published by the individual companies. In areas where data is insufficient, attempts to upgrade quality are made by consulting companies. If data quality is still insufficient generic proxy data is applied based on assumptions. All sources of data are disclosed in the LCI matrix within the external appendix. A guide for importing the LCA model can be found in the Appendix A.1 . The results of the LCA will serve as an indication of the environmental performance of the expanded ISN network and a foundation for the discussion of the applicability of the improved LCA model.

2.4 Sub-question 3 - Barriers and Potentials

Considering the methodological structure of the improved LCA model, the final sub-question focuses on the opportunities and expected barriers of quantifying environmental impacts of the IS networks. The following question is hence posed:

> **Question 3:** What are the opportunities and barriers in quantifying systemic environmental improvement potential and how can these be overcome?

For Chapter 8 the potential application possibilities of the LCA model are discussed as well as the value propositions offered by PARD in implementing systematic quantification practices. As described in Section 2.1.1, the pragmatic approach is applied with the focus on creating a solution that has potential for use in practice. Therefore, the discussion focuses on application barriers and opportunities for the LCA model and important elements for successfully implementing the solution. To support the interpretation and discussion of the experience gained in the analysis, certain theories are included to support specific elements of the discussion. These are the three theories shown earlier in Table 2.1; (i) Dimensions of Circular Economy (ii) Innovation of Ecodesign (iii) Implementation Theory. The application and purpose of theory is additionally shown in Table 2.1 and will be further elaborated upon in Chapter 8.

All topics for discussion will consider PARD's role in maturing the ISN network. To put the experience concerning maturing the ISN network, an interview with Per Møller, Senior Symbiotic Developer and Head of Symbiosis, from the Kalundborg Symbiosis (KS) is conducted. The interview information is given in table Table 2.2. The interview transcription can be found in Appendix E.1.

Respondent	Date	Relevance	Description
Per Møller, Kalundborg Symbiosis	Feb/2022	Per Møller is Head of Symbiosis at the Kalundborg Symbiosis (KS) in Denmark and has extensive experience with the facilitating role of managing an IS network.	The purpose of this interview is to obtain knowledge of maturing symbiotic networks by using KS as the case. The KS is older and more well established than ISN and GRØN, and has had a facilitating organization attached for a longer period. For this reason, KS is expected to have gained deeper insight to challenges in maturing IS networks.

Table 2.2: Overview of interviews conducted including relevance for choosing the respondents and a description of the data/information generated during the interviews

A semi-structured methodological approach is chosen because of its flexibility that allows divergence from the interview guide if needed (Brinkmann and Tangaard 2010). Moreover, an interview-guide has been developed with the objective of planning a course of action during (Kallio et al. 2016). It is expected that specific points made by Per Møller during the interview could position the interviewer in a situation where it would be necessary to diverge from the interview guide to pursue particular details of the topic. The interview is conducted in danish, and all quotes taken from the transcription are translated to best resemble the original quote.

Literature Review

Chapter 3

Environmental Assessment of IS Networks

The following chapter will explore state-of-the-art literature concerning the utilization of life cycle assessment to quantify the environmental performance of Industrial Symbiosis (IS) networks. A scoping review is performed with four focal points:

1. Clarification of key concepts within the field of quantifying environmental performance in IS networks.
2. Clarification of the underlying purposes to quantifying the environmental performance for IS networks as well as the context surrounding the studies.
3. Characterization of quantification models that are utilized in representing the foreground and background systems and whether the evaluation is on a flow-, entity-, or network level.

It is expected that by investigating the four focal points, it becomes possible to determine how best to quantify the environmental improvement potentials in the context of ISN, and support the network in maturing.

3.1 Corpus Definition and Description

A total of 61 studies have been identified, of which 36 are selected based on their merit in answering the aforementioned focal points. Of the selected articles, seven are chosen as they investigate the methodology surrounding quantification, while the remaining 29 studies assess the environmental performance of IS networks. Case studies are distributed between Europe (11), East Asia (8), South East Asia (3), USA (2), and five theoretical studies. Table 3.1 provides an overview of the selected case study papers.

No.	Authors	Year	Title	Journal
1	Ammenberg et al.	2015	Improving the CO2 performance of cement, part III: The relevance of industrial symbiosis and how to measure its impact	Journal of Cleaner Production
2	Brondi et al.	2018	Sustainability-based Optimization Criteria for Industrial Symbiosis: The Symbioptima Case	Procedia CIRP
3	Daddi et al.	2017	Using Life Cycle Assessment (LCA) to measure the environmental benefits of industrial symbiosis in an industrial cluster of SMEs	Journal of Cleaner Production
4	Dong et al.	2017	Highlighting regional eco-industrial development: Life cycle benefits of an urban industrial symbiosis and implications in China	Ecological Modelling
5	Eckelman and Chertow	2013	Life cycle energy and environmental benefits of a US industrial symbiosis	International Journal of Life Cycle Assessment
6	Haq et al.	2021	Modelling sustainable industrial symbiosis	Energies
7	Hashimoto et al.	2010	Realizing CO2 emission reduction through industrial symbiosis: A cement production case study for Kawasaki	Resources, Conservation and Recycling

(Continued on next page)

Table 3.1: Case study papers composing the corpus

No.	Authors	Year	Title	Journal
8	Hildebrandt et al.	2019	Revealing the Environmental Advantages of Industrial Symbiosis in Wood-Based Bioeconomy Networks: An Assessment From a Life Cycle Perspective	Journal of Industrial Ecology
9	Ismail	2020	Potential Benefit of Industrial Symbiosis using Life Cycle Assessment	Journal of Physics: Conference Series
10	Kerdlap et al.	2019	Collaboration platform for enabling industrial symbiosis: Application of the industrial-symbiosis life cycle analysis engine	Procedia CIRP
11	Kerdlap, Low, Tan, et al.	2020	M3-IS-LCA: A Methodology for Multi-level Life Cycle Environmental Performance Evaluation of Industrial Symbiosis Networks	International Journal of Life Cycle Assessment
12	Kerdlap et al.	2022	UM3-LCE3-ISN: a methodology for multi-level life cycle environmental and economic evaluation of industrial symbiosis networks	International Journal of Life Cycle Assessment
13	Kim et al.	2018	Evaluation and Allocation of Greenhouse Gas Reductions in Industrial Symbiosis	Journal of Industrial Ecology
14	Liu et al.	2011	Life cycle assessment of an industrial symbiosis based on energy recovery from dried sludge and used oil	Journal of Cleaner Production
15	Marcinkowski	2019	The spatial limits of environmental benefit of industrial symbiosis - Life cycle assessment study	Journal of Sustainable Development of Energy, Water and Environment Systems
16	Martin	2015	Quantifying the environmental performance of an industrial symbiosis network of biofuel producers	Journal of Cleaner Production
17	Martin	2020	Evaluating the environmental performance of producing soil and surfaces through industrial symbiosis	Journal of Industrial Ecology
18	Martin and Harris	2018	Prospecting the sustainability implications of an emerging industrial symbiosis network	Resources, Conservation and Recycling
19	Mattila et al.	2010	Quantifying the total environmental impacts of an industrial symbiosis-a comparison of process-, hybrid and input-output life cycle assessment	Environmental Science and Technology
20	Sacchi and Ramsheva	2017	The effect of price regulation on the performances of industrial symbiosis: A case study on district heating	International Journal of Sustainable Energy Planning and Management
21	Sokka et al.	2011	Analyzing the Environmental Benefits of Industrial Symbiosis: Life Cycle Assessment Applied to a Finnish Forest Industry Complex	Journal of Industrial Ecology
22	Soratana and Landis	2011	Evaluating industrial symbiosis and algae cultivation from a life cycle perspective	Bioresource Technology
23	Subramanian et al.	2021	Capital-based life cycle sustainability assessment: Evaluation of potential industrial symbiosis synergies	Journal of Industrial Ecology
24	Van Phi et al.	2020	Industrial symbiosis in insect production— A sustainable eco-efficient and circular business model	Sustainability
25	Vitale et al.	2021	Cement-matrix composites using cfrp waste: A circular economy perspective using industrial symbiosis	Materials
26	Wang et al.	2019	Life cycle assessment of reduction of environmental impacts via industrial symbiosis in an energy-intensive industrial park in China	Journal of Cleaner Production
27	Yu, Li, et al.	2015	Quantifying CO2 emission reduction from industrial symbiosis in integrated steel mills in China	Environmental Science and Pollution Research
28	Yu, Han, et al.	2015	Assessment of life cycle environmental benefits of an industrial symbiosis cluster in China	Journal of Cleaner Production
29	Zhang et al.	2017	Life cycle assessment of industrial symbiosis in Songmudao chemical industrial park, Dalian, China	Journal of Cleaner Production

Table 3.1: Case study papers composing the corpus (Continued)

The European studies were largely published in Sweden, Finland, and Denmark, which is logical considering the number of methodological papers published in these countries investigating the advancement of quantifying the environmental performance of IS networks (Martin et al. 2015a; Martin 2013; Mattila et al. 2012; Sokka 2011). Six of the case studies conducted in East Asia are from China based on high population density and rapid economic growth, which encourages environmental management through industrial ecology of planned industrial parks. A similar sentiment is seen among papers published in Southeast Asia (Singapore and Indonesia). While the theoretical studies do not investigate a specific area, the conceptual IS networks are often represented as self-organized or facilitated (See Table 1.1). Table 3.2 presents an overview of the selected papers concerning LCA methodology.

No.	Authors	Year	Title	Journal
1	Aissani et al.	2019	Life cycle assessment of industrial symbiosis: A critical review of relevant reference scenarios	Journal of Industrial Ecology
2	Dumoulin et al.	2017	A Framework for Accurately Informing Facilitated Regional Industrial Symbioses on Environmental Consequences	Journal of Industrial Ecology
3	Kerdlap, Low, and Ramakrishna	2020	Life cycle environmental and economic assessment of industrial symbiosis networks: a review of the past decade of models and computational methods through a multi-level analysis lens	International Journal of Life Cycle Assessment
4	Lütje and Wohlgemuth	2020	Tracking sustainability targets with quantitative indicator systems for performance measurement of industrial symbiosis in industrial parks	Administrative Sciences
5	Martin et al.	2015	Who gets the benefits? An approach for assessing the environmental performance of industrial symbiosis	Journal of Cleaner Production
6	Mattila et al.	2012	Methodological Aspects of Applying Life Cycle Assessment to Industrial Symbioses	Journal of Industrial Ecology
7	Viganò et al.	2020	The LCA modelling of chemical companies in the industrial symbiosis perspective: Allocation approaches and regulatory framework	Life Cycle Assessment in the Chemical Product Chain

Table 3.2: Methodology papers composing the corpus

All papers were published less than 12 years ago. In fact, the first case study of an IS concerns the aforementioned Kalundborg Symbiosis published only 25 years ago (Ehrenfeld and Gertler 1997). Initial studies concerning quantification largely revolve around the characterization of networks and their metabolism utilizing assessment tools such as MFA. However, an underlying consensus regarding that IS should contribute to environmental improvement has resulted in a shift towards life cycle assessment (LCA) (Martin 2013). As a result, an increase in published articles has been seen over the last decade as presented by Figure 3.1.

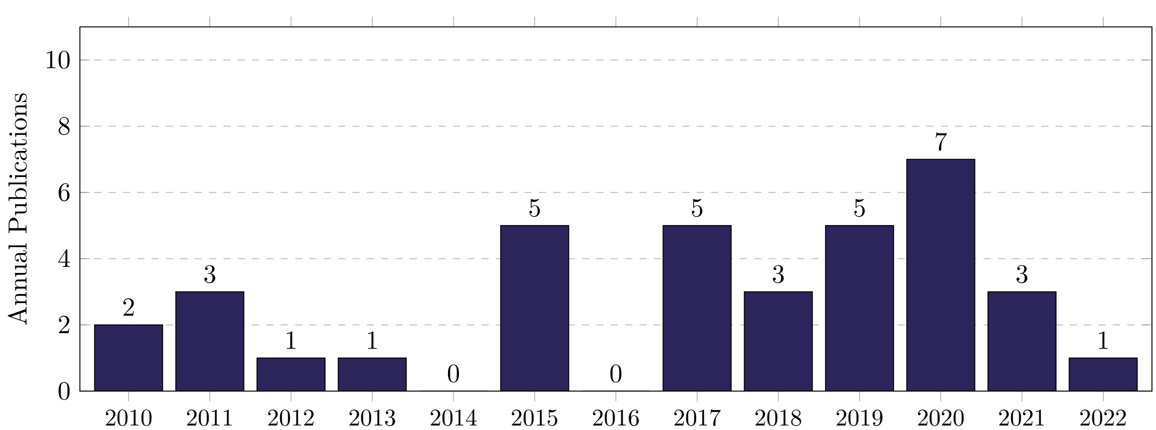


Figure 3.1: Annual publications concerning quantification of environmental performance of IS networks

3.1.1 Definition of Terms and Typologies

In order to prevent any possible ambiguity between the terms applied in the literature, it is necessary to define a typology precisely. Due to the review focus on the purpose of quantification, a clear distinction is made between a *studied scenario*, a *reference scenario*, and an *alternative scenario*. The quantified environmental performance of a studied scenario is compared to that of reference- or alternative scenarios. A reference scenario is utilized as a benchmark, which serves as the basis for comparison – usually, this is in the form of a business as usual (BaU) scenario. Conversely, an alternative scenario serves as a version of the studied scenario that presents a set of differences, typically in activities or data, to examine the implications of a defined change. Overall, four different typologies are proposed:

1) Typology for Studied Scenarios:

To understand the purpose of quantification, cf. the focal points, it is first relevant to investigate the studied scenarios. As presented by Mattila et al. (2012) IS research can be classified into five thematic groups: (i) the quantification of environmental impacts of an IS, (ii) the optimization of the system, (iii) the definition of the boundaries of the studied system, (iv) the environmental assessment of a designed symbiosis, and (v) the assessment of wider circular systems. In this regard, the quantification of environmental performance and potential is an important topic related to four of the groups of this classification. This classification serves as a foundation for distinct typology for the studied scenarios.

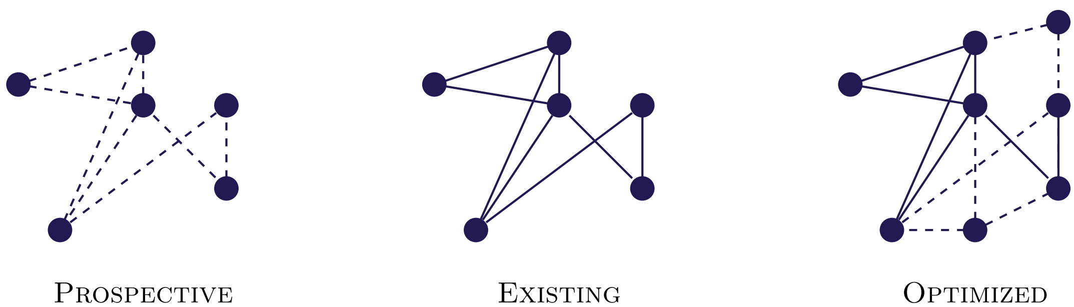


Figure 3.2: Variation of studied scenarios applied in IS studies utilizing LCA

Prospective: The studied scenario investigates the prospective establishment of an IS, which does not exist. It is therefore composed of both existing connections between current companies and the addition of new processes, thereby creating a potential IS network.

Existing: The studied scenario is an existing IS intending to benchmark the network's performance. The IS is developed at an industrial scale, with both material and organizational connections between the various companies, constituting the symbiotic network.

Optimized: The studied scenario is an expansion of a pre-existing IS network with additional connections or new processes added to the exchanges. Hence, the scenario aims to optimize the environmental performance by assessing a potential future scenario.

2) Typology for Reference and Alternative Scenarios:

Concerning the reference- and alternative scenarios, a distinction is made in terms of two dimensions based on the typology applied by Aissani et al. (2019). Firstly, a differentiation is made between symbiotic and non-symbiotic scenarios. Secondly, current and hypothetical scenarios are distinguished leading to four different types of reference- and alternative scenarios as displayed by Figure 3.3.

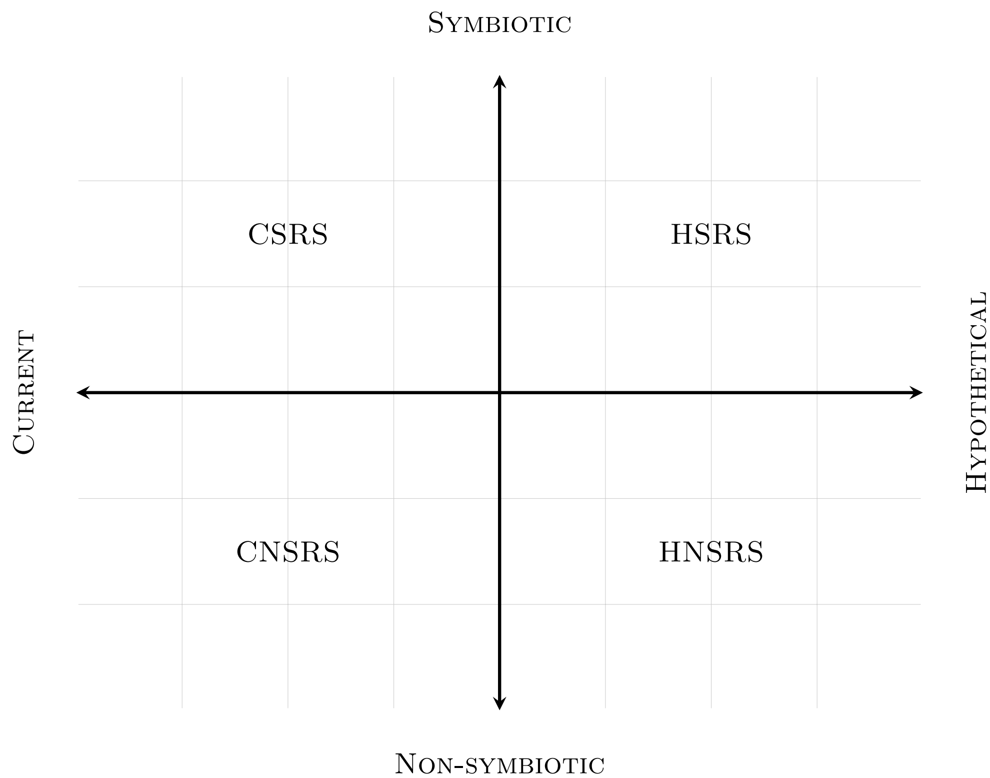


Figure 3.3: Dimensions of reference- and alternative scenarios applied in IS studies utilizing LCA

CNSRS: A current non-symbiotic reference scenario (CNSRS) represents current industrial processes with no symbiotic exchanges between companies.

HNSRS: A hypothetical non-symbiotic reference scenario (HNSRS) built with no symbiotic exchanges between companies. This does not represent current industrial processes but a hypothetical scenario that is an alternative to the business-as-usual scenario.

CSRS: A current symbiotic reference scenario (CSRS) built with symbiotic exchanges between companies. It represents current industrial processes.

HSRS: A hypothetical symbiotic reference scenario (HSRS) built with symbiotic exchanges between the companies concerned. This reference scenario does not represent current industrial processes but instead a hypothetical scenario as an alternative to the current IS.

(Aissani et al. 2019, p. 976)

3) Typology for LCA Methodologies:

Moreover, it is necessary to define the range of LCA methodologies applied in the studies of IS networks. As presented by Crawford et al. (2018) one may view the selection as a spectrum of methodologies extending from a process-based bottom-up approach to a top-down input-output analysis (IOA). In between is a selection of hybrid methodologies presenting a range of options as illustrated by Figure 3.4.

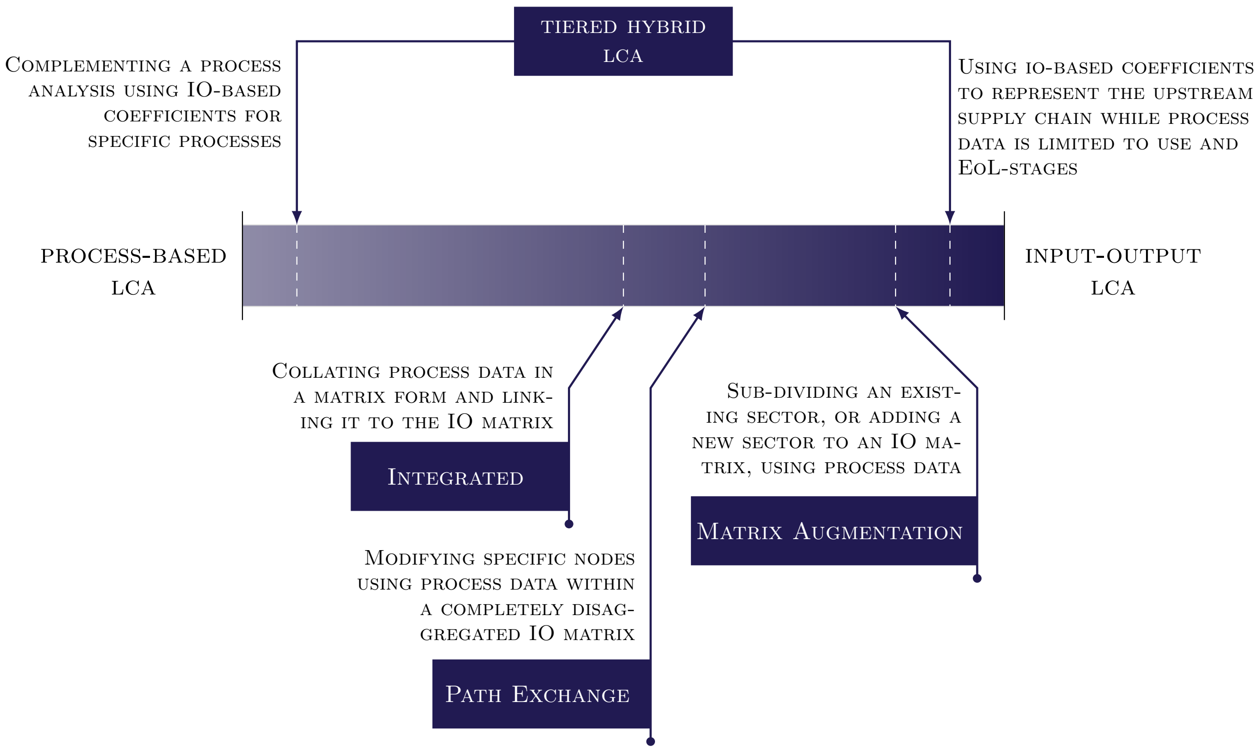


Figure 3.4: Spectrum of LCA methodologies applied in IS network studies as illustrated by Crawford et al. (2018)

Process-based: Utilizing a bottom-up approach to assess the environmental impacts associated with the specified inputs and outputs of product or service within the scope of the LCA.

IO-based: Applying an environmentally extended input-output analysis (EEIOA) to represent the foreground and background systems of the IS network in addition to the waste-to-resource exchanges taking place within the system.

Tiered Hybrid: Combining the input-output and process coefficients to merge the strengths that both methodologies offer, hereby expanding the boundaries of the analyzed network. This includes information typically not represented in a conventional process analysis or IO-analysis.

(Kerdlap, Low, and Ramakrishna 2020, pp. 1668-1669)

4) Typology for IS Taxonomy:

In an IS network, several stakeholders are involved, e.g., policymakers, land-use planners, individual companies, economists, or resource managers. Because of this, the different types of stakeholders will be interested in the performance on varying levels (Kerdlap, Low, Tan, et al. 2020). Since an IS network is based on a series of connections, it is necessary to distinguish between the level of perspective applied in the assessment. This study aligns itself with the typology of Kerdlap, Low, and Ramakrishna (2020):

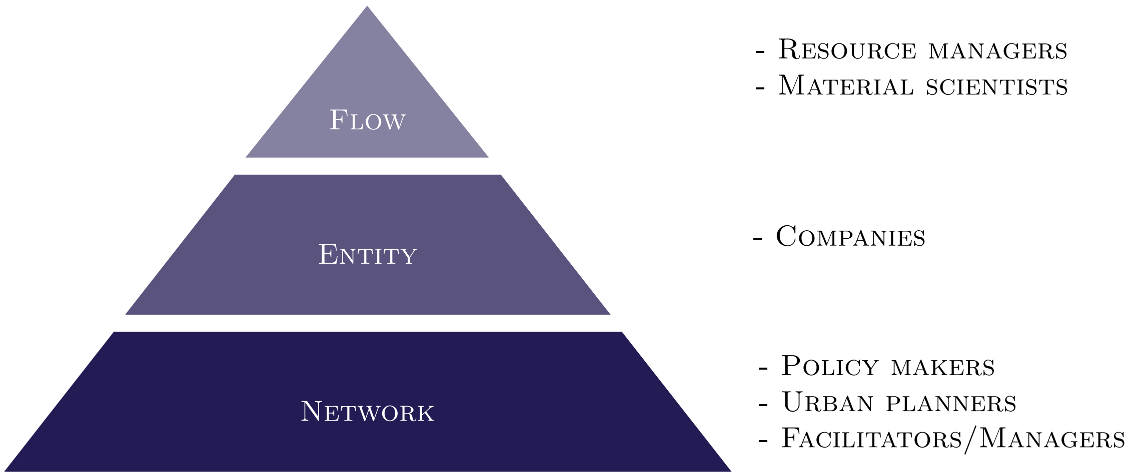


Figure 3.5: Different levels of IS taxonomy applied in quantification of environmental performance.

Flow-level: The environmental performance of a specific flow (product, intermediary resource, waste, resource converted from a waste flow) in an IS network e.g. fly ash.

Entity-level: The environmental performance of an particular entity (factory, plant, facility) that is participating in an IS network e.g. Aalborg Portland

Network-level: The environmental performance of the entire IS network e.g. Industrial Symbiosis North

(Kerdlap, Low, and Ramakrishna 2020, p. 1665)

3.2 Key Themes in Existing Literature

Within the corpus of literature, several themes present themselves when applying the previous typology. The following section will investigate the three focal points of this review by initially examining the purpose of quantifying the environmental performance of IS networks and, subsequently, the methodological considerations and utilization of models in representing foreground and background data of the entities in question. Lastly, a meta-perspective will be established in which this study will be positioned relative to the existing body of literature following the principles of Snyder (2019). Consequently, this study will serve as the grounds for continuous development in quantifying environmental performance and the improvement potential of IS networks.

3.2.1 Purpose of Quantification

In order to investigate the purpose of quantification, one might primarily examine the studied scenario. Within the corpus of case studies, research is primarily focused on quantifying prospective (63%) and existing (33%) IS networks. Conversely, only one study (4%) investigates the optimization of a pre-existing network. Moreover, the studied scenarios can be cross-referenced with the typology of reference scenarios as illustrated by Figure 3.6.

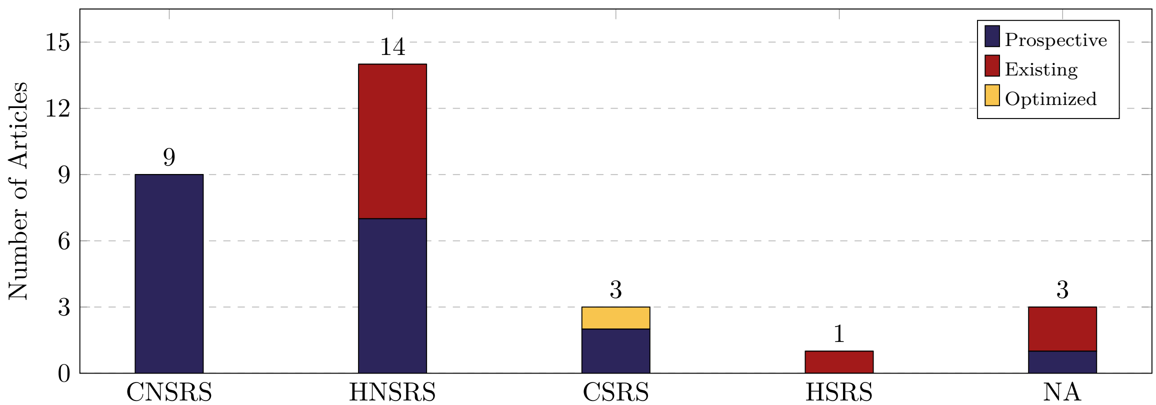


Figure 3.6: Distribution of publications between studied- and reference scenarios

Overall, non-symbiotic reference scenarios (77%) are the most commonly applied scenario, while symbiotic reference scenarios are only utilized to a limited extent (13%). This distribution can predominantly be attributed to the broader application of prospective and existing scenarios studied within the literature. In this regard, two trends are clear: (i) When assessing the environmental performance of current and prospective symbiosis scenarios, LCA practitioners logically utilize an HNSRS and a CNSRS, respectively. In this regard, non-symbiotic reference scenarios are utilized to benchmark IS networks' performance when examining prospective establishments or evaluating the performance of an existing network. Here it should be understood that the HNSRS is an assumptive scenario building on average or marginal data contrary to the CNSRS, which is typically based on site-specific or average data (Aissani et al. 2019). (ii) On the contrary, the limited application of symbiotic reference scenarios indicates an overall lack of studies benchmarking pre-existing IS networks with the objective of expansion or optimization.

This disparity between scenarios can be understood as a product of the state of progression concerning industrial ecology. Because IS networks are a relatively new phenomenon, and the quantification hereof even more so (See Figure 3.1), research will rationally focus on the challenges at hand. At the given moment, this is the prospective establishment of new IS networks. Nonetheless, as new networks are established, there will be an innate shift toward optimizing the existing systems in which LCA will play a central role. All waste-to-resource exchanges do, however, not necessarily benefit the environment (Mohammed et al. 2018). Failure to measure the environmental performance of IS networks from a life cycle perspective can lead to burden shifts through a rebound effect (Zink and Geyer 2017). In this regard, the environmental benefits which a company gains through recycling in an IS network can result in increased environmental impacts for another company (Kerdlap, Low, Tan, et al. 2020). Moreover, without assessing the environmental and economic performance at different taxonomy levels of the IS (See Figure 3.5), stakeholders are not capable of deciding whether or not engaging in an IS network contributes to the respective business- and organizational objectives (Kerdlap, Low, and Ramakrishna 2020). For this reason, there is an inherent need to benchmark performance and assess choices for optimization.

On this note, it is worth examining the IS taxonomy applied within-corpus of literature (See Figure 3.5). Here, a majority of articles evaluate the performance of IS on a network level and, to a lesser extent, the entities within the systems.

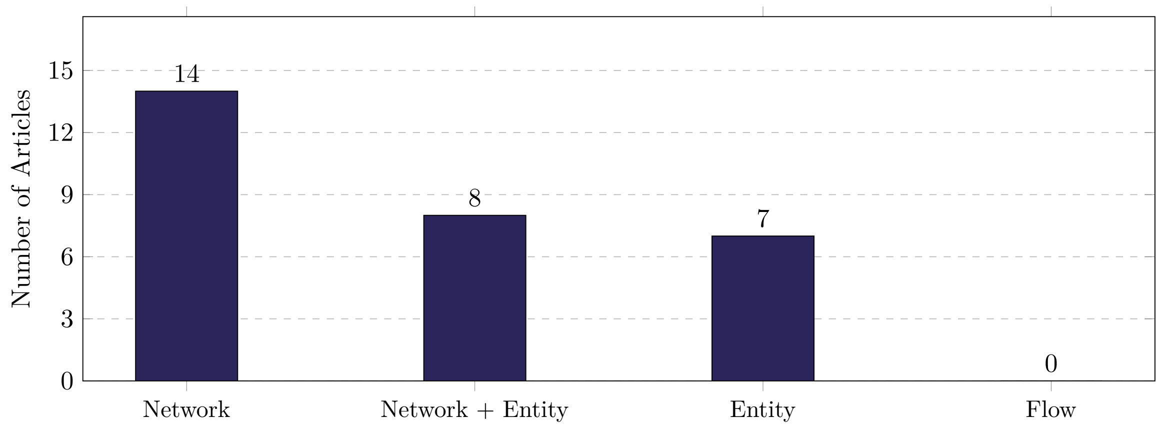


Figure 3.7: Distribution of publications between IS taxonomy levels

As presented by Figure 3.7 a significant amount of studies assess the environmental performance of entire IS networks (48%), while an additional portion opt to evaluate the performance at both a network- and entity level (28%). Within these papers, models are typically built around a multi-dimensional functional unit to allow for disaggregation of results between the two taxonomy levels (Mattila et al. 2010a; Yu, Han, et al. 2015; Martin and Harris 2018; Kerdlap et al. 2022). Furthermore, studies, to a less extent, exclusively assess the impact of production activities for a given entity (24%). These particular cases tend to focus on quantifying the environmental performance of a product for a distinct entity utilizing a one-dimensional function unit (Hashimoto et al. 2010; Soratana and Landis 2011; Ammenberg et al. 2015). None of the papers reviewed solely concentrates on a specific flow.

3.2.2 Applied Methodology

Examining models applied in the corpus yields an additional set of observations in line with the purpose of quantification. As presented by Figure 3.4 methodologies can be viewed as a spectrum. To this extent, a bottom-up approach is prominently represented, with process-based LCA representing the majority of case studies. Figure 3.8 provides an overview of the distribution between LCA methodologies used within the body of literature based on the applied typology.

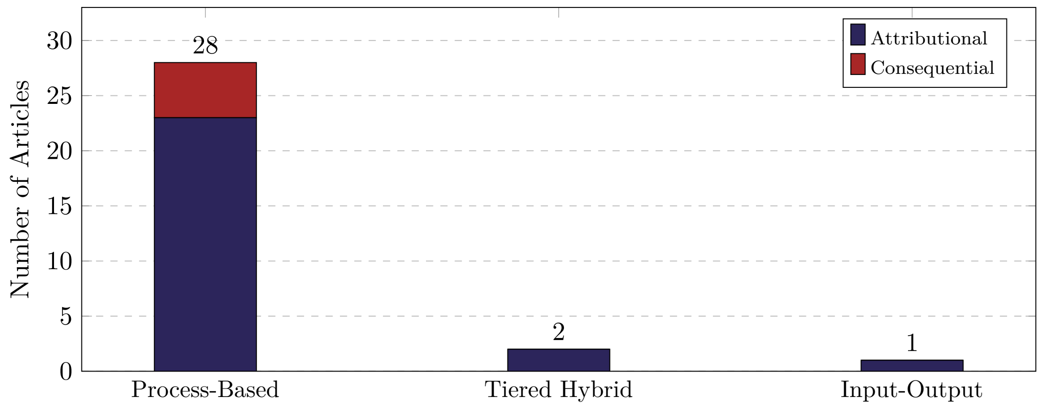


Figure 3.8: Distribution of publications between LCA methodologies

Overall, process-based LCA studies make up the vast majority of cases (90%), while input-output studies are only seen in a single instance (3%) and tiered hybrid models twice (6%). This distribution can partly be attributed to the focus on quantifying prospective and existing symbiotic networks at a network level. In this regard, practitioners will either (i) develop a holistic matrix-based model that represents all network entities and their respective intermediary flows (Yu, Li, et al. 2015; Brondi et al. 2018; Haq et al. 2021) or (ii) construct multiple individual models each representing a given entity and its corresponding waste-to-resource exchanges (Martin 2015; Kim et al. 2018; Hildebrandt et al. 2019). For the matrix-based model, the environmental performance of the network can subsequently be assessed in a single-dimensional function unit, typically economic turnover, or a multi-dimensional functional unit by defining multiple values in the demand vector (Heijungs and Suh 2002). Conversely, the multi-model methodology opts to take the sum of results from each process-based LCA model relative to the defined functional unit (Kerdlap, Low, and Ramakrishna 2020).

In addition, a significant portion of studies utilizes an attributional methodology (79%) in representing the product system, while a consequential model is only used to a lesser extent (21%). In this regard, a strict differentiation is applied in identifying the methodological framework based on core definitions of ISO (2006a). Hence, it is assumed that an attributional methodology is utilized for studies in which the procedures associated with co-production and market averages are unclear.

3.3 Contextualizing A New LCA Model

With a foundation established on behalf of the pre-existing body of literature examined, one may review how the gaps in the corpus can be accounted for to answer sub-question 1 (See Section 1.4). In this respect, the following section will detail how the LCA study of ISN positions itself within the pre-existing body of literature and the implications hereof.

Scope: As detailed in Section 3.2.1, the predominant focus on prospective IS networks with current or hypothetical non-symbiotic reference scenarios (CNSRS and HNSRS) can largely be seen as a product of the current state of progression concerning industrial ecology (IE). However, as IS networks progressively gain an increasing presence in the environmental planning of industry, one can expect a shift towards optimizing systems. For this reason, there is an inherent need for additional knowledge concerning the quantification of environmental potential among symbiotic networks. Previous models have examined prospective and existing networks. Conversely, this project will examine how Industrial Symbiosis North (ISN) and similar collaborative efforts can utilize quantitative tools such as LCA models to mature the network. Figure 3.9 illustrates how the following LCA study of ISN positions itself within the typology applied for reference scenarios (See Figure 3.3).

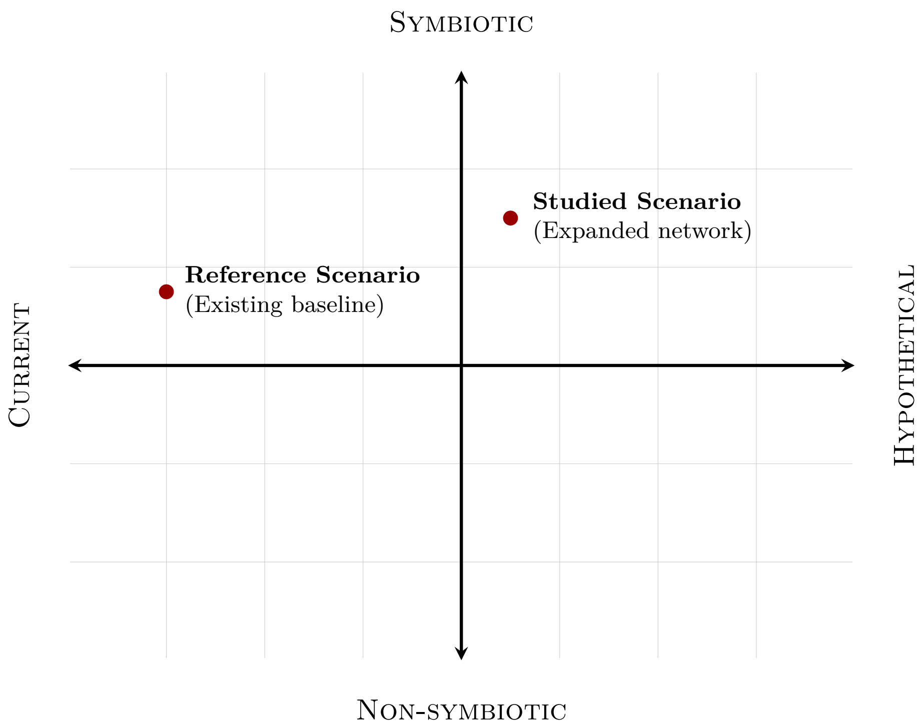


Figure 3.9: The LCA study of ISN positioned within the two-dimensional typology of reference scenarios.

A baseline reference scenario is applied as a foundation to contextualize how changes within ISN will affect the network's performance. It should, however, be recognized that IS networks are not static entities and will continuously change over time (Gibbs 2008). Due to this dynamic nature, consistency is a critical factor in tracking the performance of symbioses as production and technology evolve. Therefore, one could argue that to comprehensively assess the performance, it is necessary to develop a model that can account for the inbound changes within the product system. Consequently, this new LCA model (See Chapter 4) is developed with annual reporting of the baseline in mind. Conversely, the model will not assess a scenario in which there were no symbiotic exchanges.

The studied scenario represents the future integration of the GRØN project into ISN to assess how a conceptual expansion of the IS network would influence the performance. In this regard, the studied scenario exemplifies how the LCA model can be applied in optimizing the network. Moreover, the studied scenarios expands on the reference scenario by assessing the expansion of the network. See Chapter 4 for additional information concerning the product systems and life cycle inventory (LCI).

Taxonomy: As detailed in the typology applied for IS taxonomy (See Figure 3.5), there are multiple different stakeholders interested in varying levels of perspectives within IS networks (Kerdlap, Low, Tan, et al. 2020). As highlighted in Section 3.2 no studies within the body of literature specifically explore the flow level within the taxonomy. This level does however provide the possibility of evaluating the environmental effects of individual flows, contrary, to being aggregated as part of the entity or network assessment. In this regard, it important to recognize the resource flow in the perspective of a broader network to determining alternative application. A desire is therefore to encapsulate all taxonomic levels to the LCA model, thereby setting the best conditions to provide informative results for developing the symbiotic network.

The failure to address this gap within the majority of existing literature hence demands attention. Figure 3.10 displays how the foreground system of the LCA study will account for all three IS taxonomy levels, which will be further discussed in both Section 4.2 and 8.1.

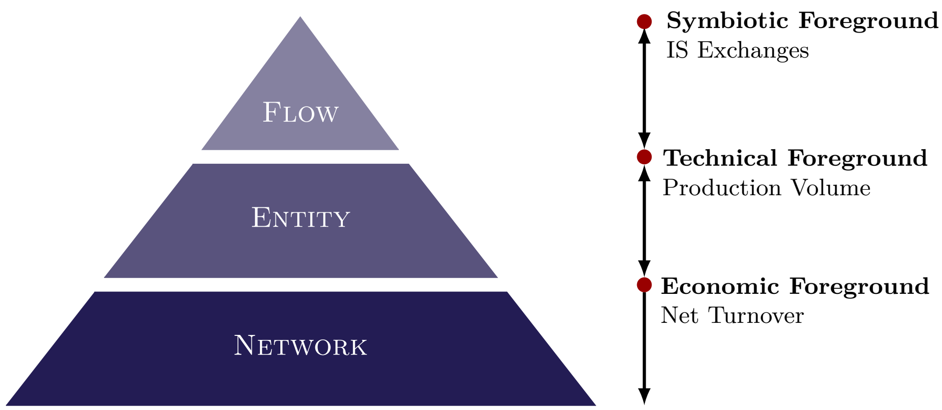


Figure 3.10: The LCA study of ISN positioned within the typology of IS taxonomy

Due to the structure of the foreground system, it can be categorized into three connected parts each with their own distinct function: (i) An economic foreground representing financial net turnover for each entity. (ii) A technical foreground representing the subsequent products/services of activities for each linked by their contribution to the net turnover. (iii) A symbiotic foreground representing the flow of IS exchanges connected to the technical foreground as a consequence of said activities.

Methodology: While process-based LCA is primarily used for quantifying the performance of networks (See Figure 3.8), it should be recognized that IO databases (e.g., FORWAST and EXIOBASE 3) allow practitioners to avoid any cut-off on economic flows and accounts for both products as well as service (Beylot et al. 2019). Moreover, environmentally-extended IO databases, such as FORWAST and EXIOBASE, are built as a hybrid model, which implies that the transactions in the models are in different units: (i) flows of products that have a physical mass are accounted in dry matter mass. (ii) electricity/heat/steam flows are accounted for in energy units. (iii) Other flows of mainly service products are accounted in monetary unit (Schmidt and Muñoz 2014). In this respect, there is a direct link between economic data of national accounts and the output of producing industries, which is practical in the field of IS, where data is often a limiting factor (Zheng and Jia 2017; Ormazabal et al. 2018).

As highlighted by Mattila et al. (2010a) IO-models can, however, lead to both over-and underestimation of environmental impacts due to aggregation errors and flawed monetary allocation in the national accounts. Conversely, tiered hybrid models successfully address the several inherent limitations of both process-based and IO methodology (Crawford et al. 2018). Because of this, the following LCA study of ISN adopts a tiered hybrid methodology utilizing EXIOBASE 3 as the background system. Employing the typology of LCA methodologies (See Figure 3.4), the ISN model applies a tiered hybrid model in between integration and matrix augmentation as visualized by Figure 3.11. Henceforth, this model will be referred to as an integrated matrix augmentation system (IMAS).

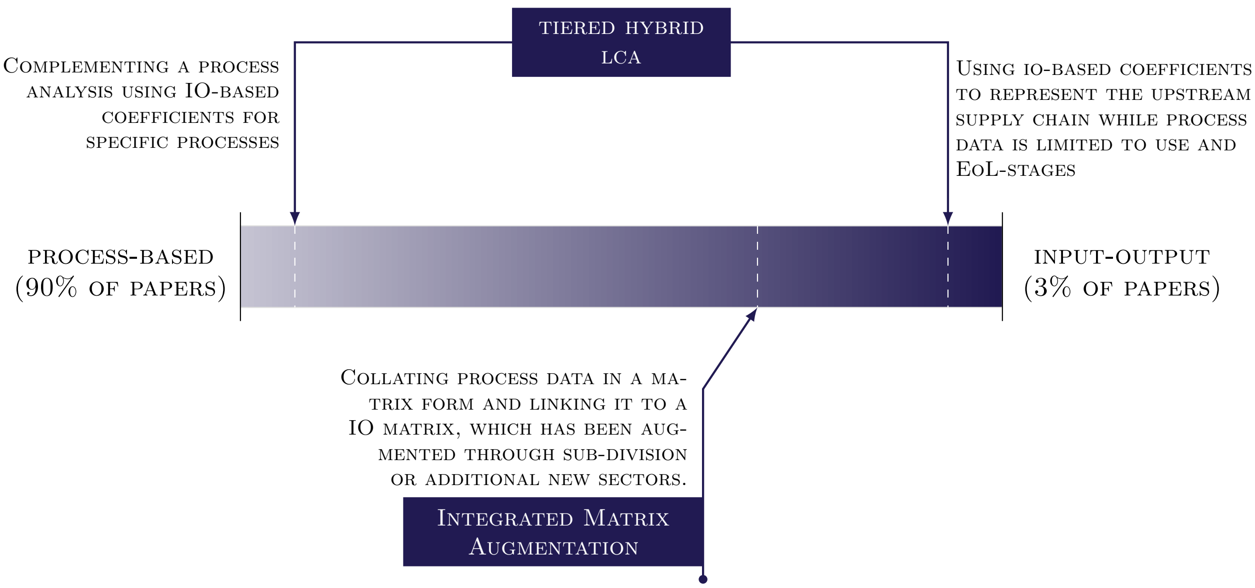


Figure 3.11: The LCA study of ISN positioned within the typology of LCA methodologies (Model adapted from Crawford et al. (2018))

IMAS utilizes both collated process data in the form of net monetary turnover, symbiotic exchange flows, and the subsequent intermediary processes linked to an augmented matrix representing the entities within a given sector. Matrix augmentation is based on site specific resource consumption and emissions used to adjust a normalized set of inputs to reflect local production conditions accurately. Where site-specific production data is not available, average data from Ecoinvent 3.8 is used as a proxy for augmenting the matrix. In cases where sectors of EXIOBASE 3 are sufficiently disaggregated, augmentation can be omitted without significant effect. In this sense, a core strength of the ISN model is the flexibility concerning the data availability demanded when quantifying the performance of IS networks. The model can thus be seen as an attempt to bypass the challenges and barriers of IS development first described in Section 1.2. Lastly, a consequential methodology is applied as opposed to an attributional despite it being the most common within the body of literature (See Figure 3.8). This should primarily be understood as a result of this study assessing an optimized network instead of a prospective. The decision can be ascribed to two points:

1. Decisions within LCA are preferably based on natural science i.e., general scientific principles such as mass balances (ISO 2006a). In this respect, consequential system expansion avoids mixing allocative rules, which can obscure both the identification of the system boundary and the results of the study (Weidema 2017).
2. It is expected that activities within the production system will change as a consequence of shifting demand (Weidema et al. 2018; Consequential-LCA 2021). Because the ISN model is developed as a tool to support the basis for decision-making, reflecting both physical and monetary causalities of the product system can be seen as a core foundation of the philosophy behind the model.

Life Cycle Assessment Methodology

Chapter 4

Goal and Scope

The following chapter will present the goal and scope for the quantification of environmental performance and improvement potential concerning the expanded ISN network. As described in the research design in Chapter 2, the LCA follows the framework presented by ISO 14040 with start in the goal and scope by defining the purpose of the LCA, the system boundary, and the functional unit to which after the LCI and LCIA is described.

4.1 Goal

The goal of the LCA is to evaluate the potential environmental benefits from implementing new symbiotic exchanges identified in the GRØN project, and incorporating these into ISN. This is conducted by first creating a reference baseline scenario (RBS) known as a current symbiotic reference scenario (CSRS), for ISN. This baseline will include production activities, and established symbiotic exchanges. Next, two scenarios for GRØN will be constructed to assess the environmental potential of implementing new symbiotic exchanges, one current non-symbiotic reference scenario (CNSRS) and one hypothetical symbiotic reference scenario (HSRS) (See Figure 3.9). The effect identified in the comparison of the latter two scenarios will then be coupled and sat in relation to ISN.

The target audience is primarily the knowledge hub Port of Aalborg Research and Development (PARD) as the facilitator of ISN. However, as detailed in Section 3.3 the model is designed to account for the varying levels of perspective within the network. In this respect, the multiple stakeholders within ISN (i.e. companies, resource managers, policy makers, urban planners etc.) are considered a possible target audience as well. In this context, The LCA serves as a proof-of-concept model for future quantification of environmental performance and evaluation of symbiotic exchanges. For the LCA model to be successful the following key conditions has to be incorporated:

1. Comparison of the existing practice to future practices with a consequential perspective to future scenarios, taking into account evaluation of alternative uses of resources outside the system boundary.
2. Assessment of the symbiotic network on the three taxonomy levels: network level, entity level and flow level.
3. Evaluation of performance on a annual basis, taking into account how to deal with system expansion and changes to activity levels within the system over time.

4.2 Function and Functional Unit

The network activity is represented by the annual net turnover of every entity adding to a sum of the entire network as mentioned in Section 3.2.2. A direct link is established between the financial net turnover and quantified amount of product/service required to fulfill the functional unit at all taxonomy levels of the model. In this respect, the functional unit is considered multi-dimensional, as it is represented both by annual net turnover and the amount of products/services generated over the period.

The LCA model is composed by three taxonomic levels as shown previously in Figure 3.10. With the determined reporting unit it is possible to assess the performance withing the system as a whole as well as the individual entity performances. This can be done by scoping the assessment to 1 MEUR_{2018} over the span of a year or the equivalent product quantity for only one entity instead of the network. The reporting unit for the whole system should be seen as receiving a weighted share from each entity relative to each financial turnover as exemplified on Figure 4.1.

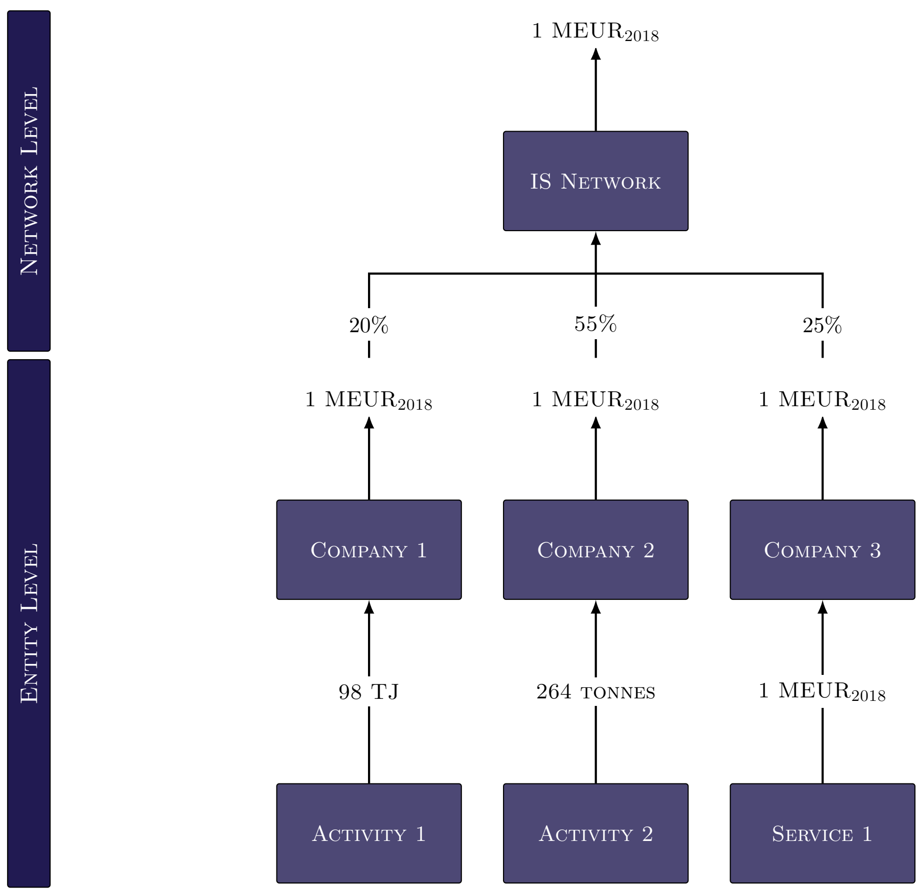


Figure 4.1: Relationship between reference unit from entity level to system level.

The function of the system is to compare performance of new symbiotic exchanges within Region Nordjylland. The functional unit can arguably be defined as a reporting unit to compare systems or organizations rather than providing a specific function. ISO (2015b) for organizational LCA defined this as a "*Quantified performance expression of the organization under study to be used as a reference*". Additionally, a common reporting unit is to be utilized when tracking environmental performance in an organization. This could be the impact per product sold or per financial turnover as examples. The reporting unit of this LCA is determined as the following:

FU: Turnover of 1 MEUR_{2018} over the span of 1 year.

This configuration of the LCA can be seen in the integrated matrix augmentation system (IMAS) attached in the external appendix. Additionally, a full list of annual net turnover for all entities within the ISN and GRØN network can be found in Appendix C.1 and D.1.

4.3 System Definition and Boundaries

As initially described in Section 3.3, the system boundary is based on the principles of a consequential methodology. In this respect, it is presumed that activities in the system will change as a consequence of shifts in demand (Weidema et al. 2018; Consequential-LCA 2021). Furthermore, decisions within LCA are preferably based on natural science as dictated by the priority of scientific approach of ISO 14040:2006 (ISO 2006a). For this reason, general scientific principles like mass balances have a main priority within the system. This results in the economic allocation of an attributional LCA is thus a last resort, since mixing allocative rules will obscure the system boundary and results of the study (Weidema 2017). Within the LCA model, utilizing system expansion while applying a broader projections of marginal market mixes is hence seen as a favorable choice. Two systems diagrams are designed to reflect a current, and future scenario for the ISN network:

- Reference Baseline Scenario (See Figure 4.2)
- Expanded Network Scenario (See Figure 4.3)

The first diagram, presented in Figure 4.2 is defined as the reference baseline scenario (RBS). This network system is embodied by the entities and material flows documented in the established ISN. The second network system diagram, presented in Figure 4.3 is defined as the Expanded Network Scenario (ENS). The ENS product system consist of the identified entities and symbiotic exchanges within GRØN. Additionally, a stand-alone visualization for the network system for the non-symbiotic reference scenario for GRØN have been omitted, with the difference to Figure 4.3 being an absence of symbiotic flows and points of substitution.

The system boundary for both product systems is defined as cradle to gate, with the cut-off established once the product exits the factory gate. Both Figure 4.2 and 4.3 display a system boundary indicating the border of inclusion for the collection of entities and flows within the IS networks corresponding to the goals of the LCA model (Matthews et al. 2014, p. 90). The limitations of a cradle to gate system boundary is further discussed in Section 8.1 and 8.3.

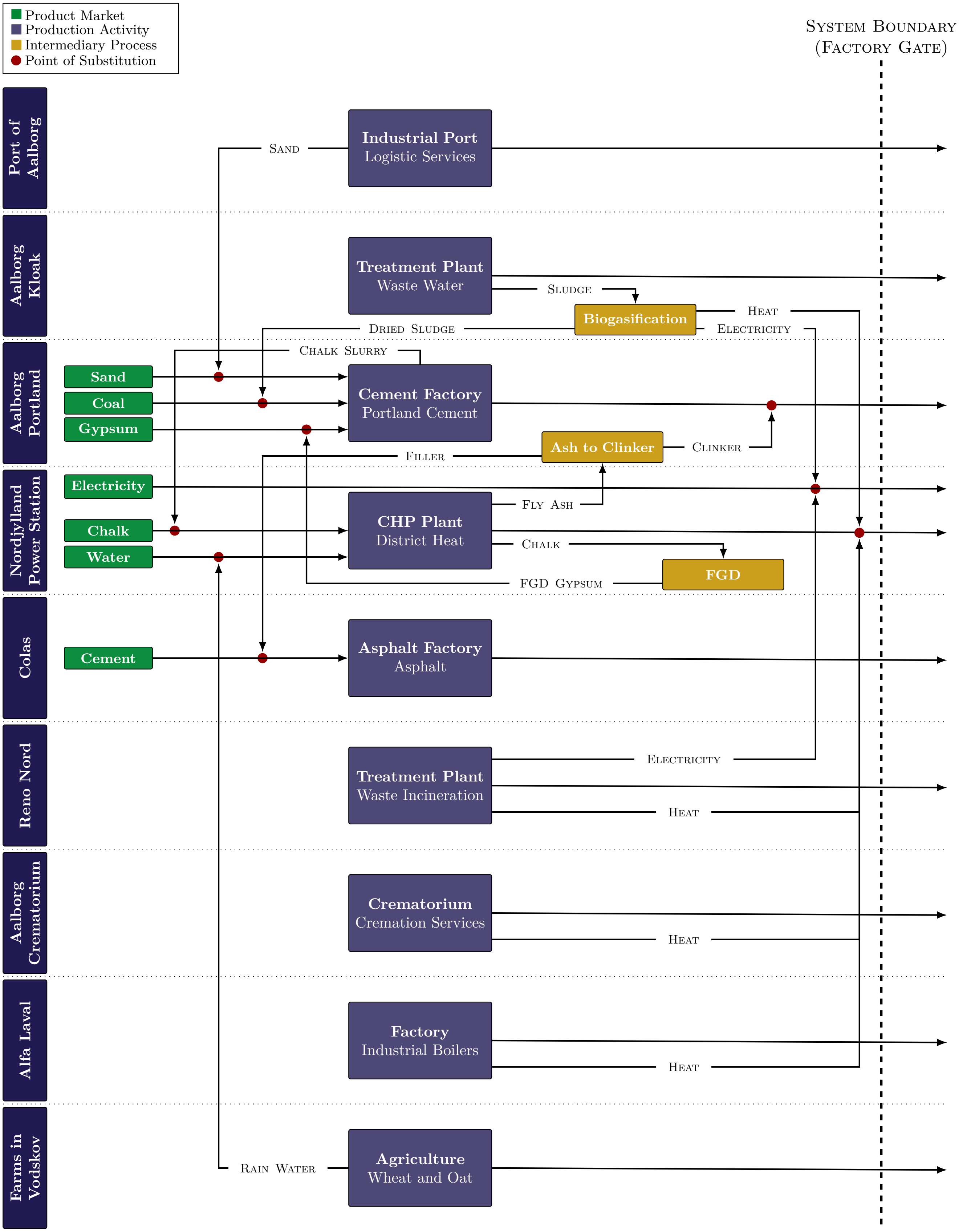


Figure 4.2: Network system diagram of the Reference Baseline Scenario (RBS) representing the ISN Network

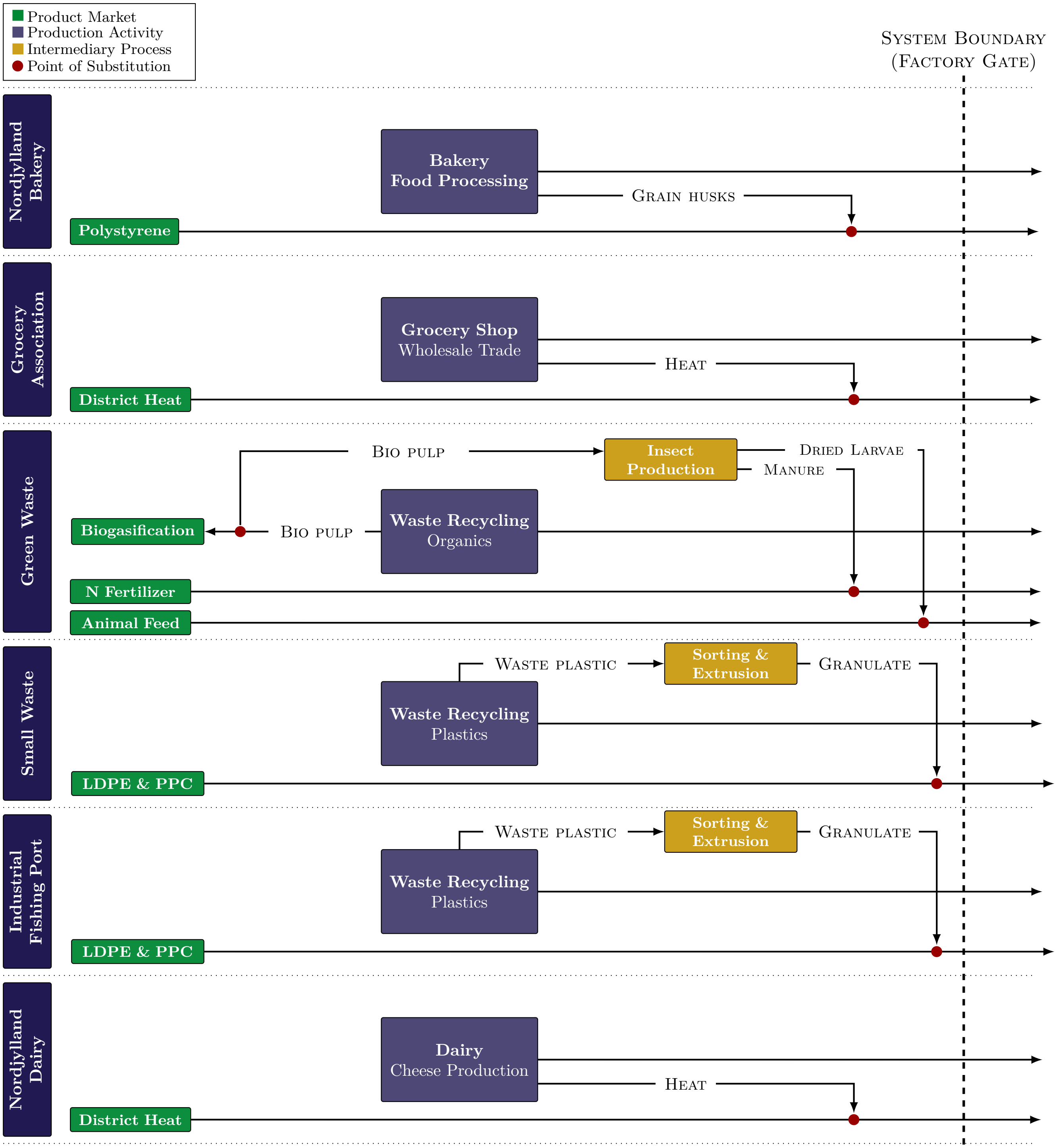


Figure 4.3: Network system diagram of the Expanded Network Scenario (ENS) representing the GRØN Network. Excluding ISN entities.

Chapter 5

Life Cycle Inventory (LCI)

The LCI is mainly constructed by modifying Exiobase sector activities performed by normalizing the contributing process values with the sector total produced. Subsequently, site-specific data or process data from Ecoinvent 3.8, such as material inputs or emissions to air, may, in some instances, be applied by replacing the normalized value, thereby forming an adjusted process. This adjustment is performed to modify the Exiobase data to reflect site-specific activities for entities within ISN. Furthermore, Exiobase accounts for dry matter ratio (DM) within sector production total and has thus been accounted for within the applied site-specific data of the LCI.

Two marginal market mixes have been constructed to reflect a prospective shift in demand. The first marginal mix constitutes the local production of district heat within Aalborg municipality. The district heating process - 0A_District heating (See Appendix B.1), is comprised of unconstrained production through geothermic heat pumps and burning of wood chips. Both processes are extrapolated from the Ecoinvent 3.8 datasets:

- Heat, air-water heat pump 10kW {Europe without Switzerland}| production | Conseq, U
- Heat, district or industrial, other than natural gas {CH}| heat production, wood chips from industry, at furnace 5000kW, state-of-the-art 2014 | Conseq, U

The second marginal mix modifies the existing market mix from 2011 present in the Exiobase process - 20 Mining of coal and lignite; extraction of peat (10) {DK} (product market, hybrid units, purchaser price) to reflect 2021 imports (See Appendix B.3, by identifying trends in the period 2011-2021 Statistikbanken (2021). Consequently, the market supply is based on a projection rather than a single year, as volatility in the coal market impedes an accurate projection. This volatility is further substantiated as the generic Exiobase mix from 2011 is entirely replaced by new unconstrained supply markets by 2021.

5.1 Reference Baseline Scenario (RBS)

The reference baseline scenario (RBS) consists of the current exchanges facilitated through Industrial Symbiosis North (ISN) as of 2018. It should be noted that multiple symbiotic exchanges undocumented by PARD have been identified through disclosed site-specific data, despite officially not being included in ISN. Therefore, certain undocumented exchanges have been incorporated into the RBS if they manage to fulfill the criteria of IS exchanges set up in Section 1.1). Consequently, the RBS establishes both the total environmental performance of the current iteration of ISN and comparatively through the entity activity ($MEUR_{2018}$). Isolated foreground processes for individual symbiotic flows within the RBS have been constructed based on the IS taxonomy as described in Figure 3.5.

5.1.1 IS Exchanges - Intermediary Processes

Certain symbiotic flows require intermediate processes before being usable as a resource. These processes are modeled by augmenting Exiobase processes. Subsequently, each flow is coupled to the entity to which the production and following substitution occurs, as seen in Table 5.1.

Flow	Flow ID	Intermediate process	Substitution process ID
Heat	0A_District heating	-	Marginal Heat Supply)
Electricity	0B_Electricity	-	Electricity mix DK (product market, hybrid units, purchaser price)
Fly ash, cement	0C_Flyash - Cement	Adjusted - 70 Re-processing of ash into clinker DK (product market, hybrid units, purchaser price)	Aalborg Portland - Cement
Fly ash, asphalt	0D_Flyash - Asphalt	Adjusted - 70 Re-processing of ash into clinker DK (product market, hybrid units, purchaser price)	69 Manufacture of cement, lime and plaster DK (product market, hybrid units, purchaser price)
Dry sludge, fuel	0E_Dry sludge	-	20 Mining of coal and lignite; extraction of peat (10) DK (product market, hybrid units, purchaser price)
Dry sludge, biogas	0F_Biogas	Adjusted - 148 Biogasification of paper, incl. land application DK	112 Steam and hot water supply DK (product market, hybrid units, purchaser price)
		-	Electricity mix DK (product market, hybrid units, purchaser price)
Sand	0G_Sand	-	33 Quarrying of sand and clay DK (product market, hybrid units, purchaser price)
Gypsum	0H_Gypsum	-	32 Quarrying of stone DK (product market, hybrid units, purchaser price)
Chalk slurry	0I_Chalk slurry	-	32 Quarrying of stone DK (product market, hybrid units, purchaser price)
Water	0J_Rain Water	-	113 Collection, purification and distribution of water (41) DK (product market, hybrid units, purchaser price)

Table 5.1: Description of how symbiotic flows are coupled with adjusted intermediate processes, and how these subsequent flows substitute production

Intermediary Process - Fly Ash

It is assumed that before fly ash can become part of new products, it is treated by an intermediary process transforming fly ash into clinker. The initial intermediary process, fly ash, is a waste product derived from coal and biomass combustion. As fly ash is commonly reused, there is already a generic fly ash to clinker activity within Exiobase. Fly ash is exchanged with Aalborg Portland A/S and Colas A/S, where it becomes part of the cement and asphalt production, respectively. For Aalborg Portland, it is assumed that clinker derived from fly ash substitutes Aalborg Portland A/S' cement production. At Colas, the clinkers substitute the generic market mix for cement production used as filler. The substitution is by default to the model part of the intermediary process to ensure that both the benefits and the costs of the symbiotic exchanges are attributed to the resource supplier.

Activities	Unit	Normalized Value	Adjusted Cement	Adjusted Asphalt	LCI data
RF	ton	1	1	1	
FU fulfilled	ton	1	1	1	
Avoided production					
Cement, market	ton/ton	-9,30E-01	0,00E+00	-9,30E-01	69 Manufacture of cement, lime and plaster DK (product market, hybrid units, purchaser price)
Cement, Aalborg Portland	ton/ton	0,00E+00	-9,30E-01	0,00E+00	Aalborg Portland - Cement

Table 5.2: Disaggregated intermediary process based on generic Exiobase process: 70 Re-processing of ash into clinker {DK}

Intermediary Process - Biogasification

Concerning the exchange of dry sludge between Aalborg Kloak A/S and Aalborg Portland A/S, the mass is initially treated by a biogasification process. The biogasification process is based on the pre-existing process in Exiobase for the treatment of sewage sludge as described in Table 5.3. A significant loss of methane through gas slippage has been identified for biogas production. This loss is extraordinarily high at wastewater treatment plants, averaging 6% in Denmark according to a report by Rambøll (2021). The specific calculations can be found in the LCI matrix within the external appendix. Because the process is based on sewage treatment for both biogas and land application, but the dry sludge in Aalborg Municipality is exclusively utilized for the production of biogas, all fertilizer substitutions in the generic data are adjusted to zero. Site-specific data for substitution of heat and electricity was available and included for the marginal heat mix and electricity mix.

Activities	Unit	Normalized Value	Adjusted Value	LCI data
RF	ton	1063	1	
FU fulfilled	ton	1	1	
Materials/fuels				
N-fertilizer	ton/ton	1.12E-04	0.00E+00	61 N-fertiliser {DK} (product market, hybrid units, purchaser price)
P-fertilizer	ton/ton	-1.61E-05	0.00E+00	62 P- and other fertiliser {DK} (product market, hybrid units, purchaser price)
Heat	TJ/ton	-1.77E-02	0.00E+00	112 Steam and hot water supply {DK} (product market, hybrid units. purchaser price)
Electricity	TJ/ton	-7.33E-03	0.00E+00	Electricity mix DK (terminated)
Avoided production				
Heat	TJ/ton	0.00E+00	8.02E-03	0A_District heating
Electricity	TJ/ton	0.00E+00	1.09E-02	0B_Electricity
Emissions to air				
Methane	ton/ton	2.15E-02	6.36E-02	Methane, fossil

Table 5.3: Disaggregated intermediary process based on generic Exiobase process: 149 Sewage sludge for treatment: biogasification and land application

5.1.2 Aalborg Crematorium

Aalborg Crematorium partakes in ISN by feeding excess heat during the cremation process into the district heating network, substituting heat production at NPS. However, limited data have been made available for Aalborg Crematorium, prompting the disaggregation to be restricted to the utilization of a proxy value for turnover, as well as reported consumption of natural gas as seen in Table C.2 within the appendix. Thus, the Exiobase process - 162 Other service activities (93) {DK} has been disaggregated to reflect natural gas, and the emissions hereof as seen in Table 5.4.

Activities	Unit	Normalized Value	Adjusted Value	LCI data
RF	$MEUR_{2018}$	0.92	1	
FU fulfilled	$MEUR_{2018}$	0.92	1	
Materials/fuels				
Natural gas	ton/$MEUR_{2018}$	1.10E-01	2.23E+02	22 Extraction of natural gas and services related to natural gas extraction. excluding surveying {DK} (product market, hybrid units, purchaser price)
IS Exchanges				
Heat	TJ/ton	0.00E+00	1.50E+00	0A_District heating
Emissions to air				
CO_2	ton	3.14E+01	5.68E+02	Carbon dioxide, fossil
Nitrous oxides	ton	1.70E-03	7.66E-01	Nitrogen oxides
Methane	ton	1.55E-01	2.98E-01	Methane, fossil

Table 5.4: Disaggregated process based on generic Exiobase process: 162 Other service activities (93) {DK}, with data integration from Aalborg Crematorium

5.1.3 Aalborg Forsyning A/S - Nordjylland Power Station (NPS)

Nordjylland Power Station (NPS) is a subsidiary of Aalborg Forsyning A/S, which supplies Aalborg Municipality with electricity and heat through a combined heat and power (CHP) plant. The plant utilize coal as a primary fuel, supplemented to a lesser degree with refined fuels (See Table C.3 within the appendix for site-specific data). NPS facilitates the symbiotic exchange of fly ash. However, only ≈15% of fly ash output is exchanged within the ISN network. The rest is thus unaccounted for, however, reportedly fully utilized by other industries and thereby included on entity level by substituting the production of cement (Nordjylland Power Station A/S 2018). Furthermore, FDG gypsum is produced through a flue gas desulfurization process through the cleaning of emissions of the smokestack and has a substitution ratio of 1. The FDG process is incorporated as part of on-site production and is therefore not considered an intermediary process.

With heat identified as the determining product, disaggregation of Exoibase process 112 Steam and hot water supply {DK} has been performed as seen in Table 5.5. The process has been adjusted to reflect NPS's site-specific production, utilizing coal as a primary source. Thus, adjustments to the input of fuels, such as biofuel and natural gas, have all been applied. Furthermore, emissions to air have been adjusted to reflect the significant utilization of coal as per site-specific data. Lastly, regarding the symbiotic outputs, fly ash and gypsum are coupled with their respective foreground flow processes, substituting original production.

Activities	Unit	Normalized Value	Adjusted Value	LCI data
RF	$MEUR_{2018}$	0.92	1	
FU fulfilled	TJ	86.6	30.7	
Materials/fuels				
Biofuel	ton/TJ	2.07E+00	0.00E+00	8 Cultivation of crops nec {DK} (product market, hybrid units, purchaser price)
Wood	ton/TJ	2.75E+00	0.00E+00	18 Forestry, logging and related service activities (02) {DK} (product market, hybrid units, purchaser price)
Coal	ton/TJ	3.28E+01	1.34E+02	20 Mining of coal and lignite; extraction of peat (10) {DK} (product market, hybrid units, purchaser price)
Natural gas	ton/TJ	9,93E+00	0.00E+00	22 Extraction of natural gas and services related to natural gas extraction, excluding surveying {DK} (product market, hybrid units, purchaser price)
Chalk	ton/TJ	1.29E-02	2.69E+00	32 Quarrying of stone {DK} (product market, hybrid units, purchaser price)
Oil	ton/TJ	1.25E+00	2.10E-01	57 Petroleum Refinery {DK} (product market, hybrid units, purchaser price)
Fly ash	ton/TJ	1.05E+00	1.01E+01	70 Re-processing of ash into clinker {DK} (product market, hybrid units, purchaser price)
Electricity	TJ/TJ	-3.87E-01	1.03E-01	Electricity mix {DK} (terminated)
Heat	TJ/TJ	1.48E-01	1.74E-03	112 Steam and hot water supply {DK} (product market, hybrid units, purchaser price)
IS Exchange				
Fly ash, cement	ton/TJ	0.00E+00	9.45E-01	0C_Flyash - Cement
Fly ash, asphalt	ton/TJ	0.00E+00	4.94E-01	0C_Flyash - Asphalt
FGD Gypsum	ton/TJ	0.00E+00	5.72E+00	0H_Gypsum
Electricity	TJ/TJ	0.00E+00	-1.25E+00	0B_Electricity
Emissions to air				
CO_2	ton	1.06E+02	3.09E+02	Carbon dioxide, fossil
N_2O	ton	4.17E-03	2.63E-03	Dinitrogen monoxide
Nitrous oxides	ton	7.70E-02	2.50E-13	Nitrogen oxides
SO_2	ton	1.85E-02	8.81E-03	Sulfur dioxide
Methane	ton	1.65E-02	4.93E-03	Methane, fossil
CO	ton	7.10E-02	3.28E-02	Carbon monoxide
NMVOC	ton	1.05E-02	4.93E-03	NMVOC, non-methane volatile organic compounds, unspecified origin
PPM2.5	ton	4.09E-03	1.47E-02	Particulates, < 2.5 um

Table 5.5: Disaggregated process based on generic Exiobase process: 112 Steam and hot water supply {DK}, with site-specific data integration from Nordjylland Power Station A/S (2018)

5.1.4 Aalborg Kloak A/S - Treatment Plant East and West

Aalborg Kloak is a combination of the activities of Treatment Plant East and West within Aalborg Municipality (See Table C.4 within the appendix for site-specific data for Treatment Plant East and West). The main activity is the treatment of wastewater for which Exiobase - 153 WASTEWATER TREATMENT, OTHER {DK}, represents the overall activity. The symbiotic output of Aalborg Kloak is a leftover sludge of waste material extracted during the water treatment process. This sludge is first utilized at Aalborg Kloak biogasification plant as feed for biogas production. Subsequently, once this process is saturated, the now dried-out sludge is sent to Aalborg Portland A/S as fuel for their kilns, thereby substituting coal in a 0.46 ratio Durdević et al. (2019). The dry matter ratio for wastewater is accounted for in Aalborg Forsyning (2020) as being 27.5%. This holds close to the predefined dry matter ratio in Exiobase between 20-25 % for different wastewater treatments. The adjusted processes in Exiobase 153 WASTEWATER TREATMENT, OTHER {DK} are electricity, district heating, and natural gas consumption. Biogas production is adjusted to zero as there is a specific flow (0F_Biogas) for biogasification of sludge, as well as dry sludge for fuel (0E_Dry sludge).

Activities	Unit	Normalized Value	Adjusted Value	LCI data
RF	$MEUR_{2018}$	0.92	1	
FU fulfilled	ton	816.56	288.38	
Materials/fuels				
Natural gas	ton/ton	5.31E-03	3.81E-03	22 Extraction of natural gas and services related to natural gas extraction, excluding surveying {DK} (product market, hybrid units, purchaser price)
Heat	TJ/ton	1.41E-05	1.68E-04	112 Steam and hot water supply {DK} (product market, hybrid units, purchaser price)
Biogas	ton/ton	1.29E-01	0.00E+00	149 Biogasification of sewage slugde, incl. land application {DK} (product market, hybrid units, purchaser price)
Electricity	TJ/ton	1.55E-04	3.45E-03	Electricity mix {DK} (terminated)
IS Exchanges				
Dry sludge, biogas	ton/ton	0.00E+00	9.63E-02	0F_Biogas
Dry sludge, fuel	ton/ton	0.00E+00	9.26E-02	0E_Dry sludge

Table 5.6: Disaggregated process based on generic Exiobase process: 153 Waste water treatment, other {DK}, with site-specific data integration from Aalborg Forsyning (2020)

5.1.5 Aalborg Portland A/S

Aalborg Portland A/S is a cement producer and is considered one of the largest contributors to global warming in the Danish industry. However, Aalborg Portland A/S is also a central stakeholder and primary beneficiary of symbiotic material exchanges within the ISN network. Relevant site-specific data for Aalborg Portland A/S in 2018 can be seen within Table C.5 in the appendix.

Two symbiotic exchanges are identified with Aalborg Portland A/S as the sender. The first is the integration of excess heat into the district heating system, thereby substituting heat production at NPS. The second is supplying NPS with chalk slurry, which utilizes the material for flue gas desulfurization

(FGD), substituting raw chalk. The disaggregation of the Exiobase process 69 MANUFACTURE OF CEMENT, LIME, AND PLASTER {DK}, is adjusted to reflect the mix of used raw materials, electricity, utilized fuels, as well as the reported emissions as presented in Table 5.7 (See Table C.5 for site-specific data).

Activities	Unit	Normalized Value	Adjusted Value	LCI data
RF	$MEUR_{2018}$	0.92	1	
FU fulfilled	ton	2609.15	8812.77	
Materials/fuels				
Sand	ton/ton	1.33E+00	1.09E-01	33 Quarrying of sand and clay {DK} (product market, hybrid units, purchaser price)
Chalk & Gypsum	ton/ton	5.03E-04	1.87E+00	32 Quarrying of stone {DK} (product market, hybrid units, purchaser price)
Oil	ton/ton	4.04E-02	1.00E-01	57 Petroleum Refinery {DK} (product market, hybrid units, purchaser price)
Coal	ton/ton	8.85E-03	3.51E-02	20 Mining of coal and lignite; extraction of peat (10) {DK} (product market, hybrid units, purchaser price)
Natural gas	ton/ton	2.37E-02	0.00E+00	22 Extraction of natural gas and services related to natural gas extraction, excluding surveying {DK} (product market, hybrid units, purchaser price)
Electricity	TJ/ton	5.20E-04	5.19E-04	Electricity mix {DK} (terminated)
IS Exchanges				
Heat	TJ/ton	0.00E+00	5.51E-04	0A_District heating
Chalk slurry	ton/ton	0.00E+00	1.90E-09	0I_Chalk Slurry
Emissions to air				
CO_2	ton/ton	7.31E-01	1.02E+00	Carbon dioxide, fossil
SO_2	ton/ton	6.95E-04	4.16E-04	Sulfur dioxide
Nitrous oxides	ton/ton	2.27E-03	1.16E-03	Nitrogen oxides
CO	ton/ton	4.20E-04	1.68E-03	Carbon monoxide
Ammonia	ton/ton	1.03E-06	4.00E-05	Ammonia
Mercury	ton/ton	4.42E-09	1.30E-08	Mercury
PPM2.5	ton/ton	7.97E-04	4.14E-05	Particulates, < 2.5 um

Table 5.7: Disaggregated process based on generic Exiobase process: 69 Manufacture of cement, lime and plaster {DK}, with site-specific data integration from Aalborg Portland A/S (2019)

5.1.6 Alfa Laval AB

Alfa Laval AB in Aalborg is a manufacturer of industrial boilers. Due to data constraints, significant assumptions are made. The product portfolio for Alfa Laval AB is determined as a 100 kW boiler for heat transfer. As detailed in Section 3.2.2, the hybrid structure of Exiobase allows converting the financial turnover into a turnover of products in tonnes. The Exiobase process is disaggregated based on the energy and material inputs from Ecoinvent 3.8 - OIL BOILER, 100KW {CH} PRODUCTION | CONSEQ, U. The total material and energy input estimated to represent Alfa Lavals business activities can be found in Table C.6 within the Appendix C. Having estimated the activity data for Alfa Laval, the

Exiobase process - 86 MANUFACTURE OF MACHINERY AND EQUIPMENT N.E.C. is disaggregated. The market processes changes within the Exiobase process is shown in Table 5.8. The material inputs are characterized by the market processes of Exiobase, and the inputs are adjusted. The input of metals, re-processing of secondary metals, and reuse of metals as waste treatment are adjusted to zero (See LCI matrix in the external appendix for a full list of disaggregated metals).

Activities	Unit	Normalized Value	Adjusted Value	LCI data
RF	$MEUR_{2018}$	0.92	1	
FU fulfilled	ton	127.86	118.12	
Materials/fuels				
Polyethylene	ton	4.49E-03	2.42E-03	59 Plastics, basic {DK} (product market, hybrid units, purchaser price)
Alkyd paint & Brazing solder	ton	7.26E-03	1.47E-02	63 Chemicals nec {DK} (product market, hybrid units, purchaser price)
Stone wool, packed	ton	2.75E-01	3.28E-02	71 Manufacture of other non-metallic mineral products n.e.c. {DK} (product market, hybrid units, purchaser price)
Steel, low alloyed % chromium	ton	1.16E+00	8.81E-01	72 Manufacture of basic iron and steel and of ferro-alloys and first products thereof {DK} (product market, hybrid units, purchaser price)
Aluminium	ton	1.51E-01	2.59E-02	76 Aluminium production {DK} (product market, hybrid units, purchaser price)
Copper cathode & brass	ton	2.61E-03	4.33E-02	80 Copper production {DK} (product market, hybrid units, purchaser price)
Heat	ton	3.46E-06	4.64E-03	112 Steam and hot water supply {DK} (product market, hybrid units, purchaser price)
Electricity	TJ	2.68E-03	2.06E-03	Electricity mix {DK} (terminated)
IS Exchanges				
Heat	TJ/ton	0.00E+00	5.19E-04	0A_District heating
Emissions to air				
CO_2	ton/ton	2.78E-01	1.12E+02	Carbon dioxide, fossil
Nitrous oxides	ton/ton	4.37E-04	5.89E-02	Nitrogen oxides
Methane	ton/ton	5.96E-05	1.50E-01	Methane, fossil

Table 5.8: Disaggregated process based on generic Exiobase process: 86 Manufacture of machinery and equipment n.e.c. (29) {DK}, with process integration based on data from Ecoinvent 3.8 - Oil boiler. 100kW {CH} l production l Conseq, U .

5.1.7 Colas A/S

Colas A/S is an asphalt production company partaking in ISN and classified as Exiobase process - 69 MANUFACTURE OF CEMENT, LIME AND PLASTER {DK}. The symbiotic exchange of Colas A/S exclusively consists of fly ash received from NPS as filler instead of cement. Due to data constraints, asphalt production has been disaggregated based on site-specific data from consulting Colas A/S and generic data from Ecoinvent 3.8. The ratio between sand and cement in the asphalt composition is based on Ecoinvent process - MASTIC ASPHALT {RoW}| PRODUCTION | CONSEQ, U. (See Table C.7 within the appendix for inputs for Colas A/S). This can be seen in Table 5.9.

Activities	Unit	Normalized Value	Adjusted Value	LCI data
RF	$MEUR_{2018}$	0.92	1	
FU fulfilled	ton	2609.15	1762	
Materials/fuels				
Sand	ton/ton	1.33E+00	9.28E-01	33 Quarrying of sand and clay {DK} (product market, hybrid units, purchaser price)
Asphalt	ton/ton	4.04E-02	5.00E-02	57 Petroleum Refinery {DK} (product market, hybrid units, purchaser price)
Cement	ton/ton	2.01E-03	2.24E-02	69 Manufacture of cement, lime and plaster {DK} (product market, hybrid units, purchaser price)

Table 5.9: Disaggregated process based on generic Exiobase process: 69 Manufacture of cement, lime and plaster {DK}, with process integration based on site-specific data

5.1.8 Farms in Vodskov

Farms in Vodskov is an unspecified number of farms located in Vodskov based on an allocated proxy area of 2000 hectares of farmland. This area of farmland supplies NPS with 120000 m3 of drainage water used as cooling water, substituting treated tap water. The turnover is divided based on annual production classified by generic data from two Exiobase processes 2 Cultivation of wheat {DK} and 3 Cultivation of cereal grains nec {DK} in a 23.83% - 76,17% split (See Table C.8 within the appendix) to reflect nationalized production activities (Ministeriet for Fødevarer, Landbrug og Fiskeri 2021). Consequently, an additional input of raw water has been added to the cultivation of crops to reflect the water drained for substitution per 1 million in production as seen in Table 5.10.

Activities	Unit	Normalized Value	Adjusted Value	LCI data
RF	$MEUR_{2018}$	0.92	1	
FU fulfilled	ton	2860.91	2642.86	
Input from nature				
Water, wheat	ton/ton	3.15E+00	1.41E+01	Water, unspecified natural origin/kg
Water, Cereal grains	ton/ton	5.49E+00	1.89E+01	Water, unspecified natural origin/kg
IS Exchanges				
Water, wheat	ton/ton	0.00E+00	-1.09E+01	0J_Water
Water, cereal grain	ton/ton	0.00E+00	-1.34E+01	0J_Water

Table 5.10: Disaggregated process based on generic Exiobase process: 2 Cultivation of wheat {DK} and 3 Cultivation of cereal grains nec {DK}.

5.1.9 I/S Reno Nord

I/S Reno Nord is a waste management company that utilizes a combined heat and power (CHP) plant to convert waste into district heat and electricity, substituting energy production at NPS. However, the distribution of waste fractions holds great significance as calorific value and emissions differ depending on the waste fraction incinerated. Specific waste fractions for households and businesses have been calculated based on the fractions determined by Miljøstyrelsen (2017) (See Table C.9 within the appendix for waste fraction distribution and site-specific data). A foreground process for 1 ton of combined waste at I/S Reno Nord has thus been constructed, presented in Table 5.11. It should be noted that certain materials/fuels and emissions to air have been adjusted to zero for each waste fraction within the constructed foreground process. Specifically the input of biofuel and the subsequent production of electricity and heat through the burning of waste. Additionally, so are select emissions to air (See Table 5.11 as reference for emissions modified). Thus, the foreground process consists of all the individual processes combined into one, which composition is presented within Table 5.11 (See LCI in the external appendix for a full list of disaggregated processes). Consequently, presented emissions are comprised of site-specific data sourced from (I/S Reno Nord 2018).

Activities	Unit	Value	LCI data
RF	MEUR2018	1	
FU fulfilled	ton	288.38	Reno Nord - Total
Materials/fuels			
Waste, food	ton/ton	4.20E-01	140 Incineration of waste: Food {DK}
Waste, paper	ton/ton	1.03E-01	141 Incineration of waste: Paper {DK}
Waste, plastic	ton/ton	1.80E-01	142 Incineration of waste: Plastic {DK}
Waste, metals	ton/ton	6.06E-02	143 Incineration of waste: Metals and Inert materials {DK}
Waste, textiles	ton/ton	2.12E-02	144 Incineration of waste: Textiles {DK}
Waste, wood	ton/ton	8.78E-02	145 Incineration of waste: Wood {DK}
Waste, oil/hazardous	ton/ton	1.28E-01	146 Incineration of waste: Oil/Hazardous waste {DK}
Bio fuel	ton/ton	7.14E-02	18 Forestry, logging and related service activities (02) {DK}
Substituting materials/fuels			
Heat	TJ/ton	1.39E-02	0A_District heating
Electricity	TJ/ton	3.29E-03	0B_Electricity
Emissions to air			
CO_2	ton	1.78E+00	Carbon dioxide, fossil
Nitrous oxides	ton	1.51E-03	Nitrogen oxides
SO_2	ton	3.95E-05	Sulfur oxides
CO	ton	9.94E-05	Carbon monoxide
PM2.5	ton	3.68E-06	Particulates, < 2.5 um
Ammonia	ton	4.31E-06	Ammonia
Mercury	ton	3.63E-08	Mercury

Table 5.11: Process composition: Combination of waste fractions with integration of site-specific emission data I/S Reno Nord (2018)

5.1.10 Port of Aalborg A/S

Port of Aalborg is the administrating entity of Aalborg Industrial Port, with its main business activities in real estate and logistic services. The business activities differ and therefore divided into Exiobase process - 132 Real estate activities (70) {DK} and 133 Renting of machinery and equipment without operator and of personal and household goods (71) {DK} with a distribution of 54% and 46% respectively. The turnover is divided based on the annual financial report Port of Aalborg A/S (2019) (See Table C.10 in appendix). The output of sand is the symbiotic exchange with Aalborg Portland A/S and is expected to be a byproduct of maintaining the ports.

Activities	Unit	Normalized Value	Adjusted Value	LCI data
RF	$MEUR_{2018}$	0.92	1	
FU fulfilled	$MEUR_{2018}$	0.92	1	
Substituting materials/fuels				
Sand	ton/ton	0.00E+00	9.22E+03	0G_Sand

Table 5.12: Foreground process: Combination of business activity and its output of sand

5.2 Studied Scenario - Expanded Network Scenario (ENS)

As ISN and its participating stakeholders strive to further the IS network, an expanded network scenario (ENS) is created to gauge the environmental potential through network expansion. First, an ENS for GRØN will be created, after which a scenario containing the symbiotic exchanges will be applied and compared. The rationale behind selecting entities is based on data available on the symbiotic exchanges. It, therefore, does not reflect the environmental potential of fully integrating GRØN into ISN, which remains the underlying intention after the GRØN project concludes. It should be noted that the additional entities within the ENS are granted anonymity, as the GRØN project is still in its infancy. In contrast to the RBS, limited site-specific data except for turnover and symbiotic exchange amounts have been applied, primarily due to the absence of reported data.

5.2.1 IS Exchanges - Intermediary Processes

Table 5.13 presents the symbiotic flows present in ENS, their intermediate processes, and subsequently what the flows substitute. Lastly, it should be noted that flows pertaining to district heat within ENS is set to utilize the marginal mix for Aalborg Municipality, despite an inherent geographical disparity (See Appendix B.1 for the marginal mix of district heat).

Flow	Flow ID	Intermediate process	Substitution process ID
Heat	0A_District heating	-	Marginal Heat Supply
Grain husks	1A_Grain Husks	-	59 Plastics, basic DK (product market, hybrid units, purchaser price)
Waste, pastic	1B_Waste Plastic	60 Re-processing of secondary plastic into new plastic DK	59 Plastics, basic DK (product market, hybrid units, purchaser price)
Waste, organic	1C_Organic Waste	Custom: Insect Production	140 Incineration of waste: Food DK (product market, hybrid units, purchaser price)

Table 5.13: Description of how symbiotic flows are coupled with adjusted intermediate processes, and how these subsequent flows substitute production (Excel-sheet in appendix display full flow of each process)

Two intermediate processes are present in GRØN. A custom process for the production of insects has been constructed based on an LCA concerning the specific topic by Salomone et al. (2017). Moreover, this LCA designates the produced insects as substituting production of fertilizer and animal feed, which corresponds with the practice of the receiving company partaking in ENS. It should be noted that this process is a distinct extension of the scope within this LCI as it pertains to the receiving company's substitution potential. Lastly, the custom process incorporates the avoided production of biogas, as the waste is instead used as insect feed. The custom process is presented in Table 5.14.

Activities	Unit	Value	LCI data
RF	$MEUR_{2018}$	1	
FU fulfilled	ton	1	
Materials/fuels			
Tap Water	$MEUR_{2011}$/ton	1.08E-07	113 Collection, purification and distribution of water (41) {DK} (product market, hybrid units, purchaser price)
Transport	$MEUR_{2011}$/ton	5.28E-05	122 Other land transport {DK} (product market, hybrid units, purchaser price)
Electricity	TJ/ton	3.58E-06	Electricity mix {DK} (product market, hybrid units, purchaser price)
Avoided production			
Animal feed	ton/ton	-2.84E-02	43 Processing of Food products nec {DK} (product market, hybrid units, purchaser price)
Fertilizer	ton/ton	-4.88E-02	61 N-fertiliser {DK} (product market, hybrid units, purchaser price)
Waste, wood	ton/ton	-5.50E-03	145 Incineration of waste: Wood {DK} (product market, hybrid units, purchaser price)
Biogas	ton/ton	-1.00E+00	147 Biogasification of food waste, incl. land application {DK} (product market, hybrid units, purchaser price)
Emissions to air			
CO_2	ton/ton	1.60E-02	Carbon dioxide, fossil
Methane	ton/ton	5.12E-05	Methane, fossil

Table 5.14: Foreground process: Custom process 1C_ Organic Waste - Includes insect feed, production and substituting outputs for 1 ton of organic waste based on Salomone et al. (2017)

Additionally, an intermediary process for re-processing of plastic is present for entities with recycling activities. This process is based on the generic Exiobase process: 60 Re-processing of secondary plastic into new plastic {DK}. This process is not modified as no knowledge or data is available for the actual process.

5.2.2 Nordjylland Bakery

Nordjylland Bakery produces flour-based products and is a supplier of various raw grains. Nordjylland Bakery partakes in a symbiotic exchange with a pillow manufacturer, where grain husks substitute the polystyrene plastic in the manufactures products. Nordjylland Bakery is classified under Exiobase process - 43 Processing of Food products nec {DK} and has been normalized according to economic turnover. Furthermore, avoided production of polystyrene through grain husks is coupled with the Exiobase process - 59 Plastics, basic {DK} (product market, hybrid units, purchaser price) in a substitution ratio of 0.36. Lastly, no disaggregation except coupling of the substitution potential have been performed as presented in Table 5.15.

Activities	Unit	Normalized Value	Adjusted Value	LCI data
RF	$MEUR_{2018}$	0.92	1	
FU fulfilled	ton	215.20	198.81	
Materials/fuels				
Waste, food	ton/ton	1.29E-02	0.00E+00	140 Incineration of waste: Food {DK} (product market, hybrid units, purchaser price)
IS Exchanges				
Grain husks	ton/ton	0.00E+00	-3.12E-02	1A_Grain Husks

Table 5.15: Disaggregated process based on generic Exiobase process: 43 Processing of Food products nec {DK}.

5.2.3 Local Grocery Association

Local Grocery Association is a consortium of grocery stores and is classified under Exiobase - 118 Wholesale trade and commission trade, except of motor vehicles and motorcycles (51) {DK}. The association has a symbiotic exchange where excess heat is fed into the local district heating network, thereby substituting a marginal heat supply. Lastly, as presented in Table 5.16 no disaggregation except coupling of the substitution potential have been performed, this utilizing the marginal mix for district heat, as described in section 5.

Activities	Unit	Normalized Value	Adjusted Value	LCI data
RF	$MEUR_{2018}$	0.92	1	
FU fulfilled	$MEUR_{2018}$	1	1	
IS Exchanges				
Heat	TJ/MEUR2018	0.00E+00	1.80E-01	0A_District Heating

Table 5.16: Foreground process: Coupling of substituting output flow from 118 Wholesale trade and commission trade, except of motor vehicles and motorcycles (51) {DK}.

5.2.4 Green Waste

Green Waste is a waste management company that specializes in utilizing organic waste in circular resource flows and is classified under Exiobase process - 94 Recycling of waste and scrap {DK}. The company has a symbiotic output of bio pulp produced from organic waste, which is used as feed for the production of insects, an alternative to the regular practice of utilizing it for the production of biogas.

Activities	Unit	Normalized Value	Adjusted Value	LCI data
RF	$MEUR_{2018}$	0.92	1	
FU fulfilled	$MEUR_{2018}$	1	1	
IS Exchanges				
Bio pulp	ton/MEUR2018	0.00E+00	4.90E+01	0A_Organic Waste

Figure 5.1: Disaggregated process based on generic Exiobase process: 94 Recycling of waste and scrap {DK}.

5.2.5 Small Waste Management Company

Small Waste Management Company is classified as the Exiobase process - 94 Recycling of waste and scrap {DK}. The company supplies a manufacturer of recycled plastic products with plastic waste from the maritime industry, substituting virgin plastic production in the appendix for site-specific data). Subsequently, plastic is recycled through the Exiobase process - 60 Re-processing of secondary plastic into new plastic {DK}, an intermediate process that accounts for material loss and extrusion during the recycling process of plastic. Thus, no disaggregation except coupling of the substitution potential have been performed, see Table 5.17.

Activities	Unit	Normalized Value	Adjusted Value	LCI data
RF	$MEUR_{2018}$	0.92	1	
FU fulfilled	$MEUR_{2018}$	0.92	1	
IS Exchanges				
Waste, plastic	ton/ton	0.00E+00	3.61E+02	1B_Waste Plastic

Table 5.17: Disaggregated process based on generic Exiobase process: 94 Recycling of waste and scrap {DK}.

5.2.6 Industrial Fishing Port

Industrial Fishing Port is classified as a split between Exiobase processes - 132 Real estate activities (70) {DK} & 133 Renting of machinery and equipment without operator and of personal and household goods (71) {DK}. Industrial Fishing Port supplies a manufacturer of recycled plastic products with plastic waste from the maritime industry, thereby substituting virgin plastic production in the appendix for site-specific data). Subsequently, plastic is substituted through Exiobase process - 60 Re-processing of secondary plastic into new plastic {DK}, an intermediate process which accounts for material loss, and extrusion during the recycling process of plastic, see Table 5.18 .

Activities	Unit	Normalized Value	Adjusted Value	LCI data
RF	$MEUR_{2018}$	0.92	1	
FU fulfilled	$MEUR_{2018}$	0.92	1	
IS Exchanges				
Waste, plastic	ton/ton	0.00E+00	4.45E+02	1B_Waste Plastic

Table 5.18: Disaggregated process based on generic Exiobase process: 94 Recycling of waste and scrap {DK}.

5.2.7 Nordjylland Dairy

Nordjylland Dairy is a producer of dairy products classified under the Exiobase process - 40 Processing of dairy products {DK}. Nordjylland Dairy has a symbiotic exchange where excess heat is fed into the local district heating network. Note that the specific amount is a proxy value. As displayed by Table 5.19 no disaggregation except coupling of the substitution flow has been performed utilizing the marginal supply for district heat, as described in Section 5.13.

Activities	Unit	Normalized Value	Adjusted Value	LCI data
RF	MEUR2018	0.92	1	
FU fulfilled	ton 56.77		52.47	
IS Exchanges				
Heat	TJ/MEUR2018	0.00E+00	1.19E-03	0A_District Heating

Table 5.19: Disaggregated process based on generic Exiobase process: 40 Processing of dairy products {DK}

Chapter 6

Life Cycle Impact Assessment Methodology (LCIA)

After the LCI is constructed, the next step is creating the life cycle impact assessment (LCIA). This is done by initially classifying the results to the selected impact categories and subsequently calculating the indicator results before converting the indicators with a weighting factor ISO (2006a). The LCIA has multiple purposes for the study. It will interpret the results of the LCA to outline the environmental performance and improvement potential of ISN and GRØN as described in the research design within Section 2. Moreover, the LCIA will interpret whether the LCI can fulfill the conditions set in the goal and scope for the study as described in Section 4.1.

6.1 Characterization

To characterize the impact categories, the Stepwise2006 v.1.7 method is applied. Stepwise2006 is an amalgamation of the methodologies Impact 2002+ and EDIP 2003, with modifications and additional impact categories not included within the methodologies above Weidema et al. (2008). Consequently, the method is utilized to calculate physical midpoint values in the same unit within the following impact categories of Table 6.1.

Impact Category	Unit	Description
Acidification	M^2 UES	Acidification of water and soil from releases of nitrogen- and sulphur oxides. Expressed as area (m2) of unprotected ecosystem (UES)
Terrestrial and aquatic ecotoxicity	Kg TEG-eq s	Impact on land and in water organisms when emissions of toxic substances occur. Expressed as kg of triethylene glycol (TEG) equivalent (eq)
Aquatic eutrophication	kg NO_3-eq	Nutritional elements in water due to emissions of nitrogen or phosphor. Expressed as kg NO_2 equivalents (eq).
Terrestrial eutrophication	M^2 UES	Nutritional elements to land due to emissions of nitrogen or phosphor. Expressed as m^2 of unprotected ecosystem (UES)
Global Warming	Kg CO_2-eq	Potential for global warming from GHG emissions over 100 years. Expressed as kg CO_2-equivalent (eq). Impacts are divided between fossil and non-fossil

(Continued on next page)

Table 6.1: Overview of Impact Categories in Stepwise2006 together with each of the units and a description of the categories (Hauschild and Potting 2000; Jolliet et al. 2003; Weidema et al. 2008)

Impact Category	Unit	Description
Human toxicity	Kg C_2H_3CL-eq	Potential harm to humans due to chemicals released into the environment. Expressed as chloroethylene equivalents emitted to air, which are divided between carcinogens and non-carcinogens.
Ionizing radiation	Bq C-14-eq	Potential harm to humans from radiation. Expressed as Bq-equivalents of carbon-14 emitted to air.
Mineral Extraction	MJ extra	Additional energy consumption expressed as MJ.
Nature Occupation	PDF*m^2a a	Impact of nature displacement due to human land occupation. Expressed as the occupation of one m^2 arable in one year multiplied with a PDF-score, which is *potentially disappeared fraction* of species during the specific time.
Non-renewable energy	MJ primary	Total use of non-renewable energy from primary sources
Photochemical ozone, vegetat.	m^2*ppm*h	Photochemical ozone formation impacts on vegetation. Expressed as the accumulated exposure (duration times exceedance of threshold) above the threshold of 40 ppb times the area that is exposed as a consequence of the emission
Respiratory Inorganics	Kg PM2.5-eq	Intake fraction of 2.5 micrometer or smaller particles. Expressed as kg PM2.5 equivalents (eq)
Respiratory Organics	pers*ppm*h	Intake of fine particles expressed as the exposure of a person inhaling fine particles in one hour.

Table 6.1: Overview of Impact Categories in Stepwise2006 together with each of the units and a description of the categories (Hauschild and Potting 2000; Jolliet et al. 2003; Weidema et al. 2008) (Continued from last page)

Categories without a characterized impact and no existing link to the LCI (e.g., Injuries, road and work) are omitted from this assessment since the project is exclusively focused on the environmental performance of the product system.

6.2 Applied Weighting

To prioritize impact categories, the results are weighted. Stepwise2006 v1.7 makes it possible to calculate monetary endpoint values by applying a weighting factor. The monetary endpoint in Stepwise2006 is based on Quality Adjusted Life Years (QALY) and is defined as a life-year lived at full well-being. The monetary value of QALY has an upper limit defined by a set budget constraint based on the maximum an average person can pay for an extra life year, this being determined as 74000 EUR2003 Weidema (2009). Therefore, the environmental impact and the subsequent monetary endpoint, ,reflect a change in life-year lived at full well-being, resulting in the loss of potential of economic production due to reduced human health. In this respect, the weighting methodology could be criticized for prioritizing an anthropocentric frame of reference regarding how environmental impacts are perceived while dismissing the inherent value of nature.

6.3 Structure and Interpretation

The impact assessment is structured as a three-step process in which the results of the Reference Baseline Scenario (RBS) and Expanded Network Scenario (ENS) are presented. It should be noted that while the ENS is considered an extension of the pre-existing baseline, the two IS networks are analyzed individually instead of comparatively. The potential is therefore not evaluated until the end of Chapter 7. This shift is because the net turnover is significantly lower for entities within the ENS. Comparing the RBS to an expanded network containing both entities from ISN and GRØN would hence prove problematic in terms of visualization, thereby impairing the interpretation. The LCIA is structured as such:

1) Characterization: Results are presented for both the RBS and ENS concerning the impact categories of Stepwise2006 v1.7 (See Table 6.1)

2) Weighting: Results are weighted as a single score denoting the monetary endpoint value ($MEUR_{2001}$) to identify which impact categories should be prioritized as KPIs.

3) Contribution: A contribution analysis is conducted for selected impact categories with the goal of highlighting certain entities and symbiotic flow contributions to visualize which entities and flows are hotspots within the IS networks.

The contribution analysis will create a foundation for discussing how IS flows may be optimized or utilized alternatively. As detailed in Section 3.3, the improved LCA model is designed for evaluation of multiple IS taxonomical levels. For this reason, the analysis will concern all three levels by initially examining the whole IS network, subsequently progressing to the individual entities and flows.

The benefit of how the LCI adheres to the IS taxonomy (See Figure 3.5) is the possibility to identify relevant characterizations on different levels within the IS taxonomy. Individual characterizations for the network itself, entities, or flows can be determined depending on the object of interest. Thus, the system can scope the assessment to a desired taxonomic level. The network results are significantly influenced by the share of turnover reported for each entity for the characterization. For reporting, it can hence be argued that, it is more beneficial to evaluate the characterized results on an entity level, comparing the environmental performance of each entity to itself. Conversely, the weighting is performed on a network level, while the contribution analysis explores both entity performance and individual flows. This provides improved insight when comparing different symbiotic exchanges between independent entities in the system. The results of the LCIA will therefore be presented at different taxonomic levels, each providing different assessment opportunities.

Network: Assessing the results on a network level contributes to different perspectives when evaluating the system's overall environmental performance. It is an opportunity to assess potential symbiotic exchanges from a system perspective that provides the information needed to prioritize efforts where the largest benefits are identified. Secondly, a weighting of the characterized results of the system helps identify impact categories that are the most influencing on the results. These can be determined as KPIs to evaluate the system performance on other taxonomic levels. Lastly, the network level estimates the total avoided impacts within the system. This is beneficial for PARD as it can potentially be part of future reporting purposes.

Entity: Assessing the results at an entity level can provide different benefits to the assessment than the network level when tracking environmental performance over time. Because the network level is based on a shared contribution from all included entities based on financial turnover, the network level is significantly influenced by the annual activity of each entity. If a comparison of environmental performance within different years were to occur, the results would presumably differ due to variations in contribution from each entity rather than changes to activity data in the symbiotic exchanges. Hence, the entity level allows for characterizing each company's environmental performance for both 1 $MEUR_{2018}$ and the main product or service provided. This allows for a comparison of the performance of each entity individually over time.

Flow: Assessing results on a flow level offers the possibility of evaluating the environmental performance and impacts on an individual flow basis. Furthermore, it can provide insight into how specific flows might be utilized alternatively, depending on exchange amount and performance. It is possible to identify which flows contribute to avoided impacts in companies and evaluate future potential symbiotic exchanges.

Results

Chapter 7

Life Cycle Impact Assessment

Based on the methodology detailed in Chapter 6, the following chapter intends to present the results of the LCA model utilized in assessing the environmental performance and improvement potential of ISN and the GRØN project. As described in Section 6.3 the LCIA will be presented as a three-step process:

1. Characterization
2. Weighting
3. Contribution Analysis

7.1 Characterized Results

To assess the environmental performance, the first part of the LCIA intends to establish a baseline for the environmental performance of the ISN network based on the characterization of Stepwise2006 v.1.7. The current symbiotic reference scenario (CNRS) represents the baseline environmental performance. Hereafter, the Expanded Network Scenario (ENS) for GRØN is characterized in two parts: (i) A business-as-usual (BaU) scenario for GRØN (GBS) is presented as a current non-symbiotic reference scenario (CNSRS). (ii) The implementation of planned symbiotic exchanges as a hypothetical symbiotic reference scenario (HSRS).

7.1.1 Reference Baseline (RBS)

Table 7.1 displays the environmental impacts of ISN emitted by each entity on a network level as well as the sum for the entirety of ISN. Multiplying the sum of results by the total turnover of ISN (725 $MEUR_{2018}$) would hence yield the sum of emissions of the entire network for the year 2018. As the ISN network already has pre-established symbiotic exchanges, these effects are included within the results by default. The purpose of the characterization is to create a baseline accounting of environmental impacts as a foundation for future tracking of performance in the system.

As presented by Table 7.1, Aalborg Portland A/S, Nordjylland Power Station (NPS), I/S Reno Nord, and Alfa Laval AB generally display elevated emissions in several impact categories such as global warming, ecotoxicity, respiratory inorganics, and human toxicity. Conversely, the avoided nature occupation for I/S Reno Nord can be prescribed to substituting heat and electricity from symbiotic exchanges, which relies on a significant amount of biomass as a marginal market mix. Concerning the elevated emissions of the four entities above, it can be attributed to two causes: (i) The use of fossil fuels notably driven by incineration of coal. (ii) The monetary distribution of net turnover within the IS network. As detailed in Section 6.3 the individual entity share of the total network turnover mathematically functions as a weighted average when applying the functional unit at the network level.

Category	Unit	Total (RBS)	Aalborg Portland	NPS	Alfa Laval	Colas	Crematorium	Farms in Vodskov	Port of Aalborg	Aalborg Kloak	Reno Nord
Acidification	m^2 UES	2.22E+05	1.44E+05	2.06E+04	2.68E+04	1.52E+04	1.25E+02	2.42E+03	2.42E+03	1.36E+03	9.53E+03
Ecotoxicity, aquatic	kg TEG-eq	5.09E+06	3.18E+06	4.04E+05	9.32E+05	2.82E+05	1.68E+03	8.05E+03	8.05E+03	2.31E+04	2.15E+05
Ecotoxicity, terrestrial	kg TEG-eq	1.02E+07	5.33E+06	1.01E+06	3.23E+06	4.59E+05	3.52E+03	1.81E+04	1.81E+04	4.63E+04	2.39E+04
Eutrophication, aquatic	kg NO_3-eq	2.80E+03	1.28E+03	8.94E+02	4.04E+02	1.47E+02	6.18E+00	2.74E+02	2.74E+02	1.54E+01	-2.41E+02
Eutrophication, terrestrial	m^2 UES	3.90E+05	2.42E+05	3.19E+04	6.31E+04	3.07E+04	3.08E+02	1.01E+04	1.01E+04	2.67E+03	6.61E+03
Global warming, fossil	kg CO_2-eq	9.24E+06	3.97E+06	1.96E+06	2.67E+06	2.76E+05	2.56E+03	8.67E+03	8.67E+03	1.03E+04	3.36E+05
Global warming, non-fossil	kg CO_2-eq	-2.39E+05	-2.03E+05	-5.14E+04	-5.54E+04	-1.54E+04	-1.71E+03	-3.78E+04	-3.78E+04	3.95E+02	1.31E+05
Human toxicity, carcinogens	kg C_2H_3Cl-eq	1.39E+05	2.08E+04	4.19E+03	1.26E+04	1.72E+03	2.28E+01	7.91E+01	7.91E+01	1.91E+02	9.84E+04
Human toxicity, non-carc.	kg C_2H_3Cl-eq	5.10E+05	9.04E+03	4.12E+03	7.79E+03	8.19E+02	2.07E+01	3.91E+01	3.91E+01	9.91E+01	4.87E+05
Mineral extraction	MJ extra	4.23E+03	1.60E+03	3.55E+02	1.85E+03	1.32E+02	1.95E+00	6.74E+00	6.74E+00	1.77E+01	2.04E+02
Nature occupation	PDF*m^2a	5.29E+04	1.70E+04	2.64E+04	7.43E+03	2.16E+03	1.14E+02	1.06E+04	1.06E+04	2.64E+02	-1.17E+04
Non-renewable energy	MJ primary	4.54E+07	2.57E+07	1.49E+07	1.74E+06	1.75E+06	3.94E+04	3.96E+04	3.96E+04	9.92E+04	9.83E+05
Photochemical ozone, vegetat.	m^2*ppm*hours	2.80E+07	1.76E+07	3.05E+06	4.57E+06	1.73E+06	1.01E+04	3.32E+04	3.32E+04	9.04E+04	8.03E+05
Respiratory inorganics	kg $PM_{2.5}$-eq	5.77E+03	4.24E+03	2.86E+02	4.36E+02	6.29E+02	1.39E+00	1.59E+01	1.59E+01	1.40E+01	1.17E+02
Respiratory organics	pers*ppm*h	2.64E+03	1.64E+03	3.41E+02	4.20E+02	1.39E+02	9.72E-01	2.88E+00	2.88E+00	9.24E+00	6.99E+01

Table 7.1: Network Level: Characterized LCIA results per 1 $MEUR_{2018}$ of net turnover for the Reference Baseline Scenario (RBS)

Table 7.2 provides an overview of the relative distribution of net turnover among entities in the Reference Baseline Scenario (RBS). As displayed in the table, the entities mentioned above with higher impacts are simultaneously responsible for the ISN network's most significant share of net turnover. In total, the four entities, Aalborg Portland A/S, NPS, Alfa Laval AB, and Colas A/S, account for almost 90% of the total net turnover of the network. For this reason, environmental impacts will innately shift towards these entities when applying the functional unit at a network level.

ISN Entity	Unit	Net Turnover	Share (%)
Aalborg Portland A/S	$MEUR_{2018}$	244.1	36.65%
Alfa Laval AB	$MEUR_{2018}$	130.5	17.99%
Nordjylland Power Station (NPS)	$MEUR_{2018}$	128.6	17.73%
Colas A/S	$MEUR_{2018}$	115.1	15.87%
Reno Nord I/S	$MEUR_{2018}$	38.3	5.28%
Aalborg Kloak A/S	$MEUR_{2018}$	36.5	5.03%
Port of Aalborg A/S	$MEUR_{2018}$	26.7	3.68%
Farms in Vodskov	$MEUR_{2018}$	3.6	0.49%
Aalborg Crematorium	$MEUR_{2018}$	2.0	0.28%
Total	**$MEUR_{2018}$**	**725.4**	**100%**

Table 7.2: Distribution of net turnover ($MEUR_{2018}$) among entities within the ISN Network

It should therefore be recognized that while applying a network perspective based on the share of net turnover is practical when assessing the performance of an entire IS network, it potentially impairs results for yearly reporting if the net turnover of entities experiences significant fluctuation. Because of this, one may alternatively report the environmental performance at an entity level by applying the functional unit of 1 $MEUR_{2018}$ for each entity. Table 7.3 provides an overview of environmental impacts for each entity per 1 $MEUR_{2018}$. The LCI file in the external appendix allows for updates to activity data in the network each year. With a common reporting unit set to 1 $MEUR_{2018}$ it is hence possible to compare performance between different years. As displayed by Table 7.3, entities involved in production utilizing fossil fuels has an elevated environmental impact compared to entities providing services. Furthermore, since all entities are scaled relative to an identical economic net turnover, it is possible to compare their respective environmental performance directly. In this regard, Table 7.3 illustrates both the functionality of building an LCI model capable of assessing multiple IS taxonomy levels and how one may utilize it for yearly reporting in the future to come.

Category	Unit	Aalborg Portland	NPS	Alfa Laval	Colas	Crematorium	Farms in Vodskov	Port of Aalborg	Aalborg Kloak	Reno Nord
Acidification	m^2 UES	2.22E+05	1.44E+05	2.06E+04	2.68E+04	1.52E+04	1.25E+02	2.42E+03	2.42E+03	1.36E+03
Ecotoxicity, aquatic	kg TEG-eq	5.09E+06	3.18E+06	4.04E+05	9.32E+05	2.82E+05	1.68E+03	8.05E+03	8.05E+03	2.31E+04
Ecotoxicity, terrestrial	kg TEG-eq	1.02E+07	5.33E+06	1.01E+06	3.23E+06	4.59E+05	3.52E+03	1.81E+04	1.81E+04	4.63E+04
Eutrophication, aquatic	kg NO_3-eq	2.80E+03	1.28E+03	8.94E+02	4.04E+02	1.47E+02	6.18E+00	2.74E+02	2.74E+02	1.54E+01
Eutrophication, terrestrial	m^2 UES	3.90E+05	2.42E+05	3.19E+04	6.31E+04	3.07E+04	3.08E+02	1.01E+04	1.01E+04	2.67E+03
Global warming, fossil	kg CO_2-eq	9.24E+06	3.97E+06	1.96E+06	2.67E+06	2.76E+05	2.56E+03	8.67E+03	8.67E+03	1.03E+04
Global warming, non-fossil	kg CO_2-eq	-2.39E+05	-2.03E+05	-5.14E+04	-5.54E+04	-1.54E+04	-1.71E+03	-3.78E+04	-3.78E+04	3.95E+02
Human toxicity, carcinogens	kg C_2H_3Cl-eq	1.39E+05	2.08E+04	4.19E+03	1.26E+04	1.72E+03	2.28E+01	7.91E+01	7.91E+01	1.91E+02
Human toxicity, non-carc.	kg C_2H_3Cl-eq	5.10E+05	9.04E+03	4.12E+03	7.79E+03	8.19E+02	2.07E+01	3.91E+01	3.91E+01	9.91E+01
Mineral extraction	MJ extra	4.23E+03	1.60E+03	3.55E+02	1.85E+03	1.32E+02	1.95E+00	6.74E+00	6.74E+00	1.77E+01
Nature occupation	PDF*m^2a	5.29E+04	1.70E+04	2.64E+04	7.43E+03	2.16E+03	1.14E+02	1.06E+04	1.06E+04	2.64E+02
Non-renewable energy	MJ primary	4.54E+07	2.57E+07	1.49E+07	1.74E+06	1.75E+06	3.94E+04	3.96E+04	3.96E+04	9.92E+04
Photochemical ozone, vegetat.	m^2*ppm*hours	2.80E+07	1.76E+07	3.05E+06	4.57E+06	1.73E+06	1.01E+04	3.32E+04	3.32E+04	9.04E+04
Respiratory inorganics	kg $PM_{2.5}$-eq	5.77E+03	4.24E+03	2.86E+02	4.36E+02	6.29E+02	1.39E+00	1.59E+01	1.59E+01	1.40E+01
Respiratory organics	pers*ppm*h	2.64E+03	1.64E+03	3.41E+02	4.20E+02	1.39E+02	9.72E-01	2.88E+00	2.88E+00	9.24E+00

Table 7.3: Entity Level: Characterized LCIA results per 1 $MEUR_{2018}$ of net turnover for each entity in the Reference Baseline Scenario (RBS)

7.1.2 Expanded Network Scenario (ENS)

Table 7.4 presents the categorized impacts, as well as differences made for the two scenarios assessed in GRØN. The negative differences between the scenarios are then the beneficial environmental effects of implementing the symbiotic exchanges to the GRØN network. Thus, the symbiotic scenario proves a reduction potential in most categorized emissions.

Category	**Unit**	**GRØN Baseline** (CNSRS)	**GRØN Symbiotic** (HSRS)	**Difference** (±)	**Change** (%)
Acidification	m^2 UES	2.02E+05	1.95E+05	-6.81E+03	-3.4%
Ecotoxicity, aquatic	kg TEG-eq	7.46E+05	6.10E+05	-1.36E+05	-18.2%
Ecotoxicity, terrestrial	kg TEG-eq	1.72E+06	1.50E+06	-2.22E+05	-12.9%
Eutrophication, aquatic	kg NO_3-eq	1.90E+04	1.90E+04	-5.89E+01	-0.3%
Eutrophication, terrestrial	m^2 UES	8.42E+05	8.30E+05	-1.19E+04	-1.4%
Global warming, fossil	kg CO_2-eq	6.39E+05	5.90E+05	-4.89E+04	-7.7%
Global warming, non-fossil	kg CO_2-eq	-1.38E+06	-1.38E+06	-7.92E+03	0.6%
Human toxicity, carcinogens	kg C_2H_3Cl-eq	1.15E+04	8.16E+03	-3.31E+03	-28.9%
Human toxicity, non-carc.	kg C_2H_3Cl-eq	2.42E+04	1.02E+04	-1.40E+04	-57.9%
Mineral extraction	MJ extra	7.23E+02	6.83E+02	-3.99E+01	-5.5%
Nature occupation	PDF*m^2a	2.36E+05	2.35E+05	-9.47E+02	-0.4%
Non-renewable energy	MJ primary	2.82E+06	2.08E+06	-7.34E+05	-26.1%
Photochemical ozone, vegetat.	m^2*ppm*hours	8.17E+06	7.52E+06	-6.44E+05	-7.9%
Respiratory inorganics	kg $PM_{2.5}$-eq	1.36E+03	1.27E+03	-8.72E+01	-6.4%
Respiratory organics	pers*ppm*h	7.40E+02	6.77E+02	-6.27E+01	-8.5%

Table 7.4: Network Level: Characterized LCIA results per 1 $MEUR_{2018}$ of net turnover for the CNSRS and HNSRS for GRØN (ENS) by utilizing Stepwise2006 v1.7

However, the impact categories are influenced differently by the implementation of the symbiotic exchanges, and a weighted assessment of the characterization will be carried out to identify KPIs representing the effects of implementing the symbiotic exchanges. The purpose is that by identifying relevant KPIs, future reporting of environmental performance will be more targeted in accordance with the production of the select entity. Much more than generalizing KPIs on a network basis which is inhabited by a variety of different production entities.

7.2 Weighting

The weighted single-score results from Stepwise2006 v.1.7. is presented to identify possible KPIs for future environmental performance reporting at ISN. It is important to note that determining relevant KPIs based on weighting impact relies on the weighting methodology utilized. In the case of Stepwise2006, a significant focus is put on impacts affecting QALY (see Figure 6.2).

Figure 7.1 visualize the weighted results of the ISN network, which is predominantly occupied by the more prominent entities, such as Aalborg Portland A/S, Colas A/S, I/S Reno Nord, Alfa Laval AB, and Nordjylland Power Station (NPS). Consequently, these entities, except for NPS, all correspond in terms of weighted impact for Respiratory, inorganics, and Global warming, fossil, a trend corresponding to the production activity of the entity per 1 $MEUR_{2018}$. Additionally, I/S Reno Nord is the primary contributor to Human toxicity, carcinogenic and non-carcinogenic. However, this is considered inconsequential as the weighted impact is tied to the municipal incineration of waste and, therefore, not suitable to base symbiotic KPIs on as the municipal waste incineration is not considered a symbiotic exchange.

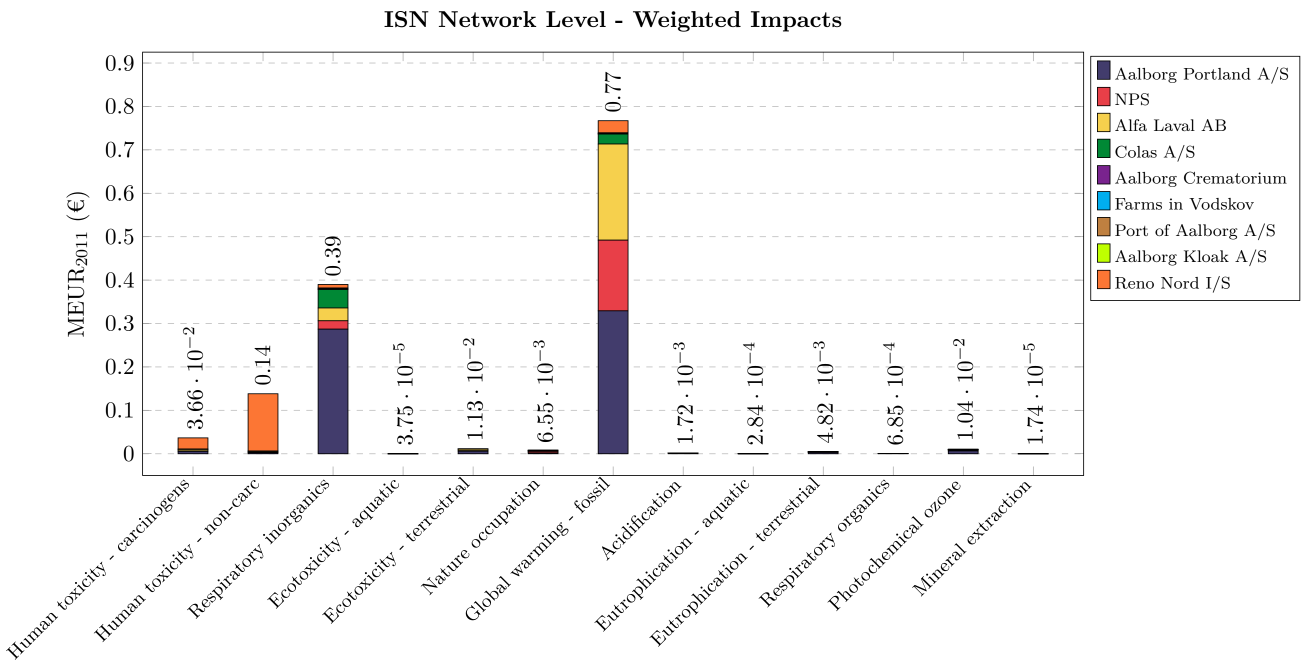


Figure 7.1: Weighted Impacts of the ISN Network per 1 $MEUR_{2018}$ of Net Turnover utilizing Stepwise2006 v1.7

Figure 7.2 presents the weighting of the GRØN symbiotic expansion scenario. The weighting within this scenario mirrors ISN in the presence of Global warming, fossil, and Respiratory, inorganics. Additionally, the impact categories for nature occupation, eutrophication, and terrestrial are present. However, these are largely attributed to milk production through Nordjylland Dairy and, therefore, are not considered a relevant, measurable KPI as these categories are not affected by the symbiotic exchanges facilitated through GRØN.

Grøn Network Level - Weighted Impacts

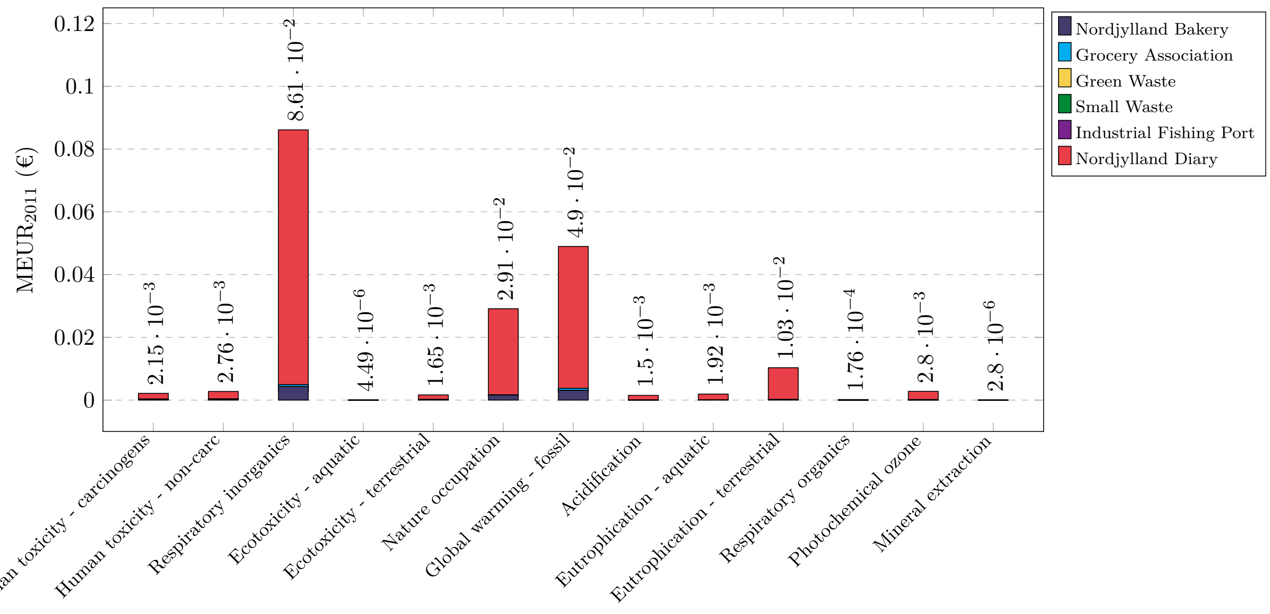


Figure 7.2: Weighted Impacts of the GRØN Network per 1 MEUR_{2018} of Net Turnover utilizing Stepwise2006 v1.7

Two relevant KPIs: Global warming and respiratory inorganics, are hence identified based on their categorized weighting presence within the two systems. This can be attributed due to Stepwise2006 v.1.7. weighting factor which favors impacts affecting human health and the subsequent loss of production as initially described in Section 6. Consequently, determining KPIs based on this approach should be performed and prioritized on a case-by-case basis as the relevance of specific impact categories may differ depending on the studied network, entities, and IS exchanges. For an IS network containing significant exchanges to the supply of district heating (i.e., as in the case of ISN), it is, therefore, logical to evaluate the impact categories most affected by the use of fossil fuels.

7.3 Contribution Analysis

This chapter will present a contribution assessment on the entities and flows present in ISN and GRØN based on the characterized results identified in Section 7.2 – Global warming potential (GWP) and respiratory inorganics (PM). The assessment conducted is in reference to the reporting unit of 1 MEUR_{2018} of net turnover at the network level. In this regard, the purpose is to identify significant hotspots within the two systems and assess whether the environmental potential of the current symbiotic flows is realized optimally. The IS taxonomy levels are examined to interpret the environmental performance of both the network, each individual entity, and the symbiotic exchanges. The contribution analysis will hence follow a top-down structure as such:

1. Performance of each entity at a network level
2. Performance of IS exchanges categorized by entity
3. Performance of IS exchanges categorized by material/energy

7.3.1 Reference Baseline Scenario (RBS)

Figure 7.3 assess the global warming potential (GWP) for the entities partaking in the ISN Network. Consequently, the results demonstrate a total output of 9,149 ton CO_2-eq per 1 $MEUR_{2018}$ for the ISN network, totaling 6,636,656 ton CO_2-eq when factoring in the turnover of the ISN network in 2018 at 725 $MEUR_{2018}$.

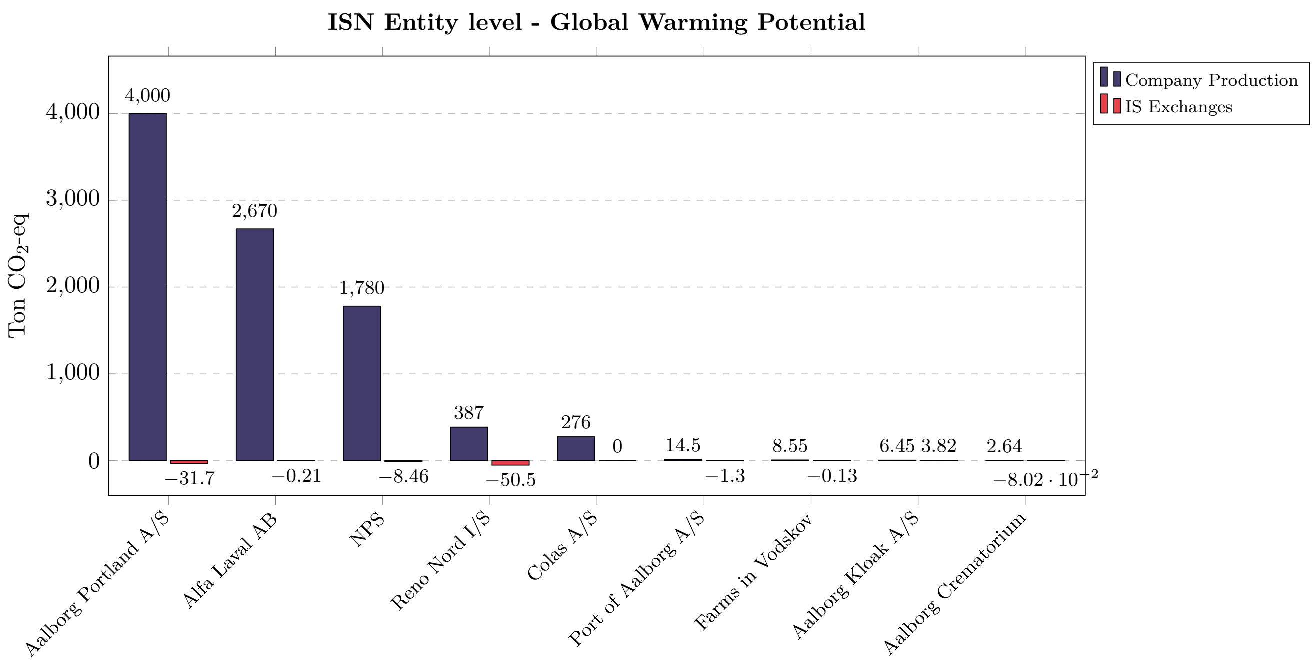


Figure 7.3: Global warming potential for entities within the ISN Network per 1 $MEUR_{2018}$ of net turnover

High emissions are primarily attributed to the larger producing entities (i.e., Aalborg Portland, Alfa Laval, and NPS), characterized by a high production output in relation to turnover. In contrast, the service-oriented entities and smaller producing entities demonstrate a lesser presence due to both the limited nature of the symbiotic exchanges facilitated by these and the low economic and production activity. Furthermore, the results indicate that the avoided emissions are relatively small compared to the general emissions from the network. Subsequently, this is explored in Figure 7.3, which presents the avoided emissions credited to the symbiotic exchanges for the individual entities, reported in ton CO_2-eq per 1 $MEUR_{2018}$ of net turnover.

In total, 92.38 tonnes of CO_2-eq is avoided per 1 $MEUR_{2018}$ of turnover, through the facilitation of the symbiotic exchanges within ISN, as seen in Figure 7.4. When applying the full turnover, the total avoided GWP emissions culminate in 67,013 ton CO_2-eq. Thus, the total avoided GWP corresponds to approximately 1% of the total GWP emissions within ISN.

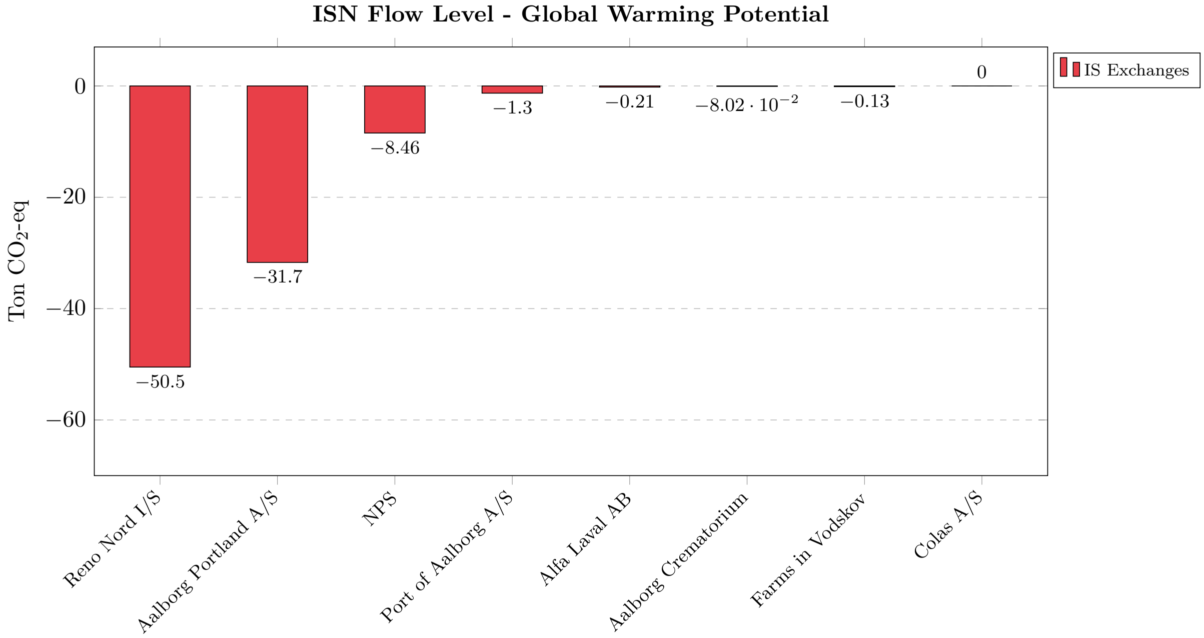


Figure 7.4: Global warming potential for IS exchanges within the ISN Network per 1 $MEUR_{2018}$ net turnover

Furthermore, Figure 7.4 gives insight to the share of avoided GWP contributed by each entity. I/S Reno Nord holds the largest share of avoided GWP, with Aalborg Portland A/S second. Aalborg Kloak A/S' symbiotic exchange of dry sludge to biogas contributes to GWP emissions. Figure 7.5 presents the avoided emissions of the entities concerning the symbiotic flow type.

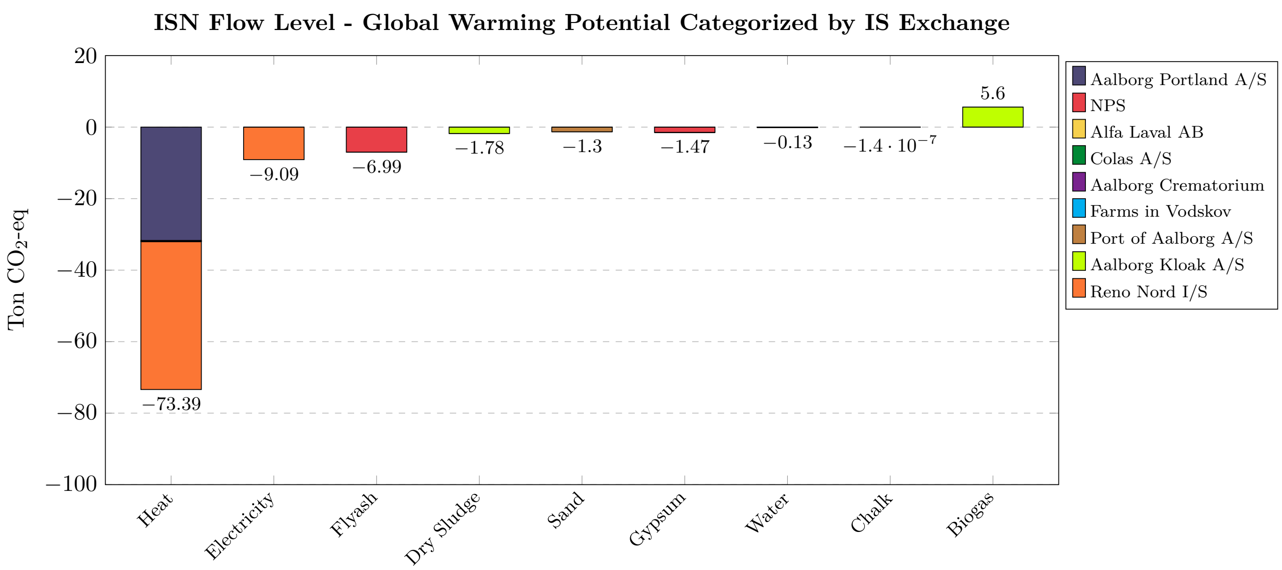


Figure 7.5: Global warming potential categorized by the type of IS exchange within the ISN network

Heat and electricity are the most prominent and account for approximately 79% and 10% of the avoided GWP emissions per 1 $MEUR_{2018}$ in the current iteration of the ISN network. This is attributed to the fact that the majority of IS exchanges consist of these flows. Conversely, the symbiotic flow for biogas by Aalborg Kloak A/S contributes to GWP and impedes any avoided emissions associated with it. This counter-intuitive outcome is linked to high slippage of methane in the biogasification process, which culminates in a total contribution of 4,062 tonnes of CO_2-eq emissions on the network level. Moreover, the symbiotic exchanges of chalk provide no significant avoided emissions, accounting for 1.05 kg CO_2 when applying the network turnover. Nevertheless, seemingly insignificant impacts derived from, i.e., gypsum, lead to the avoided emissions of 1,066 tonnes of CO_2.

Figure 7.6 assess the particulate matter ($PM_{2.5\text{-eq}}$) emissions for ISN, which results in an output of 5,621 kg $PM_{2.5\text{-eq}}$ per 1 $MEUR_{2018}$. This totals to 4,077,452 kg $PM_{2.5\text{-eq}}$ emissions on the network level when applying the network turnover. The outcome is that Aalborg Portland A/S accounts for ≈76% of the total $PM_{2.5\text{-eq}}$ emissions, a result correlated to a high production volume per 1 $MEUR_{2018}$ as described in the GWP results for Figure 7.3. Further of note is the abnormally low emissions of particulate matter by NPS. In part, this can be attributed to the substitution of electricity associated with the co-production of the CHP plant. Further analysis has shown that both the generic product market for coal in Exiobase as well as the custom marginal mix display significantly lower emissions (by a factor of ≈8) compared to that of alternative databases (i.e., Ecoinvent 3.8).

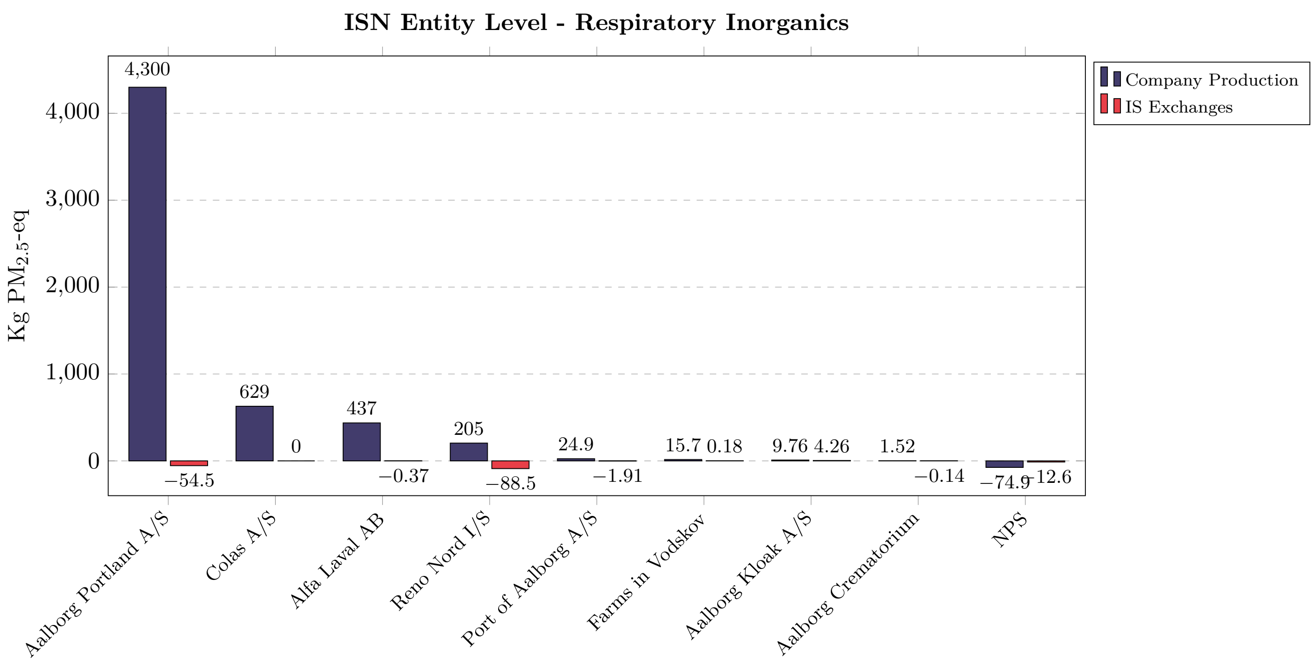


Figure 7.6: Respiratory inorganics from entities within the ISN Network per 1 $MEUR_{2018}$ of net turnover

The avoided emissions of PM presented in Figure 7.7 show similar tendencies to those presented for the GWP, in how I/S Reno Nord and Aalborg Portland A/S' symbiotic exchanges account for ≈90% of the collective avoided $PM_{2.5\text{-eq}}$ emissions. Consequently, 158 kg $PM_{2.5\text{-eq}}$ per 1 $MEUR_{2018}$ is avoided, totaling 114,758 kg $PM_{2.5\text{-eq}}$ of avoided emissions on a network level. Subsequently, these avoided emissions constitute to 2.8% of the total $PM_{2.5\text{-eq}}$ emissions within ISN.

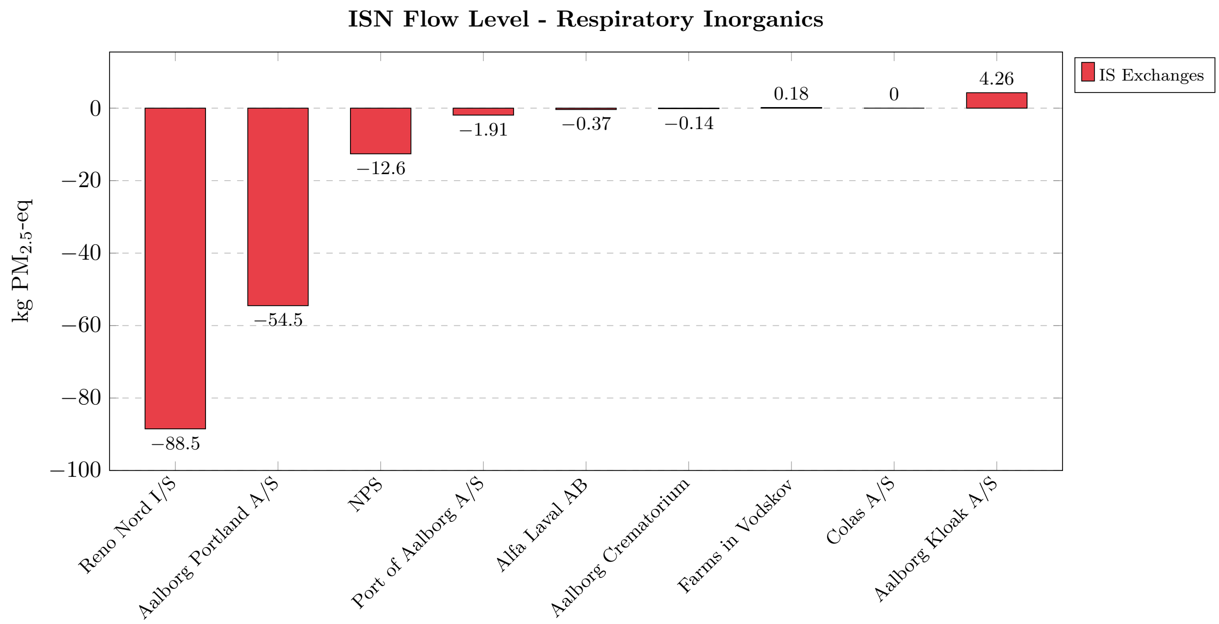


Figure 7.7: Respiratory inorganics from IS exchanges within the ISN Network per 1 MEUR_{2018} of net turnover

The breakdown of IS exchanges concerning PM is presented in Figure 7.8, which accumulates the avoided emissions of the entities in relation to the symbiotic flow type. The avoided impact linked with the heat and electricity production at I/S Reno Nord and Aalborg Portland A/S is once again emphasized.

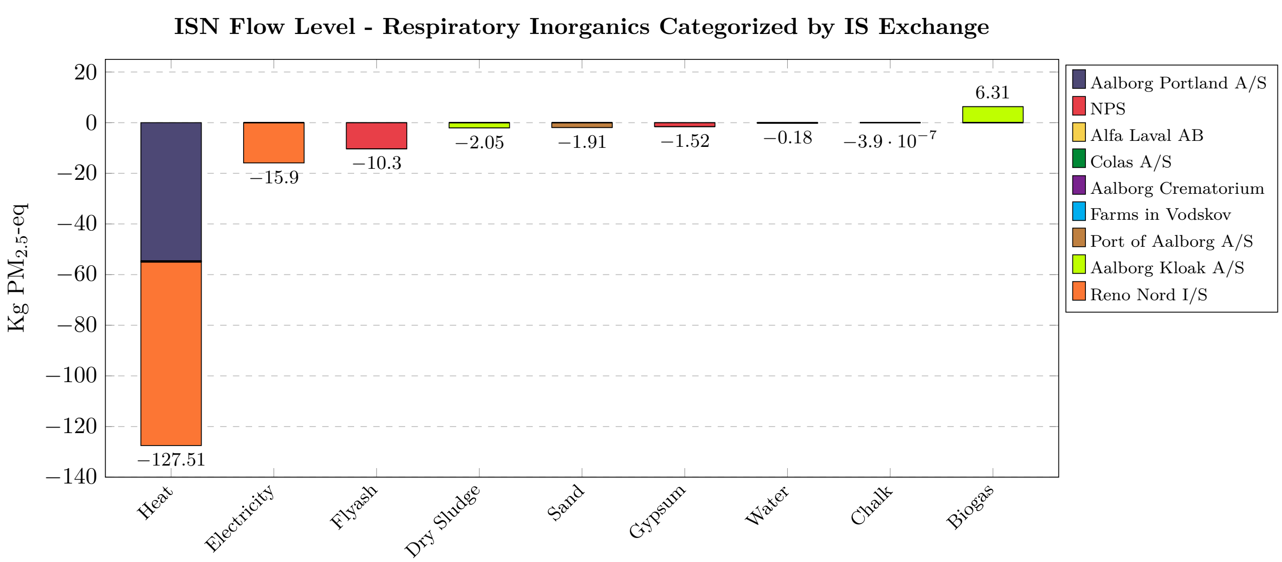


Figure 7.8: Respiratory inorganics categorized by the type of IS exchange within the ISN Network

Moreover, biogas is considered more sensitive in regards to $PM_{2.5\text{-eq}}$ relative to its GWP counterpart, contributing 4,577 kg $PM_{2.5\text{-eq}}$. This is consequently attributed to emissions linked with transport by sea, which has a significant output of $PM_{2.5\text{-eq}}$ due to the dependence on fuel oils. In the same way, fly ash also provide significant avoided emissions at 7,471 kg $PM_{2.5\text{-eq}}$, as the transport facilitating the raw cement production becomes substituted through the production of fly ash to clinker.

7.3.2 Expanded Network Scenario (ENS)

Figure 7.9 presents the GWP for entities within the ENS for the GRØN network on an entity level. This totals 606 tonnes of $CO_{2\text{-eq}}$ per 1 $MEUR_{2018}$ of turnover in 2018 and 41,601 tonnes of $CO_{2\text{-eq}}$ when applying the turnover on a network level. Consequently, Nordjylland Dairy is by far the most significant contributor accounting for ≈93% of emissions per $MEUR_{2018}$ within the ENS. However, It should be noted that not only is this entity much larger than the others, but the symbiotic exchange of heat is based on a proxy due to data constraints and does not reflect the true potential of integrating their excess heat as part of the symbiosis.

Additionally, Green Waste shows significant negated emissions attributed to the substitution of biogasification of organic waste by instead utilizing bio-pulp for the production of insects, thereby substituting nitrogenous fertilizers (N-fertilizer) and animal feed (dried larva). The same can be seen for Small Waste and Industrial Fishing Port (IPF) which are recognized by their limited size, both in terms of service/production output, as well as turnover (0.2 and 0.7 $MEUR_{2018}$ respectively), causing the symbiotic flows of recycling plastic facilitated in these exchanges to have a relatively high impact on the entities environmental performance per 1 $MEUR_{2018}$.

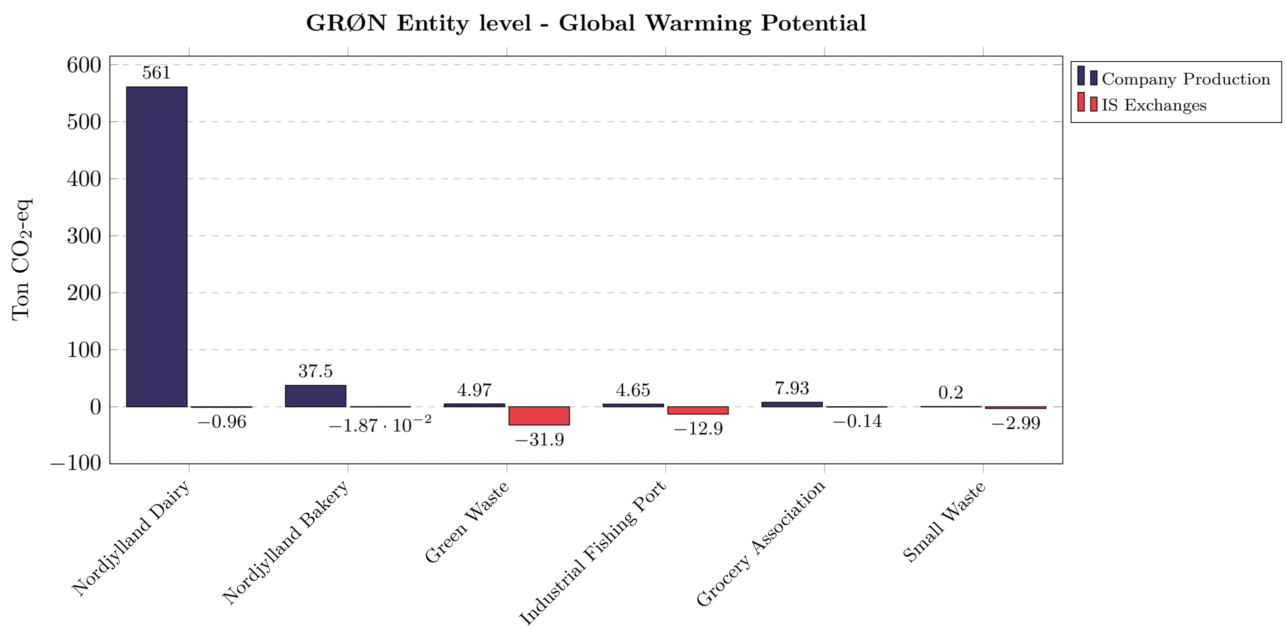


Figure 7.9: Global warming potential for entities within the GRØN Network per 1 $MEUR_{2018}$ of net turnover

Figure 7.10 presents the GWP impact per 1 $MEUR_{2018}$ on a flow level. Emphasized are the entities which account for the most in avoided GWP when applying the network level. Consequently, accrediting avoided emissions to Green Waste at 2,188 tonnes, IPF at 884 tonnes, and Nordjylland Dairy at 65 tonnes of $CO_{2\text{-eq}}$. Additionally, the exchange facilitated by Nordjylland Bakery results in an insignificant avoided GWP impact (≈1.2 ton $CO_{2\text{-eq}}$). Consequently, an insignificant impact is ascribed to the comparatively low volume of grain husks facilitated through the exchange (100 tonnes), which impact is further diminished once the dry matter ratio (0.6) and the substitution ratio of 1/0.3 in which grain husks substitute polystyrene is applied.

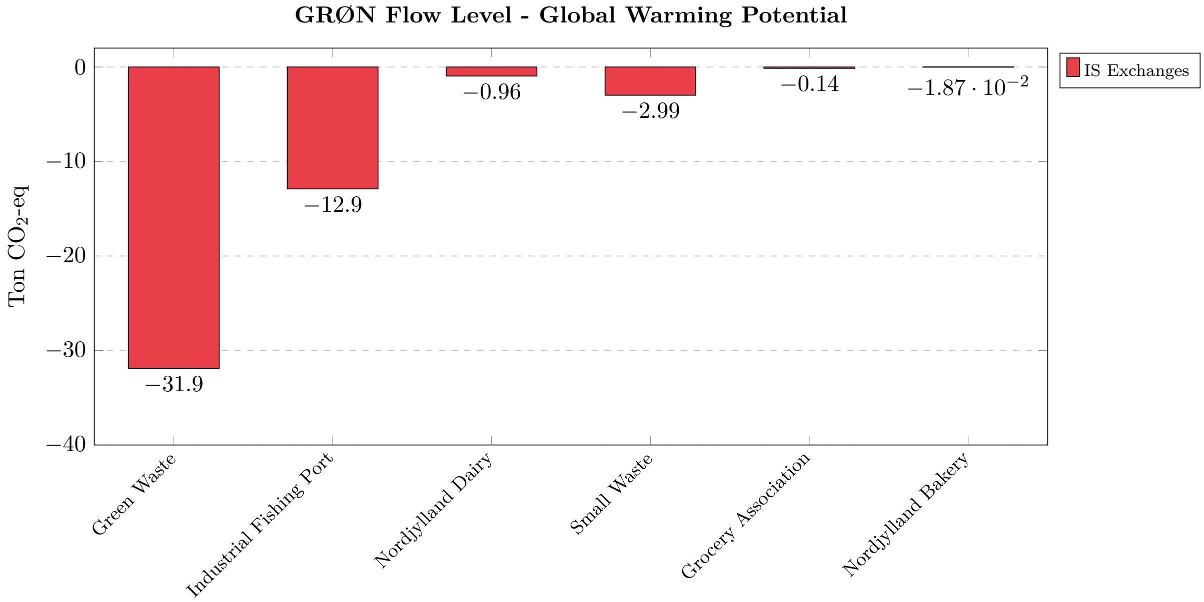


Figure 7.10: Global warming potential for IS exchanges within the GRØN Network per 1 $MEUR_{2018}$ net turnover

Figure 7.11 presents the impact on a flow level per 1 $MEUR_{2018}$. Notably, the avoided emissions associated with the production of insects, which can be attributed to the substituting processes described above. It can be seen that exchanges pertaining to heat are consequently less influential compared to ISN (See Figure 7.8), accounting for ≈13% of the avoided GWP per 1 $MEUR_{2018}$. In this regard, IS exchanges concerning energy prove less significant in reducing emissions on a network level for the GRØN project than that of the ISN baseline.

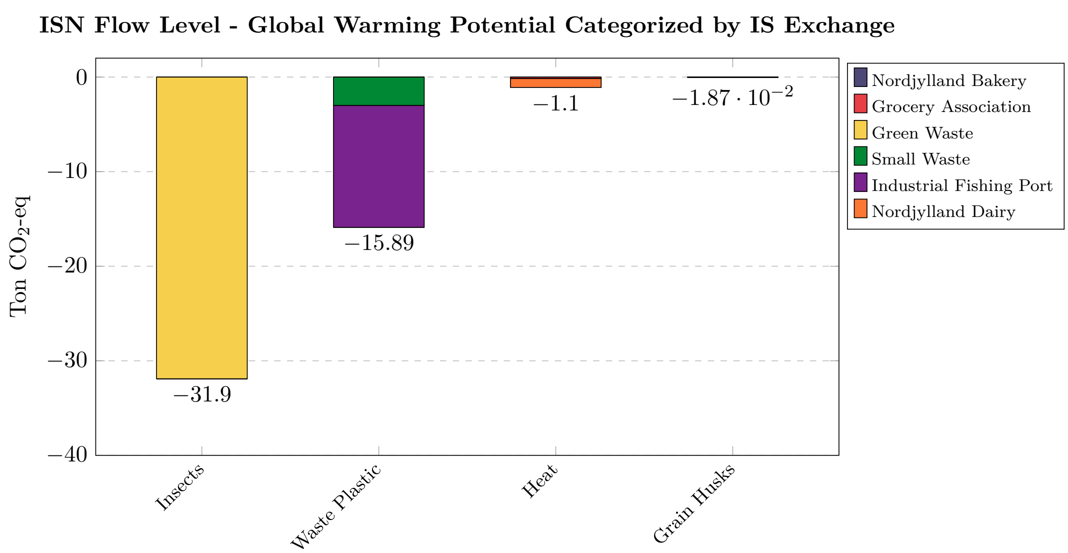


Figure 7.11: Global warming potential categorized by the type of IS exchange within the GRØN network

Figure 7.12 presents the categorized $PM_{2.5\text{-eq}}$ for entities within the GRØN, constituting 1,311 kg $PM_{2.5\text{-eq}}$ per 1 $MEUR_{2018}$, and 89,937 kg $PM_{2.5\text{-eq}}$ on a network level. Consequently, it mirrors the results presented for GWP, relatively according to the size of the entities.

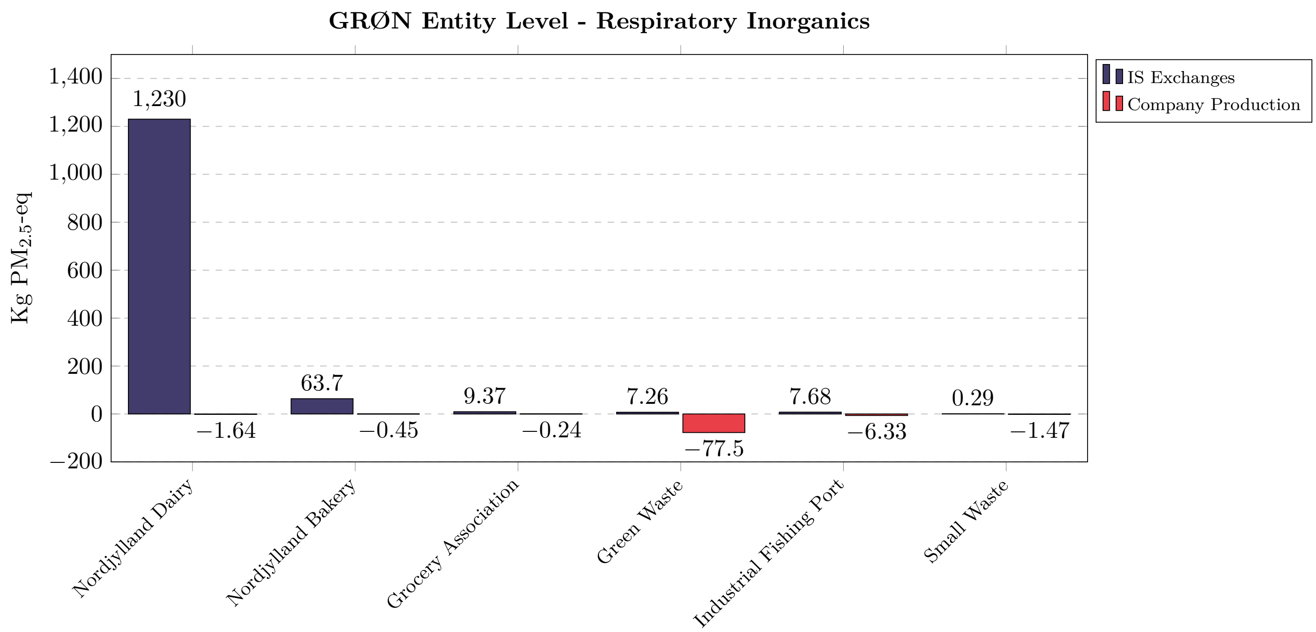


Figure 7.12: Respiratory inorganics from entities within the GRØN Network per 1 $MEUR_{2018}$ of net turnover

Figure 7.13 presents the avoided $PM_{2.5\text{-eq}}$ emissions per 1 $MEUR_{2018}$ on a flow level, totaling to 88 kg of $PM_{2.5\text{-eq}}$ per $MEUR_{2018}$ and 6.01 ton $PM_{2.5\text{-eq}}$ in relation to the total financial network turnover. Here, Green Waste should be emphasized as it contributes to 88% of the avoided emissions. This is primarily linked with the emissions tied to avoided transport by sea, which holds a substantial presence in the subsequent production of animal feed, n-fertilizer, and biogas, which all are substituted through the production of insects.

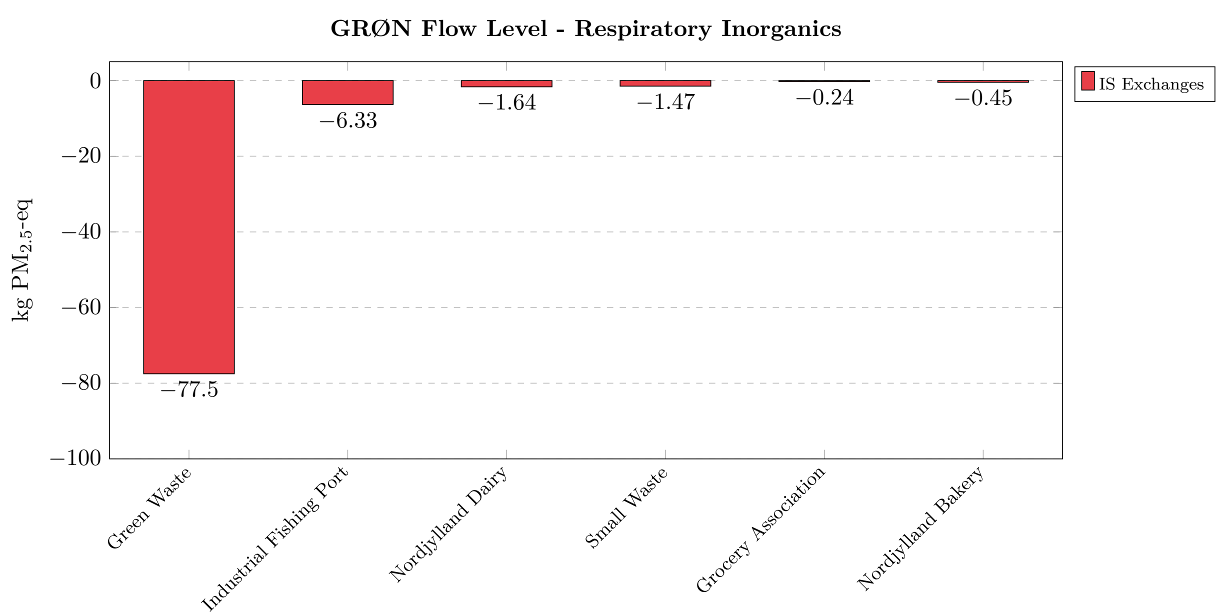


Figure 7.13: Respiratory inorganics from IS exchanges within the GRØN Network per 1 $MEUR_{2018}$ of net turnover

Symbiotic flows pertaining to heat are, as presented in Figure 7.14, of less importance compared to the GWP impact, only accounting for 1.87% of avoided emissions per 1 $MEUR_{2018}$. Additionally, Waste Plastic is attributed to an avoided production of 6.47 kg $PM_{2.5\text{-eq}}$ per 1 $MEUR_{2018}$, with the impact assessed on a network level culminating in around 9% of total avoided emissions within the EMS at 535 kg $PM_{2.5\text{-eq}}$.

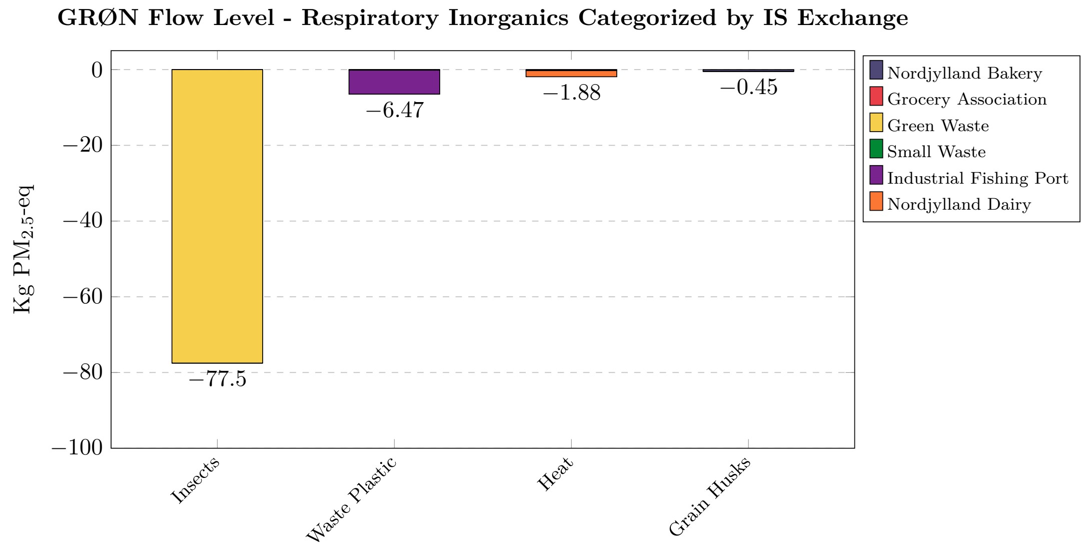


Figure 7.14: Respiratory inorganics categorized by the type of IS exchange within the GRØN Network

7.3.3 Summary of Results

After assessing the potential of GRØN, it becomes apparent that an inherent environmental improvement potential is found through the expansion of the IS network. Table 7.5 and 7.6 summarizes the environmental potential of expanding the ISN network to include the GRØN project. The *baseline* column refers to the sum of emissions from ISN (RBS) and the GRØN baseline scenario (GBS) continuing a business-as-usual production without implementing IS exchanges. Conversely, the column *expanded* presents the total emissions of the reference baseline scenario (RBS) of ISN and the expanded network scenario (ENS) of GRØN.

Category	Unit	Baseline (RBS+GBS)	Expanded (RBS+ENS)	Difference (±)	Change (%)
Company Production	ton CO_2-eq	6.67E+06	6.67E+06	0.00E+00	0.00%
IS Exchanges	ton CO_2-eq	-3.39E+04	-3.73E+04	-3.36E+03	9.89%
Total	ton CO_2-eq	6.63E+06	6.63E+06	-3.36E+03	-0.05%

Table 7.5: Total net emissions and savings for GWP from implementing the IS exchanges of the Grøn Project

Concerning the environmental potentials of GWP derived from incorporating GRØN and its subsequent symbiotic exchanges to ISN, a 9.89% increase in avoided GWP emissions, totaling 3,360 tonnes of CO_2 avoided. In addition, a 5.56% increase in avoided respiratory inorganic emissions, totaling 6.1 tonnes of $PM_{2.5\text{-eq}}$.

Category	Unit	Baseline (RBS+GBS)	Expanded (RBS+ENS)	Difference (±)	Change (%)
Company Production	ton CO_2-eq	4.11E+03	4.11E+03	0.00E+00	0.00%
IS Exchanges	ton CO_2-eq	-1.08E+02	-1.14E+02	-6.01E+00	5.56%
Total	ton CO_2-eq	4.00E+03	4.00E+03	-6.01E+00	-0.15%

Table 7.6: Total net emissions and savings for PM from implementing the IS exchanges of the Grøn Project

Compared to the total emissions of the networks, the implementation of the GRØN project's IS exchanges has a limited impact, with a 0.05% and 0.15% reduction for GWP and PM, respectively. It should, however, be recognized that the results are significantly affected by extensive emissions of entities within the network (e.g., Aalborg Portland), thus obscuring the true potential. In this respect, one could argue that the environmental improvement potential should be assessed in its own right instead of relative to the network's overall performance.

Additionally, while some of the symbiotic exchanges facilitated within ISN and GRØN are considered insignificant in terms of avoided emissions, such as Nordjylland Bakery, the argument could still be made that these. Since the exchanges, while insignificant, are still better than no exchange at all. And yet, the significance of the flow environmental improvement potential should be influential when prioritizing the expansion of the IS network. Thus, establishing symbiotic flows which support a greater environmental improvement potential should be the priority. Lastly, symbiotic flows, such as biogas, contribute detrimentally to the IS network and should, therefore, not be neither prioritized nor expanded upon from an environmental improvement potential perspective.

Discussion

Chapter 8

Realizing the Potential of Quantification

Throughout the analysis of this study, the potential environmental effects have been evaluated concerning an expansion of the ISN network with new symbiotic exchanges and entities utilizing an LCA model built on the integrated matrix augmentation system (IMAS). Moreover, the LCA model has proved sufficient in establishing a baseline for yearly reporting of environmental performance among IS entities. In this regard, the technical advantages of the model can be summarized as such:

1. Yearly reporting of environmental performance at multiple IS taxonomy levels.
    (a) Progressive tracking of performance over time based on goals and backcasting.
    (b) Circumventing a lack of data with the option to improve accuracy through IMAS.
    (c) Examination of the relative importance of multiple environmental KPIs based on case-by-case weighting.
2. Assessment of resource-saving initiatives concerning optimization and expansion of symbiotic exchanges.
    (a) Decision support concerning potential IS expansion utilizing expected activity data for flows and entities.
    (b) Evaluation of pre-existing IS exchanges with comparison to alternatives

While the LCA model poses multiple opportunities, several prerequisites and requirements have to be addressed in order to utilize the model to its full potential. Foremost, Port of Aalborg Research and Development (PARD) should expand its facilitator responsibilities from being a mere intermediary between the parties involved in ISN to taking on responsibility for ensuring that all entities are actively involved by building a surrounding identity around ISN. In this way, PARD can be recognized as the facilitator responsible for overseeing and guiding the IS network, thereby guaranteeing trustworthiness and reliability. In this respect, an inclusive community or forum where parties can interact and share ideas and experiences should be established. An open forum would create a platform for knowledge-sharing and enable the development of new symbiotic business models, inherently strengthening ISN's participatory aspects and identity.

Furthermore, through this forum, PARD should facilitate the creation of both a common understanding and shared targets among all entities, which is vital in fostering a collective identity. Moreover, addressing data quality is crucial to improving the LCA model's ability to represent individual flows and entities within the IS network. For that purpose, PARD should focus on establishing itself through the proposed forum as a data collection hub for all relevant information related to the IS network. Site-specific data is often considered sensitive. Therefore, as the intermediate facilitator between the different entities involved, PARD should ensure an appropriate level of security and discretion as to how data is utilized. The following sections will detail the opportunities and barriers for PARD to integrate consistence quantification of environmental performance and improvement potential, thereby maturing the symbiotic network.

8.1 Tracking Performance

As detailed in Section 6.3, the entity level has multiple advantages when tracking performance over time. In this regard, it is recommended to compare performance at the entity level to avoid uncertainties caused by fluctuating turnover when comparing the network level over time. In this respect, results are compared relative to each entity's own performance. PARD would hence be capable of providing information on each entity's approximate environmental performance, e.g., on an annual basis. Consistent annual reporting would make PARD capable of identifying the companies that have positive trends in minimizing environmental impacts and companies that do not. Overall, changes to the network and its entities can be accounted for as illustrated by Figure 8.1.

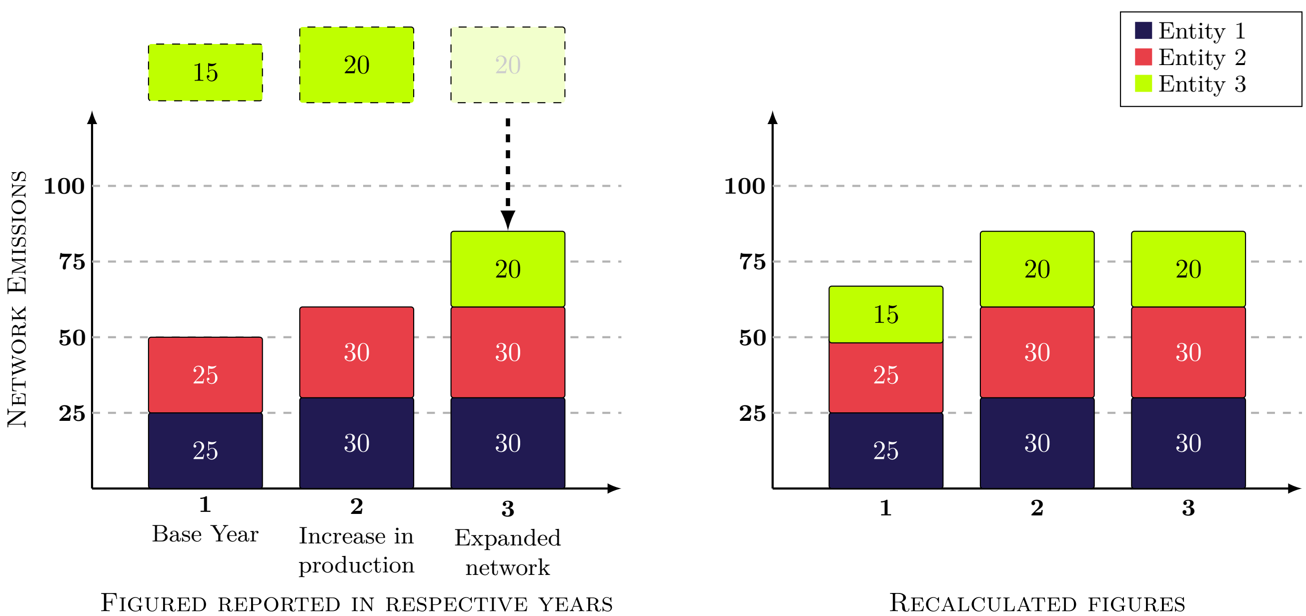


Figure 8.1: Recalculation of baseline emissions for IS network expansion. Adapted from the GHG-protocol (WBCSD, WRI 2015)

General procedures would allow PARD to point out where challenges are located concerning the sustainable development of the IS network. PARD could thus apply the LCA model to assess the most significant potential reduction measures and ensure mitigation for entities by assisting them in decision-making. For example, PARD should set targets for specific KPIs based on the model and, through backcasting, identify how they as a collective can achieve them. Additionally, PARD should incentivize a change by utilizing KPIs to communicate the performance of individual entities within the IS network. Doing so would allow the individual entities to keep track of their performances and increase awareness of how symbiotic exchange contributes to the targets. Consequently, consistency creates a sense of purpose within the network by making each entity accountable to the network as a whole. Consequently, by tracking performance, PARD would effectively extend its facilitating role to creating peer-to-peer evaluation and value proposition for the entities in the network.

When data is seen as sufficient for the entities, these results would be considered the baseline year, to which future assessments are compared. It should thus be understood that only network expansion will affect this tracking if entities are added/removed from the network or acquire new subsidiaries after the baseline calculation (See Figure 8.1). For a reliable comparison of performance over time, the Corporate Greenhouse Gas Protocol recommends that the baseline year is recalculated if such changes occur (WBCSD, WRI 2015). Another reason for updating the baseline calculation will be if substantial changes to the data quality are possible, e.g., by acquiring site-specific data for some of the influential processes within the entity. In this regard, obtaining high-quality data should be prioritized to avoid changing the baseline calculation.

8.2 Data Quality And System Boundary

Improvement of data quality is an aspect of the model which can be continuously improved upon going forward. In this regard, the IO approach is a beneficial way of modeling business activities when limited data is available, as detailed by Section 3.2.2. Furthermore, it should be acknowledged that certain entities and flows within this case study lack information regarding business activities and intermediary processes, to a degree where uncertainties potentially lead to significant differentiation in the modeled results. For this reason, it is relevant to discuss data requirements for creating a model where both flows, entities, and the network are represented sufficiently in accordance with the application purposes as described in Section 6.3. The multiple parameters for data requirements and -quality can be described as such:

Entity information:

1. Annual financial and inventory turnover of each entity within the system boundary. The inventory turnover can be applied in amounts and converted to monetary units within Exiobase for more accurate representation
2. Insight into each entity's main product or service. This can be distributed between different product or service activities if needed, as represented by Reno Nord I/S in ISN. See table 5.11

Flow information:

3. Quantities of material and energy exchanged as symbiotic flows.
4. Knowledge of how the symbiotic flows are utilized in order to identify what is subsequently substituted.
5. Insight into the intermediary processes required to support the symbiotic flow (to an extent where it can be represented as a process within the model).

If the data requirements and -quality is present, the model will have a joint base to enhance accuracy. The model can be improved over time if site-specific data allow for disaggregation as performed on, e.g., Aalborg Portland A/S within this study. While certain entities successfully adhere to the stated data requirements, numerous others fail. Therefore, the results of this study are not recommended for external customer communication due to uncertainties. However, the model can be utilized for supporting decision-making on how to prioritize new symbiosis exchanges and network expansions. Figure 8.2 displays the overall compliance of entity and flow data utilized in the current iteration of the LCI. For entity data to be considered sufficient, it must adhere to parameters 1 & 2, while entity data must comply with parameters 3-5.

Sufficient Information Acquired

Entities:
- Aalborg Portland A/S
- Reno Nord I/S
- NPS
- Port of Aalborg A/S
- Colas A/S
- Aalborg Kloak A/S

Flows:
- Heat (Aalborg Portland, Crematorium, Alfa Laval, Grocery Association)
- Chalk slurry
- Dry sludge
- Organic waste
- Fly ash (Cement, Asphalt)
- Gypsum

Insufficient Information Acquired

Entities:
- Alfa Laval AB
- Farms in Vodskov
- Aalborg Crematorium
- Industrial Fishing Port
- Green Waste
- Nordjylland Dairy
- Small Waste
- Grocery Association
- Nordjylland Bakery

Flows:
- Grain husks
- Heat (Nordjylland Dairy)
- Rain water
- Plastic (Small waste, Industrial Fishing Port)
- Sand
- Biogas

Figure 8.2: Entities and flows fulfilling the minimum recommended amount of information

It should be noted that the minimum data requirements recommended to create a common foundation are based on the chosen system boundary, which in this study is limited to a cradle-to-gate boundary. The cradle-to-gate boundary entails that the use phase and end-of-life aspects of the products and services provided within the system are not included in the assessment. The LCI model holds the potential of being upgraded to an expanded cradle-to-grave model if the necessary data is acquired. Moreover, it is relevant to consider how exchanged symbiotic materials incorporated as part of a product affect the use phase and end-of-life stage, as this could potentially change how the product is processed.

An example of how the system boundary excludes potentials at the flow level is presented in Figure 8.3. Here, the difference between what is substituted with the inclusion of a cradle-to-gate boundary versus a cradle-to-grave boundary is presented for the symbiotic flow of grain husks from Nordjylland Bakery to a manufacturer of yoga pillows.

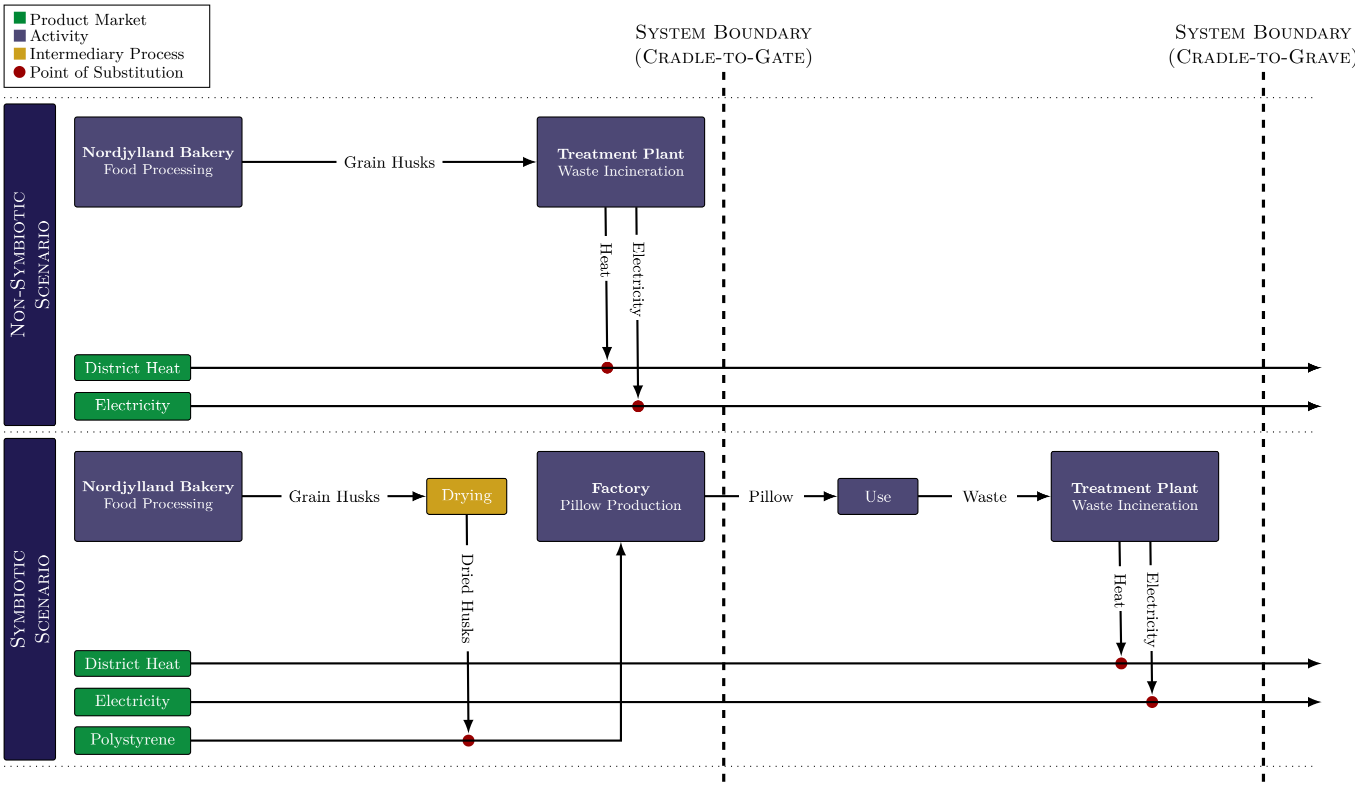


Figure 8.3: Example of potential exclusion by cradle-to-gate system boundary for Nordjylland Bakery

It can be seen that without the cradle-to-grave perspective, the system boundary presupposes a set of missed opportunities for avoided production in the end-of-life stage. Consequently, the symbiotic exchange for grain husks within the current model is limited in its substitution of polystyrene while missing the substitution of heat and electricity, which would be produced through incineration of waste under normal circumstances. Due to the cradle-to-gate system boundary, the benefits of applying grain husks in yoga pillows are presented as less beneficial than the non-symbiotic alternative. For the LCI model to be improved upon for use in decision-making processes and reporting purposes, it is recommended to include a complete cradle-to-grave system boundary. The data needed to include the cradle-to-grave perspective is recommended based on the following information requirements:

Use phase, entity-level: 6. Information on market inputs during the product use phase (I.e., Maintenance services, fuels, chemicals, or others) and quality changes effected by the applied symbiotic resources.

Use phase, flow-level: 7. Information on how the product is affected by utilization of the symbiotic resource, I.e., Changes to life span or the effectiveness in operation.

End-of-life, entity-level: 8. Information on how the products from the IS network are expected to be treated in the end-of-life stage.

End-of-life, flow-level: 9. Information on how the symbiotic resources are treated – either as part of another product or separate from these at end-of-life. For example, plastic is part of a complex product being sorted and reused once more after the end-of-life stage.
10. Information on how the symbiotic resources would have been treated at end-of-life if not utilized as an IS exchange.

8.3 Enhancing the Circular Economy

Figure 8.4 displays three dimensions of circular economy (CE) and the combining effect of implementing these. Overall, the application of LCA in industrial symbiosis could be considered as mainly focusing on the slowing aspect of resources within the network. When resources are exchanged in a symbiotic network, they follow a linear path to the grave as it does not necessarily return to the "cradle." Nevertheless, it is *slowing* as it is given a longer life span in another production. This view of an industrial symbiosis would consequently lead to scoping out two of the three ways of increasing circular economy in society as shown in Figure 8.4.

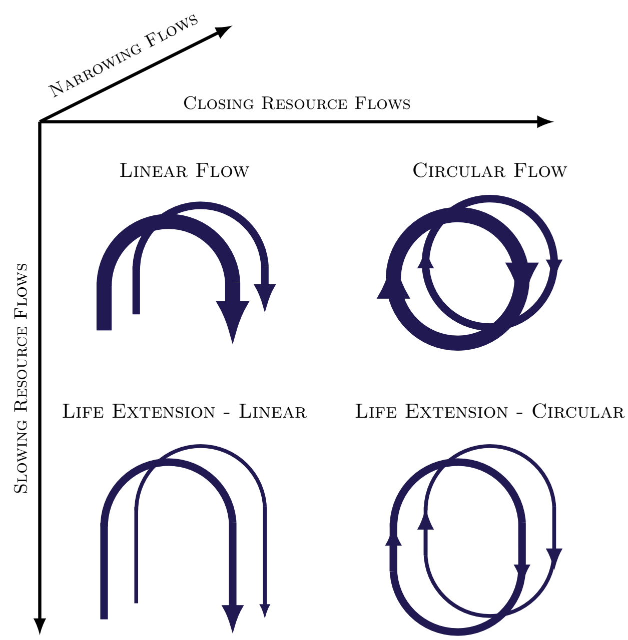


Figure 8.4: Three dimensions of circular economy: Slowing, narrowing, and closing. (Adapted from Bocken et al. (2016))

It should, however, be noted that the LCA model has a broader application than an exclusive focus on IS exchanges. An example of an alternative CE dimension would be to assess the effect of entities investing in equipment that optimizes their own production by minimizing waste generation and energy consumption, thereby *narrowing* resource consumption. Application as such can support decision-making for where investments in optimization make the most sense. It is beneficial for the facilitating organ to support companies in evaluating investments mitigating emissions. Additionally, the assessment helps decide whether to focus on implementing new symbiotic flows or optimize the pre-existing production of entities. Such a shift would transition PARD's role concerning the network by secondarily extending their focus to support each entity. The third dimension of circular economy is the *closing* of resource flows. In order to include this dimension in the LCA model, the system boundary should be extended to a cradle-to-cradle boundary, essentially allowing for resources to be put back into the system after the use phase. The *closing* flows should be modeled by adding depreciation factors determining the resource loss in each circulated round in the life cycle. Consequently, by including all three dimensions of the circular economy in the LCA model, the general prioritization of reduction measures would be improved in terms of potential symbiotic exchanges and further narrowing-, closing-, and slowing actions within the network.

8.3.1 Implementing Data Management System

The data applied from ISN was partly collected by PARD and has not been updated since the project ended in 2018, after which the GRØN project was initiated under a similar time frame. This project-based setting is notably different from Kalundborg Symbiosis, a non-profit private association facilitating a continuous network over several years. Overall, it can be argued that facilitating a continuous network provides ideal conditions for implementing substantial data management systems for the companies involved, as data quality can improve over time. It is critical to keep updating and improving data in the model for the included companies and symbiotic exchanges. As illustrated by Figure 8.5, the most significant eco-efficiency improvements are achieved through function and system innovation. To ensure that value for the IS network is continuously provided long term, it is necessary to discuss what innovations could be made.

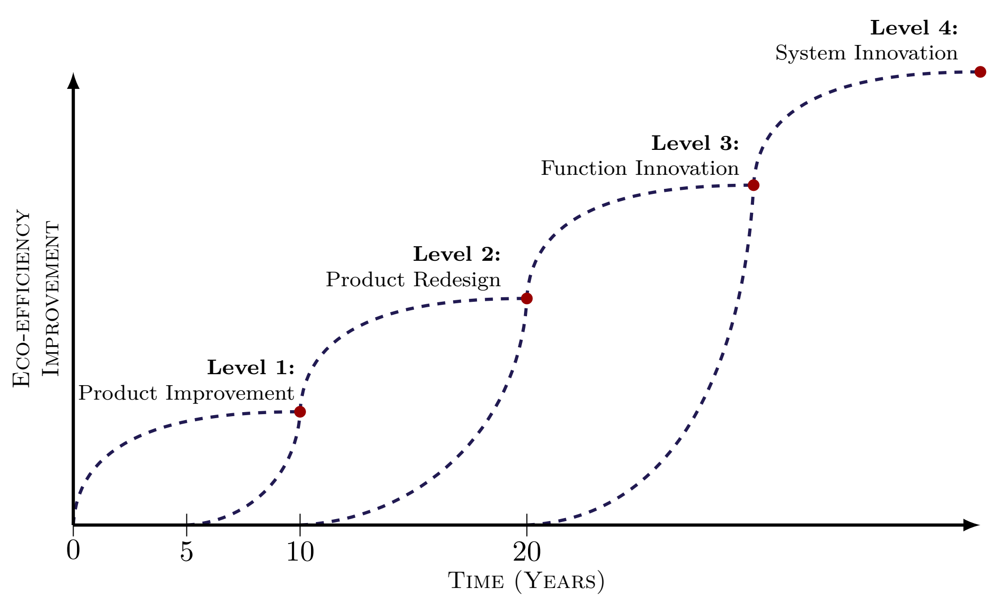


Figure 8.5: Four-stage model concerning the radicality of eco-design innovation (Adapted from Brezet (1997))

In this respect, a crucial aspect in maturing the IS network is defining the network facilitated. Otherwise, the workload of applying LCA at a network level becomes too comprehensive compared to the potential benefits. For facilitating organizations to mature, consistent data management is hence a necessity. Therefore, the focus on developing the symbiosis should be shifted from exclusively identifying new symbiotic exchanges to innovating how IS networks are structured and the subsequent functionality hereof. One could argue that it is essential to make the companies consider data collection as a means of value for both the network and the company itself. If the effort for providing data exceeds the benefits of providing it, it becomes difficult to sustain an LCA model where data will improve over time. Two main parameters can influence this: (i) Providing more value with the data gathered. (ii) Minimizing the effort needed to provide the data. Because the LCA model proposed in this study has multiple applications, different value propositions can be made for each entity.

For annual updates of data, it is necessary to provide short-term value for the companies. Gaining insight into the individual environmental performance may interest many companies that do not have time, competencies, and other resources to quantify these themselves. In this regard, annual reports could be a way of engaging the companies to provide improved data and, in return, have their environmental performance evaluated. One could thus argue that PARD has the potential to become a data hub for the companies within the network, providing quantification of environmental performance for reporting purposes along with analyzing and comparing investment opportunities for reducing the negative impact on the environment for entities with sufficient data. However, this shift would require substantial resources at the current iteration of PARD. According to Per Møller, Head of the Kalundborg Symbiosis, this transition demands the implementation of new technologies:

> "*We are trying to mature on a network level and with the individual entities. We are therefore trying to figure out how we can create software that could make it interesting for companies to provide data smartly [...].*"
>
> Per Møller, Head of Symbiosis, Kalundborg Symbiosis - (Appendix E.1)

Smart data collection inevitably points toward digitization technologies as part of the solution. Digitization technologies could become an important tool for realizing eco-efficiency improvements within IS networks. As described in Section 8.3 an expanded LCA model has the promise of promoting all three dimensions of the circular economy, further cementing the relevance of integrating digitization as a central element in establishing a data management systems. Chauhan et al. (2022) presents different digitization technologies for achieving circular economy as illustrated on Figure 8.6.

Figure 8.6 by Chauhan et al. (2022) is presents six digitization technologies whereas some are considered especially beneficial in the context IS networks. Coupled to each digitization technology is multiple capability for achieving a circular economy. In this respect, circular economy requires both contribution and commitment of stakeholders and the redesigning of pre-existing systems to align with the innovation of business models (Chauhan et al. 2022). Two technologies are found to be particularly relevant to the limited scale of the IS networks. These are the following:

Sensors Sensors have the potential to track parameters. For entities within an IS network, these could be activities influential for their environmental performance, such as emissions, fuel consumption, heat exported, or other activities relevant to the network analysis.

Internet of Things: IoT is a technology that allows data to be transferred over a network without human-to-human interaction. IoT can be a composite of multiple computing devices which transfer data from, e.g., sensors or other devices that collect data. This technology would allow PARD easier access to company activity data and less effort for companies to provide it. In this sense, IoT is especially relevant for tracking performance as this could be done each year continuously, and easy access to data becomes vital.

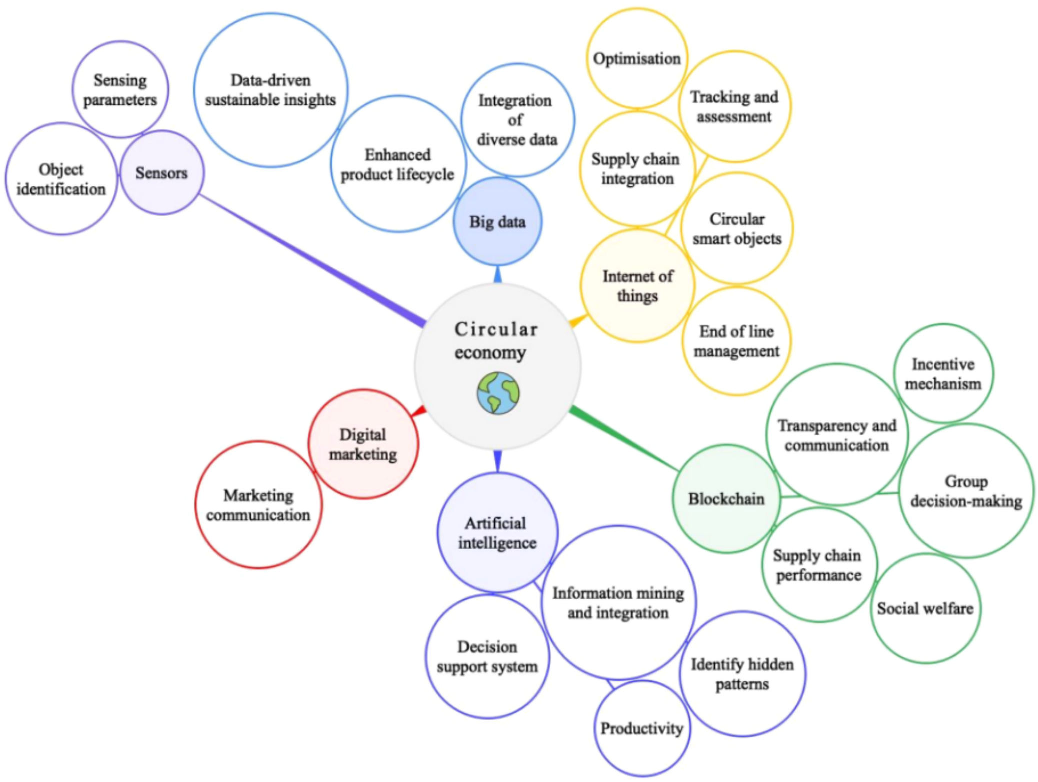


Figure 8.6: Digitization technologies to achieve circular economy (Chauhan et al. 2022).

It should, however, be recognized that the remaining digitization technologies conjointly present additional value for the quality and management of data. For this reason, it is essential to consider digitization technologies sooner than later when developing a data management system. Some digitization technologies additionally apply to the companies themselves, particularly information and communication technologies (ICT) could be providing information about the end-of-life stage of their products (Chauhan et al. 2022). Other technologies may be useful for PARD in other ways than data management, e.g., digital marketing. Digitization of marketing can simplify the process of communicating results and environmental performance to the market, help attract new entities into the network, and create transparency around the process. This simplification could also be part of PARD's strategy to solidify its place as a central facilitator in the network.

8.4 Who Gets the Benefits?

As detailed in Section 1.1, industrial symbioses are often presented as a win-win scenario for the entities partaking in the symbiotic network. However, this is more often than not based on an economic perspective. Presently, there are no standardized practices for determining whether it is the supplier or recipient of the IS exchange who gains the environmental benefits associated with its utilization as initially described in Section 1.2. This dilemma is not exclusively limited to quantifying environmental benefits within IS networks but concerns a broader discussion of which parties in a supply chain inherit and or forfeit the environmental impacts and benefits. For example, in the waste management industry, is it the supplier of recyclable waste that facilitates the waste management activity, or is the waste management company handling the activity that inherits the environmental benefit? Moreover, if this benefit was attributed to the waste management company, should they have the ability to transfer this to their customers to incentivize recycling?

IS networks typically fail to encapsulate the win-win scenario regarding the environmental benefits for the individual entities, as it is rare that quantification of the environmental performance is conducted among individual entities and flows. This is due to the overall interest typically positioned on quantifying the impact for the network as a whole or to a narrow set of entities, thereby limiting the scope of the study significantly (Martin 2013). As presented in Section 3.2.2, few studies assess the environmental performance on multiple IS taxonomy levels, which implies that the participating entities fail to gain any employable information concerning the performance of the symbiotic exchanges they facilitate. This information can prove useful in motivating the individual entity to either establish new or expand existing symbiotic relations once the underlying argument for its environmental benefits can be substantiated.

> "*Quantifying environmental performance is not limited to use for external communication but proves a vital tool for the individual organization in understanding that what they are doing by partaking in the symbiosis actually means something [environmentally, red.]. [...] Developing this understanding, therefore, leads to both maturing of the individual organization, as well as the network as a whole.*"
>
> Per Møller, Head of Symbiosis, Kalundborg Symbiosis - (Appendix E.1)

Consistency and standards are required for the distribution of environmental benefits (e.g., that of PEF) to quantify the environmental potential on multiple taxonomy levels. For this study, the approach mirroring that of Weidema (2000) has been utilized by attributing any environmental burdens from intermediate processes and benefits gained from the symbiotic exchange to that of the sender. Thus, the recipient receives a symbiotic resource that substitutes the conventional raw resource through the exchange. In this respect, the approach supplements consequential modeling and constrained symbiotic resources but contrarily provides certain downsides.

The lack of distribution of the environmental benefits between entities may prove a weakness for the approach utilized within this study since prospective entities might fail to generate interest or identify why they should participate in the IS network. It could potentially be problematic for entities to justify the adaption of symbiotic resources when no environmental benefits are obtained, which would affect the quality of their product. Equally important is that IS networks are based on supply and demand. Therefore, an entity may offer a potential symbiotic resource with obvious environmental benefits attracted to it and attribute this to themselves based on the approach utilized in this study. This logic may lead potential adopters to disregard IS exchanges in order to minimize the risk associated with incorporating constrained waste or bi-products from another production, effectively reducing the potential the IS network and symbiotic resource have (See Section 1.2).

Conversely, two other methods for determining who gets the benefits are available, such as the physical attribution of impacts which relies on attributional LCA modeling and is therefore not suitable for distributing impacts within a consequential model (Martin 2013). Alternatively, the 50/50 method, inspired by the recycling industry, bases itself on a credit system that distributes the environmental benefits and cost derived from symbiotic resources and intermediate processes evenly between entities (Martin 2013). However, this method poses certain edge cases when intermediate processes are present in exchanges with entities of unequal sizes because SMEs inherit half of the cost. Furthermore, one could question the fairness of a 50/50 distribution in cases where the resource exchange infrastructure exclusively demands significant investments from one party. This disparity can potentially skew performance where the IS exchanges contribute unevenly relative to the investment. For this reason, the methodology adopted by this study can be argued as reasonable in distributing environmental benefits. Although, it is prone to fail at incentivizing new adaptions of symbiotic resources, specifically for the recipient, as they are not attributed any of the benefits associated thereof.

8.5 Creating Meaningful Change

With a foundation established for the opportunities and barriers concerning the quantification of environmental performance, one could question the implementation of change hereof. This section presents a series of recommendations grounded in implementation theory by utilizing the 8-step change model by Kotter (2012) to assess the implementation needs and organizational prerequisites for PARD and the expanded ISN network. As illustrated by Figure 8.7 these steps can be divided into 3 phases:

1. Establishing a sense of urgency for change.
2. Developing a vision for the future
3. Implementing and sustaining the change

These phases are not sequential but rather overlap and influence each other (Kotter 2012). For example, if there is no urgency to implement quantification, the change cannot be sustained in the long term. Likewise, an organization may begin with strong motivation, but these factors will fail to sustain the process without a clear vision. Because of this, the following section will focus on assessing the implementation of the LCA model by PARD concerning consistent quantification of the environmental performance of the expanded ISN network.

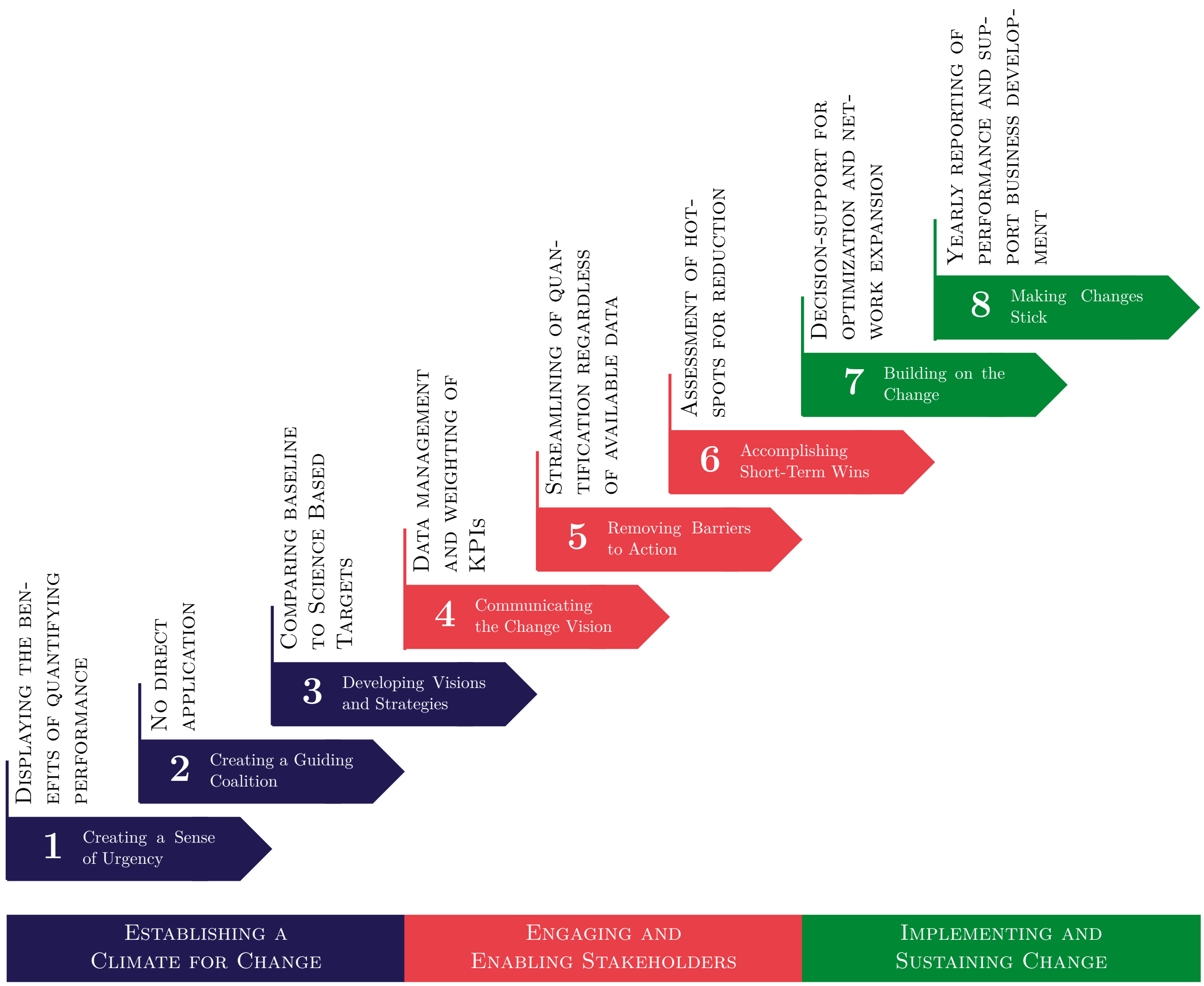


Figure 8.7: 8 Step Model for organizational change and the application of the LCA model (Adapted from Kotter (2012))

8.5.1 Establishing a Climate for Change

These first three phases of Kotter (2012) concern the initial prerequisites for organizational change to occur, namely, developing a sense of urgency for change, creating a guiding coalition whose purpose is to assist the change, and establishing a strategic plan as a means of achieving the desired outcome.

Step 1 - Creating a Sense of Urgency: Creating a rationale for why IS networks are beneficial is necessary before an entity is willing to embrace the value proposition. Environmental legislation and regulation can play a decisive role in creating a sense of urgency for joining the IS network. As an increasing focus is being put on reducing emissions, organizations need to show commitment toward mitigating climate change through eco-friendly actions, such as participating in an IS network. Therefore, it is essential to emphasize how being part of the IS network enables an organization to optimize environmental performance by participating in networks that are willing to exchange alternative resources and know-how with each other. The case needs to be made that by partaking in the IS network, entities have an opportunity to be part of an initiative that develops localizing resource procurement through symbiotic exchanges while promoting sustainable development. Thus, choosing to partake in an IS network brings economic benefits and resource security. Additionally, participation presents an opportunity for utilizing the network and the environmental potential in branding the given organization.

Step 2 - Creating a Guiding Coalition: To promote the quantification of environmental performance, PARD ought to act as the intermediary and facilitator of the ISN network. In order to do so, they must create a joint coalition for the entities involved in the IS network. In this regard, including additional stakeholders (aside from PARD) is essential. The coalition should, therefore, among others, include representatives from entities within the network to foster community and trust between them. Furthermore, one could include city planners (i.e., Aalborg Municipality) and IS/LCA experts (e.g., universities or consultancies). Establishing a guiding coalition will support a joint trustful environment where members feel safe engaging in collaborative initiatives and symbiotic exchanges. While PARD has partially created the necessary trust, it is additionally crucial that coalition members feel empowered to establish a trusting relationship among themselves. By establishing a trusting coalition, PARD can facilitate the process toward an IS network that is beneficial for all members involved.

Step 3 - Developing Vision and Strategies: The coalition should collaborate on deciding the specific vision for the ISN network. The reference baseline scenario (RBS) within this study, as presented in Chapter 7, could serve as a starting point for ISN's future targets by setting up relevant KPIs according to the characterized impacts. It should be noted that each IS network is different. In this respect, PARD should not strive to imitate state-of-the-art scenarios such as Kalundborg Symbiosis. Instead, PARD must adopt its own vision where an increased focus on data quality and information sharing are at the center, with data requirements specified in section 8.2. Thereby, easily applicable quantification of the environmental performance and improvement potential can be created. Creating this foundation would allow PARD to build upon it in subsequent years and hence make ISN and the LCA model presented within this study more adaptable and responsive to the needs of its current and new members.

8.5.2 Engaging and Enabling Stakeholders

The proceeding Step 4 through 6 of the model focus on how to enable the organizational change by removing barriers to success and how to facilitate continued engagement for the change to sustain itself (Kotter 2012). Concerning PARD, this particularly entails the engagement of entities within the expanded ISN network.

Step 4 - Communicating the Change Vision: PARD should focus on broadening the scope of informed parties participating in the IS network to ensure all organizational layers of IS entities have an opportunity to contribute or, at the very least, be aware of inherent value in the symbiotic network.

One strategy to achieve this is to connect the data management of the IS network to the pre-existing environmental management systems (EMS) where present (ISO 2015a). A direct link could centralize the ISN network as part of individual EMS frameworks, which would enable both enhanced data collection and -quality. Furthermore, incorporating ISN into EMS allows for utilizing the individual environmental performance KPIs from Step 3 in the management system. This inclusion will incentivize the employees to become involved in the environmental initiatives and encourage sharing site-specific data, improving the accuracy of the LCA model.

Step 5 - Removing Barriers to Action: As suggested by Chapter 8, there is a need for PARD and the unified coalition to overcome multiple barriers before the full potential of quantification can be realized. These obstacles include:

- Current lack of engagement from entities regarding participation in ISN.
- Destabilizing circumstances of facilitating an IS network on a fixed project-based schedule.
- Availability and quality of data attainable by PARD.
- Extensive requirements for expertise concerning the quantification of environmental performance.

The lack of engagement is already discussed in Step 1 through 4. Concerning the stability surrounding planning of ISN, the fixed project schedule puts long-term value propositions at risk. Therefore, an argument could be made in favor of more persistent funding schemes to ensure consistency on a long-term basis. Additionally, PARD should adopt a standardized protocol for data collection based on the checklist presented in Section 8.2. Well-defined procedures would effectively eliminate the discrepancies in data quality due to different standards. Lastly, it should be recognized that circumventing the technical requirements associated with quantification is a crucial step in guaranteeing persistence. Overall, this can either be achieved by attaining the proper competencies (e.g., collaborations, consultancy, or recruiting) or developing and integrating the necessary tools as described in Section 8.3.1. The LCI-file found in the external appendix is considered a preliminary proof of concept.

Step 6 - Accomplishing Short-Term Wins: PARD and the coalition should establish achievable targets for how the expanded ISN network should perform. As mentioned in Step 3, these targets should coincide with achievable KPIs that are measurable and verifiable in relation to the RBS presented in this study, e.g., a target for increasing avoided GWP emissions through symbiotic exchanges. Furthermore, PARD, assisted by the LCA model, has the potential to track and evaluate the environmental performance of individual entities annually or by identifying hotspots, thereby guiding how to mitigate these issues, I.e., through symbiotic resource exchanges. Individual KPIs and mitigation measures could thus be created for the individual entity, which would create retention incentives for partaking in ISN. Moreover, the RBS presents multiple *low-hanging fruits*, in which a course of action for reducing emissions is clear and easily attainable, as seen with the case of biogas compared to the production of insect or incineration. The initial quantification of performance is thus an opportunity to accomplish multiple short-term wins in quick succession.

8.5.3 Implementing and Sustaining Change

Step 7 and 8 focus on the final implementation and the subsequent retention of sustaining the change. For PARD, this pertains to maintaining continued performance quantification on a long-term basis.

Step 7 - Build on the Change: Once the LCA model is implemented, and the initial short-term wins have been achieved, continuous improvement and evaluation must be facilitated. Therefore, the model is required to be reviewed annually to reflect changes in entity impacts and symbiotic flows while accounting for the expansion or reduction of entities within the IS network. In addition, while consolidating from the short-term wins, more significant long-term wins for the network should be made to further the established vision for the IS network set up in step 4. Target wins, and possible failures should always be evaluated to identify what worked and assess how the practice or prioritization should move forward.

Step 8 - Make Change Stick: It is vital to ensure continuous engagement for ISN to realize its full potential. The key to such engagement relies on fostering community and shared identity around ISN, which can only be achieved through a sustained effort to solidify interest in, and value for, the entities partaking. Fostering this common network identity at all levels within the entities leads to personal investment, confidence, and trust in that being part of ISN is valuable enough to contribute to a collective value proposition. Furthermore, it is vital for PARD to imprint, or at the very least encourage, the fostering of identity among the individual entities. Means of achieving this include communication, education, workshops, hiring new talent, etc., to reinforce the foundational vision for quantification.

Evidently, the 8 steps for creating meaningful change concerning PARD can be considered as inspiration since it outlines the most crucial elements for maturing the symbiotic network. The recommendations are especially deemed relevant for complex changes such as innovation at a function or system level, as previously detailed in Section 8.3.1. In this regard, it is advised that both the specific pointers laid out in this report and the 8 Step approach to organizational change are incorporated in outlining a road map to develop the expanded ISN network further.

Conclusion

Chapter 9

Conclusion

Through the embedded case study concerning the expansion of Industrial Symbiosis North (ISN), this project report has investigated the quantification of environmental performance and improvement potential regarding industrial symbiosis (IS) networks. The conclusion has the objective of summarizing the key findings in answering the research question posed:

> How can activity data from industries be applied to track and assess the systemic environmental improvement potential of resource flows to mature industrial symbiosis networks?

To mature IS networks, the development and expansion of networks should extend beyond sporadic occurrences of symbiotic exchanges between a few entities with financial benefits as the primary incentive. Instead, the development of networks should actively apply activity data from industries to additionally consider the environmental improvement potential from a life cycle perspective. In this respect, quantification of environmental performance should be regarded as an essential tool in maturing IS networks.

The initial scoping review highlights a substantial gap in knowledge regarding the continuous assessment of environmental performance and improvement potential. The LCA model suggested in this study is characterized by the IMAS approach, IO background data, multidimensional functional units, and inclusion of three taxonomic levels. By quantifying environmental performance with the application of these elements, this report has highlighted that multiple value propositions are achievable for symbiotic networks, even with limited data accessibility and quality. The LCA model allows consideration of the three dimensions of a circular economy by supporting the individual entities in decision making and comparing environmental mitigation possibilities across dimensions and taxonomic levels within the network. In this regard, the taxonomic levels incorporated in this study (network, entity, flow) each provide unique insights into the IS network's environmental performance:

- The network level allows for comparing improvement potentials and characterization of environmental performance across the network, providing scale to mitigating actions.
- The entity level enables short-term and continuous value propositions for the entities involved by making the facilitating organization capable of consulting entities individually and tracking environmental performance over time. Individual consulting of entities is a key value proposition for keeping companies engaged in ensuring access to updated and improved site-specific activity data.

- The flow level permits interpretation of resource flows independent from the entities involved. This allows for consideration of alternative applications of resources both within and outside the network, which will give a more accurate representation of substitution measures and minimize risks of burden shifting.

Decision-support is a critical feature of quantifying environmental improvement potentials, which is why data must accurately reflect reality. There is hence a conflict between the desired quality and the current presence of data in the network. The application of the hybrid database, Exiobase 3, as background data is by these means seen as a necessity in creating meaningful results from the beginning in networks with limited data accessibility and quality. From the baseline calculation, the LCI can be adjusted with improvements in data quality later on. As a whole, the suggested LCA methodology can thus be applied to symbiotic networks of all levels of maturity, regardless of accessibility and quality of activity data. In this respect, the model is considered to have applicability outside the scope of the ISN case study.

Bibliography

Aalborg Forsyning. 2020. *Miljø- og arbejdsmiljøredegøreslse 2020 for Vanddivisionen.* Accessed 21-04-2022 https://aalborgforsyning.dk/media/iaxdiudd/vanddivision-milj%C3%B8-og-arbejdsmilj%C3%B8redeg%C3%B8relse-2020.pdf.

Aalborg Portland A/S. 2019. *Environmental Report 2019.* Accessed 21-04-2022 https://www.aalborgportland.dk/wp-content/uploads/2020/10/Aalborg_Portland_Environmental_Report_2019_web.pdf.

Aissani, L., A. Lacassagne, J.-B. Bahers, and S.L. Féon. 2019. "Life cycle assessment of industrial symbiosis: A critical review of relevant reference scenarios." *Journal of Industrial Ecology* 23 (4): 972–985.

Ammenberg, J., L. Baas, M. Eklund, R. Feiz, A. Helgstrand, and R. Marshall. 2015. "Improving the CO2 performance of cement, part III: The relevance of industrial symbiosis and how to measure its impact." *Journal of Cleaner Production* 98:145–155.

Berners-Lee, Mike, David C Howard, J Moss, Kim Kaivanto, and WA Scott. 2011. "Greenhouse gas footprinting for small businesses—The use of input–output data." *Science of the Total Environment* 409 (5): 883–891.

Bessant, John. 2008. *Innovation and Entrepreneurship.* Chichester: John Wiley.

Beylot, Antoine, Michela Secchi, Alessandro Cerutti, Stefano Merciai, Jannick Schmidt, and Serenella Sala. 2019. "Assessing the environmental impacts of EU consumption at macro-scale." *Journal of Cleaner Production* 216:382–393.

Biesta, Gert. 2015. "Understanding Research philosophies and Approaches." Chap. 4 in *SAGE Handbook of Mixed Methods in Social & Behavioral Research,* edited by Abbas Tashakkori and Charles Teddlie, 94–124. Thousand Oaks: SAGE Publications.

Bocken, Nancy, Karen Miller, and Steve Evans. 2016. "Assessing the environmental impact of new Circular business models." *Proceedings of the "New Business Models"—Exploring a Changing View on Organizing Value Creation, Toulouse, France* 1:16–17.

Brezet, Han. 1997. "Ecodesign: The search for new strategies in product development." *Dynamics in ecodesign practice.* 20 (1): 557–569.

Brinkmann, Svend, and Lene Tangaard. 2010. "Interviewet: Samtalen om forskningsmetode." Chap. 1 in *Kvalitative Metoder: En grundbog,* 1st ed., edited by Svend Brinkmann and Lene Tangaard, 29–53. København: Hans Reitzel Forlag.

Brondi, C., S. Cornago, A. Ballarino, A. Avai, D. Pietraroia, U. Dellepiane, and M. Niero. 2018. "Sustainability-based Optimization Criteria for Industrial Symbiosis: The Symbioptima Case." *Procedia CIRP* 69:855–860.

Bundgaard, Asbjørn Uldbjerg. 2022. "Improving EPD Practices: A Case Study on Supporting the Growing Prevalence of EPDs Through the Practices of Consultancie." Master's thesis, Aalborg University, January.

Center for Logistics & Collaboration. 2022. *Om CLS: Et videnscenter i det havnenære erhvervsområde.* Last visited d. 23-02-2022, Link: https://logsam.dk/om-cls/.

Chauhan, Chetna, Vinit Parida, and Amandeep Dhir. 2022. "Linking circular economy and digitalisation technologies: A systematic literature review of past achievements and future promises." *Technological Forecasting and Social Change* 177:121508.

Chertow, Marian. 2000. "Industrial symbiosis: Literature and taxonomy." *Annual Review of Energy and The Environment* 25:313–337.

———. 2007. ""Uncovering" Industrial Symbiosis." *Journal of Industrial Ecology* 11 (1): 11–30.

Consequential-LCA. 2021. *Why and when?* Accessed 04-05-2022 Link: https://consequential-lca.org/clca/why-and-when/.

Crawford, Robert H., Paul-Antoine Bontinck, André Stephan, Thomas Wiedmann, and Man Yu. 2018. "Hybrid life cycle inventory methods – A review." *Journal of Cleaner Production* 172:1273–1288.

Daddi, T., B. Nucci, and F. Iraldo. 2017. "Using Life Cycle Assessment (LCA) to measure the environmental benefits of industrial symbiosis in an industrial cluster of SMEs." *Journal of Cleaner Production* 147:157–164.

Danish Symbiosis Center. 2022. *Symbiose Center about.* Accessed 21-04-2022 https://symbiosecenter.dk/om-os/.

Dawson, Marcelle C, Christopher Rosin, and Nave Wald. 2017. *Global Resource Scarcity : Catalyst for Conflict or Cooperation? (Edition 1).* 1st ed. Earthscan Studies in Natural Resource Management. Milton: Routledge.

Dong, L., H. Liang, L. Zhang, Z. Liu, Z. Gao, and M. Hu. 2017. "Highlighting regional eco-industrial development: Life cycle benefits of an urban industrial symbiosis and implications in China." *Ecological Modelling* 361:164–176.

Dumoulin, F., T. Wassenaar, A. Avadí, and J.-M. Paillat. 2017. “A Framework for Accurately Informing Facilitated Regional Industrial Symbioses on Environmental Consequences.” *Journal of Industrial Ecology* 21 (5): 1049–1067.

Durdević, Dinko, Paolo Blecich, and Zeljko Jurić. 2019. “Energy Recovery from Sewage Sludge: The Case Study of Croatia.” *Energies* 12 (10).

Eckelman, M., and M. Chertow. 2013. “Life cycle energy and environmental benefits of a US industrial symbiosis.” *International Journal of Life Cycle Assessment* 18 (8): 1524–1532.

Ehrenfeld, John, and Nicholas Gertler. 1997. “Industrial Ecology in Practice: The Evolution of Interdependence at Kalundborg.” *Journal of Industrial Ecology* 1 (1): 67–79.

Farthing, Stuart M. 2016. *Research Design in Urban Planning: A Student's Guide.* Los Angeles: SAGE.

Flyvbjerg, Bent. 2006. “Five Misunderstandings About Case-Study Research.” *Qualitative Inquiry* 12 (2): 219–245.

Fraccascia, L., I. Giannoccaro, and V. Albino. 2017. “Rethinking Resilience in Industrial Symbiosis: Conceptualization and Measurements.” *Ecological Economics* 137:148–162.

Fraccascia, L., and D.M. Yazan. 2018. “The role of online information-sharing platforms on the performance of industrial symbiosis networks.” *Resources, Conservation and Recycling* 136:473–485.

Ghali, Mohamed, Jean-Marc Frayret, and Jean-Marc Robert. 2016. “Green social networking: concept and potential applications to initiate industrial synergies.” *Journal of Cleaner Production* 115:23–35.

Gibbs, David. 2008. “Industrial Symbiosis and Eco-Industrial Development: An Introduction: Industrial symbiosis and eco-industrial development.” *Geography Compass* 2 (4): 1138–1154.

Haq, H., P. Välisuo, and S. Niemi. 2021. “Modelling sustainable industrial symbiosis.” *Energies* 14 (4).

Hashimoto, S., T. Fujita, Y. Geng, and E. Nagasawa. 2010. “Realizing CO2 emission reduction through industrial symbiosis: A cement production case study for Kawasaki.” *Resources, Conservation and Recycling* 54 (10): 704–710.

Hauschild, Michael, and José Potting. 2000. *Spatial differentiation in life cycle impact assessment - The EDIP2003 methodology.* Technical report. Danish Environmental Protection Agency, Copenhagen.

Heeres, R., W. Vermeulen, and F. de Walle. 2004. “Eco-industrial park initiatives in the USA and the Netherlands: first lessons.” *Journal of Cleaner Production* 12 (8): 985–995.

Heijungs, Reinout, and Sangwon Suh. 2002. *The computational structure of life cycle assessment.* 1st ed. Springer.

Hildebrandt, J., S. O'Keeffe, A. Bezama, and D. Thrän. 2019. "Revealing the Environmental Advantages of Industrial Symbiosis in Wood-Based Bioeconomy Networks: An Assessment From a Life Cycle Perspective." *Journal of Industrial Ecology* 23 (4): 808–822.

I/S Reno Nord. 2018. *Miljøredegørelse 2018.* Accessed 21-04-2022 https://renonord.dk/media/aarsrapporter/renonord_miljoeredegoerelse_2018_low.pdf.

International Monetary Fund. 2022. *IMF Data.* Last visited d. 02-03-2022, Link: https://www.imf.org/en/Data#data.

Ismail, Y. 2020. "Potential Benefit of Industrial Symbiosis using Life Cycle Assessment." *Journal of Physics: Conference Series* 1625 (1).

ISO. 2006a. *ISO 14040:2006, Environmental management - Life cycle assessment - Principles and framework.* 4th ed.

———. 2006b. *ISO 14044:2006, Environmental management - Life cycle assessment - Requirements and guidelines.* 2nd ed.

———. 2015a. *ISO 14001:2015, Environmental management systems — Requirements with guidance for use.* 3rd ed.

———. 2015b. *ISO 14072:2015, Environmental management - Life cycle assessment - Requirements and guidelines for organizational life cycle assessment.*

Jolliet, Olivier, Manuele Margni, Raphaël Charles, Sébastien Humbert, Jerome Payet, Gerald Rebitzer, and Ralph Rosenbaum. 2003. "IMPACT 2002+: a new life cycle assessment methodology." *The International Journal of Life Cycle Assessment* 8:324–330.

Kalaitzi, Dimitra, Aristides Matopoulos, Michael Bourlakis, and Wendy Tate. 2018. "Supply chain strategies in an era of natural resource scarcity." *International Journal of Operations & Production Management.*

Kallio, Hanna, Anna-Maija Pietilä, Martin Johnson, and Mari Kangasniemi. 2016. "Systematic methodological review: developing a framework for a qualitative semi-structured interview guide." *Journal of advanced nursing* (England) 72 (12): 2954–2965.

Kalundborg Symbiosis. 2022. *Explore the Kalundborg Symbiosis.* Accessed 21-04-2022 http://www.symbiosis.dk/en/.

Kapur, Amit, and Thomas E Graedel. 2004. "Industrial ecology." *Encyclopedia of Energy* 3:373–382.

Kelly, Leanne M., and Maya Cordeiro. 2020. "Three principles of pragmatism for research on organizational processes." *Methodological Innovations* 13 (2): 1–10.

Kerdlap, P., J. Low, and S. Ramakrishna. 2020. "Life cycle environmental and economic assessment of industrial symbiosis networks: a review of the past decade of models and computational methods through a multi-level analysis lens." *International Journal of Life Cycle Assessment* 25 (9): 1660–1679.

Kerdlap, P., J. Low, D. Tan, Z. Yeo, and S. Ramakrishna. 2020. "M3-IS-LCA: A Methodology for Multi-level Life Cycle Environmental Performance Evaluation of Industrial Symbiosis Networks." *Resources, Conservation and Recycling* 161.

———. 2022. "UM3-LCE3-ISN: a methodology for multi-level life cycle environmental and economic evaluation of industrial symbiosis networks." *International Journal of Life Cycle Assessment.*

Kerdlap, P., J.S.C. Low, R. Steidle, D.Z.L. Tan, C. Herrmann, and S. Ramakrishna. 2019. "Collaboration platform for enabling industrial symbiosis: Application of the industrial-symbiosis life cycle analysis engine." *Procedia CIRP* 80:655–660.

Kim, H., S. Ohnishi, M. Fujii, T. Fujita, and H. Park. 2018. "Evaluation and Allocation of Greenhouse Gas Reductions in Industrial Symbiosis." *Journal of Industrial Ecology* 22 (2): 275–287.

Kørnøv, Lone. 2015. "Faces and functions of theory in impact assessment research." *Journal of Environmental Assessment Policy and Management* 17 (1): 1–9.

Kørnøv, Lone, Ivar Lyhne, Jesper Raakjær, and Mette Schmidt. 2020. *Miljø++. From development project to strong partnership.* Aalborg: Port of Aalborg.

Kotter, John P. 2012. *Leading change.* Boston, Massachusetts: Harvard Business Review Press.

Kuczenski, Brandon. 2015. "Partial ordering of life cycle inventory databases." *The international journal of life cycle assessment* 20 (12): 1673–1683.

Kuhlman, J.W, and J Farrington. 2010. "What is sustainability?" *Sustainability (Basel, Switzerland),* Sustainability, 2 (11): 3436–3448.

Liu, Q., P. Jiang, J. Zhao, B. Zhang, H. Bian, and G. Qian. 2011. "Life cycle assessment of an industrial symbiosis based on energy recovery from dried sludge and used oil." *Journal of Cleaner Production* 19 (15): 1700–1708.

Lütje, A., and V. Wohlgemuth. 2020. "Tracking sustainability targets with quantitative indicator systems for performance measurement of industrial symbiosis in industrial parks." *Administrative Sciences* 10 (1).

Lybæk, Rikke, Thomas Budde Christensen, and Tobias Pape Thomsen. 2021. "Enhancing policies for deployment of Industrial symbiosis–What are the obstacles, drivers and future way forward?" *Journal of Cleaner Production* 280:124351.

Marcinkowski, A. 2019. “The spatial limits of environmental benefit of industrial symbiosis - Life cycle assessment study.” *Journal of Sustainable Development of Energy, Water and Environment Systems* 7 (3): 521–538.

Martin, M. 2015. “Quantifying the environmental performance of an industrial symbiosis network of biofuel producers.” *Journal of Cleaner Production* 102:202–212.

———. 2020. “Evaluating the environmental performance of producing soil and surfaces through industrial symbiosis.” *Journal of Industrial Ecology* 24 (3): 626–638.

Martin, M., and S. Harris. 2018. “Prospecting the sustainability implications of an emerging industrial symbiosis network.” *Resources, Conservation and Recycling* 138:246–256.

Martin, M., N. Svensson, and M. Eklund. 2015a. “Who gets the benefits? An approach for assessing the environmental performance of industrial symbiosis.” *Journal of Cleaner Production* 98:263–271.

Martin, Michael. 2013. “Industrial Symbiosis in the Biofuel Industry: Quantification of the Environmental Performance and Identification of Synergies.” PhD diss., Linköping University, April.

Martin, Michael, Niclas Svensson, and Mats Eklund. 2015b. “Who gets the benefits? An approach for assessing the environmental performance of industrial symbiosis.” *Journal of cleaner production* 98:263–271.

Matthews, H. Scott, Chris T. Hendrickson, and Deanna Matthews. 2014. *Life Cycle Assessment: Quantitative Approaches for Decisions that Matter.* Last visited d. 09-05-2021, Link: https://www.lcatextbook.com/.

Mattila, T.J., S. Pakarinen, and L. Sokka. 2010a. “Quantifying the total environmental impacts of an industrial symbiosis-a comparison of process-, hybrid and input-output life cycle assessment.” *Environmental Science and Technology* 44 (11): 4309–4314.

Mattila, Tuomas, Suvi Lehtoranta, Laura Sokka, Matti Melanen, and Ari Nissinen. 2012. “Methodological Aspects of Applying Life Cycle Assessment to Industrial Symbioses.” *Journal of Industrial Ecology* 16 (1): 51–60.

Mattila, Tuomas J, Suvi Pakarinen, and Laura Sokka. 2010b. “Quantifying the Total Environmental Impacts of an Industrial Symbiosis - a Comparison of Process-, Hybrid Input-Output Life Cycle Assessment.” *Environmental science & technology* (Washington, DC) 44 (11): 4309–4314.

Miljøstyrelsen. 2017. *Kortlægning af sammensætningen af dagsrenovation og kildesorteret organisk affald fra husholdninger 2017.* Accessed 21-04-2022 https://www2.mst.dk/Udgiv/publikationer/2018/03/978-87-93614-78-9.pdf.

Ministeriet for Fødevarer, Landbrug og Fiskeri. 2021. *Top 10: Her er de mest dyrkede afgrøder i 2021.* Accessed 01-06-2022 Link: https://via.ritzau.dk/pressemeddelelse/top-10-her-er-de-mest-dyrkede-afgroder-i-2021?publisherId=12715964&releaseId=13625966.

Mirata, Murat. 2004. "Experiences from early stages of a national industrial symbiosis programme in the UK: determinants and coordination challenges." Applications of Industrial Ecology, *Journal of Cleaner Production* 12 (8): 967–983.

Mohammed, Feisal, Wahidul K. Biswas, Hongmei Yao, and Moses Tadé. 2018. "Sustainability assessment of symbiotic processes for the reuse of phosphogypsum." *Journal of Cleaner Production* 188:497–507.

Munn, Zachary, Micah Peters, Cindy Stern, Catalin Tufanaru, Alexa McArthur, and Edoardo Aromataris. 2018. "Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach." *BMC medical research methodology* 18 (1): 1–7.

Network for Sustainable Business Development. 2021. *GRØN: Grønne Ressource-Økosystemer Nordjylland.* Last visited d. 23-02-2022, Link: https://nben.dk/groen.

Nordjylland Power Station A/S. 2018. *Aarsrapport 2018.* Accessed 21-04-2022 https://aalborgforsyning.dk/media/tavnyanp/samlet-%C3%A5rsrapport-nordjyllandsv%C3%A6rket.pdf.

O'Raghallaigh, Paidi, David Sammon, and Ciaran Murphy. 2010. "Theory-building using Typologies - A Worked Example of Building a Typology of Knowledge Activities for Innovation.," 212:371–382. January.

OECD. 1965. "Chemical Production: Profile of a growth industry." *The OECD observer.,* no. 14.

Ormazabal, Marta, Vanessa Prieto-Sandoval, Rogério Puga-Leal, and Carmen Jaca. 2018. "Circular Economy in Spanish SMEs: Challenges and opportunities." *Journal of Cleaner Production* 185:157–167.

Pigosso, Daniela C A, Andreas Schmiegelow, and Maj Munch Andersen. 2018. "Measuring the Readiness of SMEs for Eco-Innovation and Industrial Symbiosis: Development of a Screening Tool." *Sustainability* 10 (8).

Port of Aalborg A/S. 2019. *Årsrapport for 2018.* Accessed 21-04-2022 http://regnskaber.virk.dk/29137421/ZG9rdW1lbnRsYWdlcjovLzAzLzY4LzVjLzZkLzI3LzljMmQtNGFmNi04ODBkLThiM2ZmYjc5ZDg0ZQ.pdf.

Prediger, Sebastian, Björn Vollan, and Benedikt Herrmann. 2013. *Resource Scarcity, Spite and Cooperation.* 1–31. German Institute for Global / Area Studies.

Purvis, Ben, Yong Mao, and Darren Robinson. 2018. "Three pillars of sustainability: in search of conceptual origins." *Sustainability science* 14 (3): 681–695.

Rambøll. 2021. *Målrettet indsats for at mindske mentantab fra danske biogasanlæg.* Accessed 23-05-2022 Link: https://ens.dk/sites/ens.dk/files/Bioenergi/metantab_rapport.pdf.

Rogers, Everett M. 2003. *Diffusion of innovations* [in eng]. 5th ed. New York: Free P. ISBN: 9780743258234.

Sacchi, R., and Y.K. Ramsheva. 2017. "The effect of price regulation on the performances of industrial symbiosis: A case study on district heating." *International Journal of Sustainable Energy Planning and Management* 14:39–56.

Salomone, R., G. Saija, G. Mondello, A. Giannetto, S. Fasulo, and D. Savastano. 2017. "Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assessment to process using Hermetia illucens." *Journal of Cleaner Production* 140:890–905.

Saunders, Mark, Philip Lewis, and Andrian Thornhill. 2013. "Understanding Research philosophies and Approaches." Chap. 4 in *Philosophy of Science & Methodology,* edited by Richard Brooks, 94–124. Harlow: Pearson.

Schandl, Heinz, Marina Fischer-Kowalski, James West, Stefan Giljum, Monika Dittrich, Nina Eisenmenger, Arne Geschke, et al. 2016. *Global Material Flows and Resource Productivity - Assessment Report for the UNEP International Resource Panel.* UNEP.

Schlüter, Leonie, and Andrea Milani. 2018. *An Ecosystem Analysis of Industrial Symbiosis Development in Aalborg, Denmark.* Aalborg University.

Schmidt, Jannick, and Ivan Muñoz. 2014. *The carbon footprint of Danish production and consumption – Literature review and model calculations.* Technical report. Danish Energy Agency, Copenhagen.

Snyder, Hannah. 2019. "Literature review as a research methodology: An overview and guidelines." *Journal of Business Research* 104:333–339.

Sokka, Laura. 2011. "Local systems, global impacts : Using life cycle assessment to analyse the potential and constraints of industrial symbioses." PhD diss., University of Helsinki.

Sokka, Laura, S. Lehtoranta, A. Nissinen, and M. Melanen. 2011. "Analyzing the Environmental Benefits of Industrial Symbiosis: Life Cycle Assessment Applied to a Finnish Forest Industry Complex." *Journal of Industrial Ecology* 15 (1): 137–155.

Soratana, K., and A.E. Landis. 2011. "Evaluating industrial symbiosis and algae cultivation from a life cycle perspective." *Bioresource Technology* 102 (13): 6892–6901.

Statistikbanken. 2021. *SITC2R4Y: Coal Import (1000kr) 2011-2021.* Accessed 11-05-2022 Link: https://www.statistikbanken.dk/SITC2R4Y.

Subramanian, K., S.S. Chopra, and W.S. Ashton. 2021. "Capital-based life cycle sustainability assessment: Evaluation of potential industrial symbiosis synergies." *Journal of Industrial Ecology* 25 (5): 1161–1176.

The European Commission. 2020. *The European Green Deal.* Brussels.

United Nations. 1987. *Report of the World Commission on Environment and Development: Our Common Future.* Technical report. Federal Office for Spatial Development ARE.

Van Phi, C., M. Walraven, M. Bézagu, M. Lefranc, and C. Ray. 2020. "Industrial symbiosis in insect production— A sustainable eco-efficient and circular business model." *Sustainability* 12 (24): 1–14.

Viganò, E., C. Brondi, S. Cornago, A. Caretta, L. Bua, L. Carnelli, G. Dotelli, M. Martin, and A. Ballarino. 2020. "The LCA modelling of chemical companies in the industrial symbiosis perspective: Allocation approaches and regulatory framework." *Life Cycle Assessment in the Chemical Product Chain: Challenges, Methodological Approaches and Applications,* 75–98.

Vitale, P., R. Napolitano, F. Colella, C. Menna, and D. Asprone. 2021. "Cement-matrix composites using cfrp waste: A circular economy perspective using industrial symbiosis." *Materials* 14 (6).

Wang, S., C. Lu, Y. Gao, K. Wang, and R. Zhang. 2019. "Life cycle assessment of reduction of environmental impacts via industrial symbiosis in an energy-intensive industrial park in China." *Journal of Cleaner Production* 241.

WBCSD, WRI. 2015. *The Greenhouse Gas protocol - A Corporate Accounting and Reporting Standard.* Revised edition 3.51.

Weidema, Bo. 2000. "Avoiding Co-Product Allocation in Life-Cycle Assessment" [in eng]. *Journal of industrial ecology* (238 Main St., Suite 500, Cambridge, MA 02142-1046 USA) 4 (3): 11–33. ISSN: 1088-1980.

———. 2017. "Estimation of the size of error introduced into consequential models by using attributional background datasets." *The international journal of life cycle assessment* 22 (8): 1241–1246.

Weidema, Bo, Massimo Pizzol, Jannick Schmidt, and Greg Thoma. 2018. "Attributional or consequential Life Cycle Assessment: A matter of social responsibility." *Journal of cleaner production* 174:305–314.

Weidema, Bo, Marianne Wesnæs, John Hermansen, Troels Kristensen, and Niels Halberg. 2008. *Environmental Improvement Potentials of Meat and Dairy Products.* Technical report. European Commission JCR, Ispra.

Weidema, Bo Pedersen. 2009. "Using the budget constraint to monetarise impact assessment results" [in eng]. *Ecological economics,* Ecological Economics, 68 (6): 1591–1598. ISSN: 0921-8009.

Wilson, Jonathan. 2014. *Essentials of Business Research: A Guide to Doing Your Research Project.* 2nd ed. Newcastle: SAGE.

Yin, Robert K. 2009. *Case Study Research - Design and Methods.* Thousand Oaks, California: SAGE publications.

Yu, B., X. Li, L. Shi, and Y. Qian. 2015. "Quantifying CO2 emission reduction from industrial symbiosis in integrated steel mills in China." *Journal of Cleaner Production* 103:801–810.

Yu, F., F. Han, and Z. Cui. 2015. "Assessment of life cycle environmental benefits of an industrial symbiosis cluster in China." *Environmental Science and Pollution Research* 22 (7): 5511–5518.

Zhang, Y., S. Duan, J. Li, S. Shao, W. Wang, and S. Zhang. 2017. "Life cycle assessment of industrial symbiosis in Songmudao chemical industrial park, Dalian, China." *Journal of Cleaner Production* 158:192–199.

Zheng, Kaifang, and Suling Jia. 2017. "Promoting the Opportunity Identification of Industrial Symbiosis: Agent-Based Modeling Inspired by Innovation Diffusion Theory." *Sustainability* 9 (5).

Zink, Trevor, and Roland Geyer. 2017. "Circular Economy Rebound." *Journal of Industrial Ecology* 21:1–10.

Appendix

Appendix A

External LCI Matrix

A.1 Import Instructions

The LCA model developed in this project is exported into several CSV files which are ready for import into SimaPro 9.3.0.3. The CSV files are found within the external appendix. To Import the CSV-files the following steps are required to be made in order. It is assumed that before starting the import process, Exiobase v3316b2 re-structured is available as library. If not, importing this library should be the first step. If it is desired to study the results of this study, **Stepwise 2006** is applied as method, and will hence have to be imported to SimaPro as well. This is though not necessary in the process of importing the CSV-files and other methods can be chosen for the assessment if desired.

To prepare SimaPro to import of the CSV-files, a specific unit for MEUR_{2018} has to manually be created within SimaPro.

Step 1) Create Unit MEUR_{2018}:

1. Create new project in SimaPro which to import the CSV-files into.
2. Turn on the library: **"Exiobase v3316b2 re-structured"**
3. Go to **"Units"** on the left toolbar and create new unit.
4. Name the unit by **"MEUR2018"**
5. Choose **"Currency"** as quantity
6. Set factor to **"0.782928E6"**
7. Make sure that **"Metric"** is ticked on

Step 2) Import Settings

1. Go to **"Files"** and choose **"Import"**
2. In the pup-up window certain setup is needed for import. Choose **"SimaPro CSV"**.
3. Under **"Object link method"** choose **"Try to link imported objects to existing objects first"**
4. Under **"CSV format seperator"** choose **"Tab"**
5. Under **"Other options"** choose **"Replace existing processes with equal identifiers or product names"**
6. Under **"Import files"** choose **"Add"** and select the first CSV-file to import. (SimaPro is only capable of importing one file at the time.

Step 3) Import order for CSV-files

1. Import_ISN_Reference_Scenario.CSV
2. Import_GRON_Symbiotic_Scenario.CSV
3. Import_GRON_Baseline_Scenario.CSV

Appendix B

Marginal Mixes

B.1 Marginal Heat Supply - Aalborg

Activitiy	Unit	Normalized Value	Adj. HP	Adj. Biomass
RF	TJ	1	0.3333	0.6667
Materials/fuels				
8 Cultivation of crops nec {DK} (product market, hybrid units, purchaser price)	ton/TJ	2.07E+00	0.00E+00	0.00E+00
18 Forestry, logging and related service activities (02) {DK} (product market, hybrid units, purchaser price)	ton/TJ	2.75E+00	0.00E+00	0.00E+00
20 Mining of coal and lignite; extraction of peat (10) {DK} (product market, hybrid units, purchaser price)	ton/TJ	3.28E+01	0.00E+00	0.00E+00
22 Extraction of natural gas and services related to natural gas extraction, excluding surveying {DK} (product market, hybrid units, purchaser price)	ton/TJ	9.93E+00	0.00E+00	0.00E+00
57 Petroleum Refinery {DK} (product market, hybrid units, purchaser price)	ton/TJ	1.25E+00	0.00E+00	0.00E+00
63 Chemicals nec {DK} (product market, hybrid units, purchaser price)	ton/TJ	2.92E-03	4.00E-03	2.92E-03
70 Re-processing of ash into clinker {DK} (product market, hybrid units, purchaser price)	ton/TJ	1.05E+00	0.00E+00	0.00E+00
112 Steam and hot water supply {DK} (product market, hybrid units, purchaser price)	TJ/TJ	1.48E-01	0.00E+00	0.00E+00
145 Incineration of waste: Wood {DK} (product market, hybrid units, purchaser price)	ton/TJ	1.42E-01	0.00E+00	0.00E+00
Electricity mix {DK} (terminated)	TJ/TJ	-3.87E-01	2.76E-02	1.45E-03
Emissions to air				
Carbon dioxide, fossil	ton/TJ	1.06E+02	0.00E+00	1.34E+02
Carbon dioxide, biogenic	ton/TJ	5.85E+00	0.00E+00	0.00E+00
Dinitrogen monoxide	ton/TJ	4.17E-03	0.00E+00	2.88E-03
Methane, fossil	ton/TJ	1.65E-02	0.00E+00	0.00E+00
Nitrogen oxides	ton/TJ	1.06E+02	0.00E+00	1.00E-01
				CONTINUES

Table B.1: Marginal mix for District heat utilizing heat pump and biomass in disaggregation of 112 Steam and hot water supply {DK}

Activitiy	Unit	Normalized Value	Adj. HP	Adj. Biomass
Sulfur dioxide	ton/TJ	5.85E+00	0.00E+00	3.13E-03
Ammonia	ton/TJ	4.17E-03	0.00E+00	2.16E-03
NMVOC	ton/TJ	1.65E-02	0.00E+00	0.00E+00
Carbon monoxide	ton/TJ	7.70E-02	0.00E+00	0.00E+00
Lead	ton/TJ	1.85E-02	0.00E+00	3.13E-05
Cadmium	ton/TJ	3.76E-04	0.00E+00	8.75E-07
Mercury	ton/TJ	1.05E-02	0.00E+00	3.75E-07
Arsenic	ton/TJ	7.10E-02	0.00E+00	1.25E-06
Chromium	ton/TJ	1.77E-06	0.00E+00	4.95E-06
Copper	ton/TJ	2.44E-07	0.00E+00	2.75E-05
Nickel	ton/TJ	3.16E-07	0.00E+00	7.50E-06
Selenium	ton/TJ	1.41E-06	0.00E+00	0.00E+00
Zinc	ton/TJ	1.04E-06	0.00E+00	3.75E-04
Polychlorinated biphenyls	ton/TJ	1.47E-06	0.00E+00	1.47E-06
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	ton/TJ	4.24E-06	0.00E+00	3.88E-11
Particulates, < 10 um	ton/TJ	2.55E-06	0.00E+00	0.00E+00
Particulates, < 2.5 um	ton/TJ	7.91E-06	0.00E+00	6.25E-03
Benzo(a)pyrene	ton/TJ	2.75E-08	0.00E+00	6.25E-07
Benzo(b)fluoranthene	ton/TJ	2.41E-12	0.00E+00	0.00E+00
Benzo(k)fluoranthene	ton/TJ	3.02E-03	0.00E+00	0.00E+00
Indeno(1,2,3-cd)pyrene	ton/TJ	4.09E-03	0.00E+00	0.00E+00
Benzene, hexachloro-	ton/TJ	1.81E-08	0.00E+00	9.00E-12
TSP	ton/TJ	3.06E-09	0.00E+00	0.00E+00
CO2-eq (DK)	ton/TJ	2.66E-10	0.00E+00	0.00E+00

Table B.2: Marginal mix for District heat utilizing heat pump and biomass in disaggregation of 112 Steam and hot water supply {DK}

B.2 Marginal Coal Supply

Market	Unit	Amount	Share%
RF	ton	1	100%
Materials/inputs			
20 Mining of coal and lignite; extraction of peat (10) IT (terminated incl cap)	ton	0.325	32.59%
20 Mining of coal and lignite; extraction of peat (10) CA (terminated incl cap)	ton	0.0136	1.37%
20 Mining of coal and lignite; extraction of peat (10) FI (terminated incl cap)	ton	0.022	2.28%
20 Mining of coal and lignite; extraction of peat (10) IN (terminated incl cap)	ton	0.004	0.47%
20 Mining of coal and lignite; extraction of peat (10) LT (terminated incl cap)	ton	0.145	14.54%
20 Mining of coal and lignite; extraction of peat (10) GB (terminated incl cap)	ton	0.018	1.86%
20 Mining of coal and lignite; extraction of peat (10) SE (terminated incl cap)	ton	0.168	16.81%
20 Mining of coal and lignite; extraction of peat (10) US (terminated incl cap)	ton	0.300	30.09%

Table B.3: Marginal mix for coal, based on import numbers from 2021 (Statistikbanken 2021)

Appendix C

Reference Baseline Scenario - Site Specific Data

C.1 ISN - Annual Net Turnover

ISN Entity	Unit	Net Turnover	Share (%)
Aalborg Portland A/S	$MEUR_{2018}$	244.1	36.65%
Alfa Laval AB	$MEUR_{2018}$	130.5	17.99%
Nordjylland Power Station (NPS)	$MEUR_{2018}$	128.6	17.73%
Colas A/S	$MEUR_{2018}$	115.1	15.87%
Reno Nord I/S	$MEUR_{2018}$	38.3	5.28%
Aalborg Kloak A/S	$MEUR_{2018}$	36.5	5.03%
Port of Aalborg A/S	$MEUR_{2018}$	26.7	3.68%
Farms in Vodskov	$MEUR_{2018}$	3.6	0.49%
Aalborg Crematorium	$MEUR_{2018}$	2.0	0.28%
Total	**$MEUR_{2018}$**	**725.4**	**100%**

Table C.1: Distribution of net turnover ($MEUR_{2018}$) among entities within the ISN Network

C.2 Aalborg Crematorium

Data	Unit	Amount	DM Ratio
Turnover, financial	$MEUR_{2018}$	2	-
Turnover, activity	$MEUR_{2018}/MEUR_{2018}$	2945.18	-
Input			
Natural gas	ton	445.25	-
Symbiotic output			
Substituted heat	TJ	3.00	-
Emissions			
CO_2	ton/ton	2.5504	-
Methane	ton/ton	0.00344	-
Nitrogen Oxide	ton/ton	0.0013	-

Table C.2: Aalborg Crematorium: Site specific data from 2021 acquired from consulting the department. Financial turnover is a proxy value.

C.3 Aalborg Forsyning A/S - Nordjylland Power Station

Data	Unit	Amount	DM Ratio
Turnover, production	TJ	3,949	-
Turnover, financial	MEUR2018	128.62	-
Turnover, activity	TJ/MEUR2018	30.7	-
Input			
Coal	ton (DM)	530,061	1
Fuel Oil	ton (DM)	688	1
Gas Oil	ton (DM)	143	1
Chalk	ton (DM)	4,792	1
Waste, incineration	ton (DM)	72	-
Electricity, consumption	TJ	405.78	-
Heat, consumption	TJ	6.85	-
Symbiotic input			
Chalk slurry	ton (DM)	5,820	1
Symbiotic output			
Fly ash	ton/TJ	11.08	1
FDG Gypsum	ton/TJ	5.71	1
Electricity	TJ/TJ	1.25	-
Emissions			
CO_2	ton	1,222,200	-
CH_4	ton	19.47	-
Nitrous Oxides	ton	9.85E-10	-
SO_2	ton	34.8	-
CO	ton	129.71	
PM2.5	ton	57.88	
Dinitrogen monoxide	ton	10.40	-
NMVOC, non-methane	ton	19.47	-

Table C.3: Nordjylland Power Station: Site specific data for 2018 (Nordjylland Power Station A/S 2018)

C.4 Aalborg Kloak A/S - Treatment Plant East and West

Data	Unit	Amount	DM Ratio
Turnover, production	ton (DM)	11,036	(See caption)
Turnover, financial	$MEUR_{2018}$	38	-
Turnover, activity	ton/$MEUR_{2018}$	288.4	-
Input			
Electricity	TJ	38.06	-
District heat	TJ	1.86	-
Natural gas	ton (DM)	42	-
Symbiotic output			
Biogas, sludge	ton (DM)	1063.33	0.269
Dry sludge, fuel	ton (DM)	1022.20	0.269

Table C.4: Aalborg Kloak A/S - Treatment Plant East and West: Site specific data for 2018 (Aalborg Forsyning 2020) It should be noted that two DM ratios are applied within turnover, production, DM for dry sludge - 0.721 and DM for wastewater - 0.02

C.5 Aalborg Portland A/S

Data	Unit	Amount	DM Ratio
Turnover, production	ton (DM)	2,151,545	0.93
Turnover, financial	$MEUR_{2018}$	244.14	-
Turnover, activity	ton/$MEUR_{2018}$	8,813	-
Input			
Chalk	ton (DM)	3,905,097	1
Sand	ton (DM)	112,982.36	0.76
Gypsum	ton (DM)	658,50	1
Oil	ton (DM)	215,996	1
Coal	ton (DM)	75,106	1
Electricity	TJ	1115	-
Symbiotic input			
Fly ash	ton (DM)	124,225	1
Sand	ton (DM)	122,441	0.76
FDG Gypsum	ton (DM)	51,077	1
Dry sludge	ton (DM)	1,022	0.26
Symbiotic output			
Chalk	ton/ton product	0.004	1
Heat	TJ	1,185	-
Emissions			
CO_2	ton	2,190,706	-
Nitrous oxides	ton	2,494	-
SO_2	ton	895	-
CO	ton	3,624	-
PM2.5	ton	89	-
Ammonia	ton	86	-
Mercury	ton	0.03	-

Table C.5: Aalborg Portland: Site specific data from 2018 (Aalborg Portland A/S 2019)

C.6 Alfa Laval A/S

Data	Unit	Amount	DM Ratio
Turnover, production	ton	15,410	-
Turnover, financial	$MEUR_{2018}$	130.46	-
Turnover, activity	ton/$MEUR_{2018}$	118.12	-
Input based on Ecoinvent*			
Polyethylene	ton (DM)	37.27	1
Alkyd paint	ton (DM)	66.55	1
Brazing solder	ton (DM)	159.71	1
Stone wool, packed	ton (DM)	505.74	1
Steel, Chromium	ton (DM)	665.45	0.999
Steel, low-alloyed	ton (DM)	12,909.79	0.999
Aluminium	ton (DM)	399.27	0.999
Brass	ton (DM)	1.33	0.999
Copper, cathode	ton	665.45	0.999
Electricity	TJ	31,81	-
Heat, natural gas	TJ	46.00	-
Heat, other than natural gas	TJ	25.54	-
Symbiotic output			
Substituted heat	TJ	8.00	-

Table C.6: Alfa Laval: Input data from Ecoinvent 3.8 - Oil boiler, 100kW {CH} production | Conseq, U. Substituted heat is site specific data delivered by PARD.

C.7 Colas A/S

Data	Unit	Amount	DM Ratio
Turnover, products	ton	202,881	-
Turnover, financial	$MEUR_{2018}$	115.13	-
Turnover, activity	ton/$MEUR_{2018}$	1,762	-
Input			
Bitumen	ton	10,144	-
Stone	ton	182,592	-
Filler, cement	ton	2,210	-
Filler, sand	ton	5,600	-
Symbiotic Input			
Filler, fly ash	ton	2,333	-

Table C.7: Colas A/S: Site specific data acquired bu consulting the company. Supplementary generic data from Ecoinvent 3.8 - Mastic asphalt {RoW}| production | Conseq, U. is applied

C.8 Farms in Vodskov

Data	Unit	Amount	DM Ratio
Turnover, total	$MEUR_{2018}$	3.57	-
Turnover, wheat	Share %	23.83	-
Turnover, cereal grains	Share %	76.17	-
Input			
Water, grain	ton	37,336	-
Water, wheat	ton	8,248	-
Symbiotic output			
Water, NPS	ton	120,000.00	-

Table C.8: Proxy allocation of production split for Farms in Vodskov, including input of additional water for cultivation.

C.9 I/S Reno Nord

Data	Unit	Amount	DM Ratio
Turnover, production	TJ	1,534.02	-
Turnover, financial	$MEUR_{2018}$	36.4	-
Turnover, activity	ton/$MEUR_{2018}$	3,025	-
Input			
Waste, food	ton	46,280	0.60
Waste, paper	ton	11,346	0.90
Waste, plastic	ton	19,838	1
Waste, metals and inert materials	ton	6,689	0.9
Waste, textiles	ton	2,339	0.86
Waste, wood	ton	9,681	0.92
Waste, oil/hazardous	ton	14,131	0.86
Biofuel	ton	7,872	-
Symbiotic output			
Heat	TJ	1,534.02	-
Electricity	TJ	363.21	-
Emissions			
CO_2	ton	198,800	-
Nitrous oxides	ton	167.06	-
SO_2	ton	4.36	-
CO	ton	10.96	-
PM2.5	ton	0.41	-
Ammonia	ton	0.48	-
Mercury	ton	0.00	-

Table C.9: Reno Nord: Site specific data from 2018 I/S Reno Nord (2018) with calculated waste fraction amounts based on Miljøstyrelsen (2017)

C.10 Port of Aalborg

Data	Unit	Amount	DM ratio
Turnover, total	MEUR2018	26.73	-
Turnover, renting machinery and equipment	Share %	45.82	-
Turnover, real estate activities	Share %	54.18	-
Symbiotic output			
Sand	ton (DM)	112,982	0.76

Table C.10: Port of Aalborg: Site specific data from 2018 Port of Aalborg A/S (2019)

Appendix D

Expanded Network Scenario - Site Specific Data

D.1 GRØN - Annual Net Turnover

ISN Entity	Unit	Net Turnover	Share (%)
Nordjylland Dairy	$MEUR_{2018}$	54.47	79.46%
Nordjylland Bakery	$MEUR_{2018}$	5.31	7.75%
Green Waste Management Company	$MEUR_{2018}$	5.09	7.43%
Local Grocery Association	$MEUR_{2018}$	2.79	4.07%
Industrial Fishing Port	$MEUR_{2018}$	0.67	0.98%
Small Waste Management Company	$MEUR_{2018}$	0.22	0.32%
Total	**$MEUR_{2018}$**	**68.55**	**100%**

Table D.1: Distribution of net turnover ($MEUR_{2018}$) among entities within the GRØN Network

Appendix E

Interview Transcriptions

E.1 Interview with Per Møller from Kalundborg Symbiosis

The following interview was conduct in Feburary 2022 with interviewee Per Møller, Head of Symbiosis, at Kalundborg Symbiosis. This transcription is fully transcribed, with few exceptions of non-relevant material. **Note, the interview is conducted and transcribed in Danish.**

Q: = **Question**
PM: = **Per Møller**

Q: Ja, altså vi har snakket før og det kan du nok ikke huske fra nogle måneder siden hvor det var, at vi talte om at lave noget LCA over på Kalundborg symbiosen I forlængelse af det Thais hun skulle lave og det er vi så gået i gang med i stedet for heroppe I Aalborg med Industriel symbiose nord (ISN) Det jo meget klart og tydeligt at de 2 er meget langt fra hinanden i betragtning af hvor etablerede de i realiteten er og hvad der findes i dem. Og der tænker, vi egentlig er vores speciale det godt ville involvere Kalundborg, symbiosen eller anden forstand for at sammenligne de 2. Men til at starte ud med kan du så ikke introducere dig selv og hvad du laver?

PM: Jeg hedder Per Møller og jeg sidder som senior Symbiose udvikler i Kalundborg symbiosen. Ja min baggrund, jeg er faktisk uddannet biolog på Aarhus Universitet og har lavet speciale i København og her efterfølgende så lavet Ph.d. på DTU i Lyngby. Så Det er Sådan selv min uddannelsesbaggrund, så har jeg arbejdet i det private. Jeg har Sådan set specialiseret mig inden for Lipid analyser, naturlig forekommende olier I det Marine økosystem og så altså både med henblik på at forstå hvad koster ernæring, men også bruge det som biomarkør i hvordan økosystemet ligesom er skruet sammen og hvis der sker ændringer, så kan man spore det i det. Det er ligesom min baggrund, Sådan rent biokemisk, analytisk, men med en biologisk tilgang til tingene og en helt klar økosystemforståelse.

Q: Det er jo en analogi til naturvidenskaben, det der med symbiose.

PM: Ja ja og Det er sådan også sådan ej navnet det ligesom kom hertil i 89 ikke. Det her var jo studerende, som havde en forståelse inden for biologien. Det var jo ligesom symbioser som man så i naturen, så kom industrien bare på, ikke? Og så var det, det tog at derfra. Men altså, jeg sidder jo og prøver at facilitere sammen med 4 kollegaer. Industriel symbiose i hvert fald fra et sekretariats perspektiv. Og Det er ud fra den konstruktion er vi jo en nonprofit privat forening. Sådan er vi organiseret. Det er faktisk først april er det 2 år siden, at vi gik fra at være et sekretariat med et kontor i kommunen. Til faktisk at blive flyttet ind i selve foreningen og så blive ansat der før var vi ansatte I kommunen, når arbejdet fra symbiose, så Det er Sådan et rent organisatorisk. Nu sidder vi i en privat forening, men vi har hele tiden arbejdet for den private forening, så det er rent organisatorisk, så kan man gøre det på mange måder, men Det er sådan, vi har gjort det, og det er nogle grunde til. Jo, men det kan vi komme ind på senere.

PM: Så sidder jeg jo primært med chefen og facilitere, kan vi sige hele bestyrelsen, fordi vores forening består en bestyrelse med direktørernes fra hver af de virksomheder som er medlemmer af foreningen, og vi har et advisory board, og vi har et innovation board. Og den bruger vi så nu aktivt. Det er noget nyt med vores reorganisering og bruger vi så til yderligere understøtte og udvikle symbiosen, arbejde tættere sammen, blive helt konkrete og gør de ting sammen der er lidt sværere men så alligevel forsøge at gøre det fordi det de lavthængende frugter er blevet høstet nu begynder det at blive lidt sværere, men der sker hele tiden ændringer også det vi gør ligesom symbiose projekter. De kan jo nogle gange gøres bedre når Der er en teknologi, der ligesom bryder igennem, eller der er noget policy der lige pludselig åbner op for det eller noget lovgivning. Nye ressourcer eller andre ting der ændrer sig i virksomheder, en virksomhed kommer til eller virksomheder forlader, eller så ændrer sig eller Sådan noget. Så alt det. Det er så dynamisk, og det er det der vigtigt at forstå med symbiosen. Det er utroligt dynamisk.

Q: Og jeres roller der, er så også at undersøge og forske, eller er mere det der med at kommunikere mellem virksomhederne, hvad der forandrer sig. Kan du sætte nogle ord på?

PM: Altså Det er både og det vil sige, vi kan ikke det hele, men vi laver dels sådan meget direkte facilitering af netværket og organisationen, men vi laver også micro facilitering rundt omkring, men så laver vi også det som vi kalder forskning og udvikling. Og det gør vi igennem, egne projekter, men også dels igennem projekter, som finansieret af EU eller INTERREG eller Nordic Innovation, Region Sjælland eller Erhvervsstyrelsen. Og som de nu har passet, det vil sige i før i tiden, har vi nok grebet et projekt lidt mere som en del af det, man gjorde i kommunen. Sådan lidt her og dér, hvor vi de sidste ja 10 år, vil jeg sige, er blevet mere målrettet mod og levere konkret værdi ind I symbiose grøn omstilling konteksten, mere fokuseret. Også fordi at ellers så ender med at lave projekter som stritter i alle retninger, og så er der ikke ligesom specifik viden, der blev opbygget.

Q: Er det så er det så altid projekter der er fokuseret ind mod Kalundborg symbiosen. Eller er det også nogle gange projekter, der skal formidle Kalundborg symbiosen ud i verden eller?

PM: Ja og her på det seneste også endnu mere fokus på at hive noget ind. Men Det er jo fordi Vi har været eksemplet, og derimod har der været rigtig mange, der har haft behov for og ønsket at lære at forstå, hvad vi har gjort, og det har vi jo også selv skullet lære at forstå, fordi det er jo ikke noget, der har været planlagt det her. Det er organisk udviklet. Der er jo ikke nogen der havde planlagt at det er, skulle organiseres det der skulle opstå. Det er noget der er sket naturligt over tid, og så har man lige pludselig fået øjnene op for det, og så får det et navn og så lige pludselig får man hov, når? Det er det det er, det er det vi går og gør. Vi går bare laver noget vi synes det giver god mening for en forretning, og så har det jo også den afledende effekt at det er godt for miljøet og skaber noget innovation og samfundsøkonomisk giver god mening. Og spændende sted at arbejde og udvikle ens virksomhed så på den måde er det bare sket over tid, men det er der så nogen der har set, næsten før vi selv har set det, og Jeg har ikke været med hele vejen overhovedet. Jeg har været med I en 13 år nu eller Sådan noget og så kun her de sidste 2 år været med i symbiosen, altså være ansat I selve foreningen. Så det at folk har set det har så gjort, at vi selv er blevet bevidste om, at vi har faktisk noget her, en fortælling, og vi har måske Ikke være god til at fortælle den lokalt, men vi er verdenskendte, men ikke så godt kendte lokalt. Så det er det, der er lidt pudsigt og der finder man så ud af og prøver at kigge på sig selv, siger okay måske skal vi arbejde med systematik? Måske skal vi også kigge på, hvad er det for værdier, vi skaber herunder LCA. Og det er sgu ikke lige til fordi det at lave LCA ned på et partnerskab. Nu ved jeg jo ikke om det Søren Løkke i at koblet til eller, men det ved han selv. Han sad dér til eksamen, og vi havde en rigtig god snak om siger det er sgu ikke bare lige Sådan. Så det kan godt være man ved hvad man gerne vil, men og prøve at sætte det ind i sådan et økosystem betragtning der Det er lidt langhåret, så skal man der skal man gøre sig nogle antagelser der man må starte et sted og Det har vi så gjort. Og så stille og roligt månes det og så så rigtig meget ud af. Og mere endnu også hvor vi prøver så at sige, okay, Der er meget at lære ude. Der sker faktisk mange ting rundt omkring, og Vi har jo haft en tæt dialog med Aalborg jo i flere år nu og med CLS Port of Aalborg primært, men også vi kender godt miljø++ og GRØN og har lige snakket med Lucia i dag for. Hvor vi snakket om den her poster med ISN, hvor de har brugt vores logo fra symbiose netværk Danmark som Jeg har været med til at starte op. Så der er en kobling i den måde, vi også kommunikere på. Nu også meget mere nationalt, og det synes vi jo er interessant og spændende.

Q: Var du en del af det her med, at man går fra ikke at have en faciliteret symbiose til, at det bliver en faciliteret symbiose?

PM: Det har nok været før min tid. Fordi det der sker omkring 9 - 11 [Red: 2009 - 2011] Der er lidt utilfredshed omkring symbiosen. Sker der noget? Det ligger lidt stille og er det egentlig noget vi skal gøre noget ved de her symbioser. Og der bliver man faktisk enige om, at det, at det vil man gerne, og kommunen hopper faktisk ind og siger at vi vil godt lægge, ikke ryg til, men hus til. Vi vil gerne huse et sekretariat, også skaber vi en forening i 11. Før vare det ellers bare noget der har været ude i virksomhederne, også har man prøvet at have hyret en konsulent som skulle være bindeleddet eller prøve at drive det her og det stak lidt af og det hang ikke sammen. Men det her med at få etableret en forening, hvor man ligesom laver en bestyrelse, hvor man dedikerer sig ind, og vi så også senere har fået lavet en vision om en mission, og nu her for første gang overhovedet en handleplan, som peger langt frem, altså frem til 2030, har lige fået godkendt her i tirsdags til vores generalforsamling. Så alt lt det der, vores advisory board, vores innovation board, så hele den dér organisering og struktur. Det der med at blive enige om nogle ting og vedtage nogle ting og gå efter de her ting i sådan lidt isamlede flok og alligevel med egen formål får øje. Det er det der gør forskellen nu.

Q: Og så starter i kommunen, men flytter ud i jeres egen organisation?

PM: Ja altså foreningen bliver så bliver skabt der. Og så i den forbindelse begynder man stille og roligt at tænke. Hvad gør vi så? Og man snakker meget kommunikation også om branding af kommunen i den forbindelse, ikke Så grøn industri Kommune og sådan noget. Men det er man gået fra igen af en eller anden grund, men så begynder det ligesom at gro, og man begynder også at tænke projekter. COP15 der var der et Epicon anlægget som lavede anden generations bioethanol fra halm, og det var ligesom med til at skubbe til nogle ting. Det der med at kommunen var inde og prøve at facilitere og arbejde sammen yderligere og lidt mere systematisk, hvor vi søgte nogle midler og fik nogle EU-projekter og kunne lave test og demo, som også er vigtigt. Faktisk for demonstrerer hvordan nogle teknologier kan gøre sig gældende eller hvordan en rest fraktion så kan opgraderes eller genanvende i symbiose forretningsmodel. Så er det så her for 2 år siden, at vi så efter en længere periode hvor jeg kunne se vi var hæmmet af at være i kommunen fordi der var noget kommunal fuldmagt. Der er ting man ikke må, så som Kommune. Blandt andet giver det grønne udviklingsprojekter og demonstrationsprojekter må vi ikke være med i, altså partnere i. Vi måtte heller ikke undervise eller rådgive. Så der var nogle ting, der gjorde, at det var svært at skubbe det videre ud og skabe den ekstra værdi, som vi mente de var modne til og vi følte det der med at stå som Kommune ansat over for en virksomhed det var ikke altid en fordel, det kunne faktisk være ulempe nogle gange. Så det at jeg kom ind i foreninger og ligesom blive en del af familien tæt på, og at være fri af de der bånd, men også forpligtet inden at skabe noget økonomi. Det afvejede vi og valgte så at tage det her skridt, og det har været med til i hvert fald i vores modenhedsniveau på det tidspunkt været den rigtige beslutning, synes vi, måske kunne det endda have været gjort noget før.

Q: Ja den modenhed du nævner der hvad kan du sige lidt om på det tidspunkt? Er det her en veletableret symbiose allerede? Altså er virksomhederne godt klar over at det her er noget som de dyrker sammen?

PM: Jeg synes Jeg synes på eller anden måde, at det var den der snak de havde der i 9 til 11 hvor man tænkte ej giver det også noget? Der bliver de ligesom bevidst om det altså. Man så siger de ligesom også, okay Skal vi så også investere i det og? Så er de blevet mere bevidst om det nu i takt med jo flere ting de har kunnet realisere og så vinder vi den her pris for nogle år tilbage i den her win win, sustainability price, som svarer til nobelprisen, men inden for grøn omstilling. Som virkelig har skubbet tingene, og den kommer umiddelbart efter. Jeg tror Det er cirka et år efter, vi får lavet vores første “LCA” Det var det så ikke. Det var mere sådan at slå LCI Inventory, hvor vi ligesom bare ser på, hvad er det, vi flytter, og hvad fortrænger det? Og så havde vi nogle konkrete tal på, og så bliver det lige pludselig målbart og synligt. Så en milepæl, er ligesom vi får et navn, og vi får nogle tal, som vi kan dokumentere. Samfundsøkonomi Copenhagen Economic var med til at beregne nogle ting. Så ligesom at få valideret det af eksterne eksperter, og ligesom kunne kommunikere det. Det er med til at løfte og selvfølgelig ikke bare udadtil, men også indadtil at beskrive hvad gør det her, så den enkelte virksomhed også forstår, hov, Der er faktisk noget i det, og når man så stille og roligt også selv oplever, at man bliver en del af den her symbiose model også laver noget forretning. Og man kan mærke at der kommer noget forespørgsel om man kan bruge det rejser til at sælge sine produkter på baggrund af det og hele det her med cirkularitet, altså cirkulær økonomi kommer ind, hvor det her jo er Sådan én, kan man sige hjørnestenene i det, for når man så siger industri, jamen, så så er det noget med timingen og modenhed også fra samfundets side af, og det og det pres der er, de brændende platforme der er rundt omkring for alt muligt, så de kommer lidt sammen og gør at man så lige pludselig som virksomhed selv kan mærke, se og forstå. Så Modenhed, netværk, men også modenhed i den enkelte virksomhed. Og hvem er det, der sidder der eller bliver ansat som direktør og måske allerede i forvejen har et kendskab er drevet af den type af udviklingen. Så det er også person specifikt i nogle virksomheder.

Q: Ja og der er mange aktører i sådan et netværk kunne jeg forestille mig, og når man gerne vil, som du siger at have nogle samfundsøkonomiske tal på og Sådan noget, så skal man også have sammen med noget data ind. Når i nu er modne og veletableret. Hvordan føler I, at dataindsamlingen går ude hos jer? Er det en udfordring eller er det noget, som i kan overkomme?

PM: Det er en udfordring, det er det. Og overkomme? Jamen det kan man så gradbøje lidt, fordi det kan vi sagtens overkomme, fordi vi kan ikke rigtigt få lov til at gå helt ned hvor vi gerne ville, men det er ved at ændre sig nu. Jeg tror det Der er vigtigt, er at få virksomhederne selv til ligesom at sige højt, hvad er det, de har behov for, hvis de skal skubbe det her yderligere, altså hvis vi skal have skabt den ekstra værdi, som ligger lige foran en hvis bare vi gør mere af det her, hvis de selv kan sige højt, at vi har behov for mere data, ikke bare med som en rigtige kvalitet [Usikker på hvad der bliver sagt]. Hvor vi skal forstå hvad det skal anvendes til, så bliver det pludselig muligt. Men det er det her med at måske specielt i vores lille netværk at, vi har jo lægemiddelindustrien også. Der er bare nogle ting som en masse forretningshemmeligheder, og der er man sårbar og man er ekstra forsigtig, så hvordan gør vi lige det her? Så det bliver fremadrettet en stor udfordring. Vi arbejder med at modne det, sådan på netværksniveau og med den enkelte virksomhed, men vi arbejder også på at finde ud af, hvordan pokker skaber vi så. Et ordentligt, kan vi sige software setup eller gør det. Ikke bare muligt, men også interessant for virksomheden faktisk at levere data ind og gøre det ind på en smart måde, så de bruger så lidt som muligt af deres tid ressourcer på at gøre det og gerne når de alligevel indsamler som de skal afrapportere til myndigheder. Men bare så sent som i går var jeg ude ved en virksomhed og prøve at kortlægge nogle vandstrømme, fordi vand lige nu er et kæmpe udfordringen. Og selv bare på vand er det for nogle virksomheder følsomt fordi når det er inde og være i kontakt med et produkt og Sådan nogle ting, så er der altså ting som bare ikke lige er tilgængelig. Så det vil fremadrettet være en kæmpe udfordring, og især for når vi laver LCA.

Q: Når du når vi snakker om Kalundborg symbiosen og deres modenhed, er det så måske netop det her med at få samlet noget data ind der er nøglen til at blive endnu mere moden, eller?

PM: Ja, Det er simpelthen nøglen man kan sige fordi, jo selvfølgelig andre ting, men hvis de først siger ja til det, så er det andet lige som en helt naturlig ting. Har man sagt ja til det første, så bliver det en afledt effekt af det. Så bliver det andet bare ikke peanuts, men det. Det bliver en helt naturlig ting. Ja hvis vi skal kunne afdække nogle potentialer og se nogle muligheder og så også arbejde på at realisere dem. Jamen, så skal vi have de her data tilgængeligt, og man så arbejde med i hvilket rum skal det være tilgængeligt? Og vigtige detaljer, hvordan deles og opbevares det. Med det er sådan lidt begge dele, både at arbejde med netværker og den enkelte virksomhed og lade dem forstå det og se på løsninger, men også at have noget et værktøj, noget software, en eller anden tilgang som gør det sikkert og håndgribeligt og operationelt. Der ligger et stykke kommunikationsarbejde omkring det, men også utrolig stort arbejde omkring at finde hvad findes der allerede der eventuelt kunne gøre det, og hvis ikke, hvad skal vi gøre for at få det til at virke uden det kommer til at koste spidsen af jetjæger. Og så er der GDPR og alt muligt så... Men vi har nogle ideer, vi arbejder lidt med og vi gjorde det også lidt i forbindelse med Thais speciale. Og Jeg har fat i nogle virksomheder. Jeg arbejder lidt med og ser hvad vi kan. Men det kommer til at tage nogle år. Vi tager nogle konkrete forretningsmodeller og ser og vi kan drive det ud fra det.

Q: Hvis man nu har den her data her og kan lave de her analyser og kvantificere mere effekterne af, at vi har den Symbiose her... Hvad er det så for en ekstra værdi? Det giver til symbiosen og til virksomhederne? kan du sætte nogle ord på det?

PM: Jamen Det er jo mange ting man kan sige i første omgang, hvis du har data og du selv forholder dig til det som virksomhed, så forstår du lige pludselig hvad det egentlig er du går og laver. Så Det er jo Sådan set en måde at lære din egen forretning bedre at kende og blive systematisk omkring det og logge og trende og kan gribe ind i de processer, men så der også forstå, hvad er det så egentlig? Kan vi erstatte nogle af disse ressourcer, kan vi lave mere intern optimering, og kan vi egentlig sige, at vi ikke rigtig kan håndtere? Kan vi egentlig bruge det selv, eller kan vi dele det med andres, eller skal vi ændre Vores produktion? Ændrer Vores produkter alt det der, så Det er med at udvikle din egen virksomhed. Det er en ting. Og det næste er jo så at kan du lave forretning ud af at tænke Sådan? Udover at almindelige intern optimering, og det er jo der symbiose kommer ind. Der hele branding ved det der altså hvordan? Vi arbejder faktisk med at lave noget certificering for industriel symbiose hvor man faktisk får kredit for det man går og laver. Det er ikke Sådan en svanemærkning, men Det er noget med, hvordan leverer man ikke bare investeringer, og heller ikke bare CO2, men andre parametre, andre KPI'er, ligesom man arbejder med LCA, så er der jo andre KPI'er man kigger på produktivitetsmål og Sådan noget. Så Det kan man jo kommunikere bruge internt man kan bruger det over for sine investorer, sine bestyrelser sine ejere om man kan bruge det til at optimere sin egen produktion og tiltrække dygtige, nye, nyuddannede I det hele taget bare arbejdskraft, fordi du viser din virksomhed er innovativ og er ansvarlig i den måde, de tænker produktioner er at producere på ikke bare skriver det man gør det. Ja Sådan nogle ting. Konkurrencedygtighed, ikke? Fordi hvis du laver de gode forretningsmodeller, så giver det dig jo også en robusthed. Du får en robusthed i at kigge på lokal ressourcer i stedet for at skulle kigge ud på verdensmarkedet. Vi kunne jo bare se, hvad der sker indenfor de sidste 3 uger [Red: Ukraine], ikke? På verdensmarkedet direkte på olie og naturgas, men også alt det afledte. Så hvis du kan, hvis du har noget lokalt som du aftaler men, så har du en lokal forsyningssikkerhed, som jo i den grad understøtter din produktion fremfor andre konkurrenters. Der er jo rigtig mange parametre her som jo alt efter hvem du er som virksomhed og hvor langt du er og hvad du producerer, hvad du forbruger dem, så vil det jo veje forskelligt hvor meget det giver?

Q: Når I arbejder med Kalundborg symbiosen, hvordan afgrænser i så de virksomheder og de symbioseudvekslinger som i er facilitator for? Er det en fast grænse eller, er en mere sløret grænse for hvad der er med og ikke med. Eller er det geografisk?

PM: Altså det vi opererer ud fra når vi kigger på data og prøver at lege med LCA så er det jo de forretningsmodeller, der realiserede mellem virksomhederne, altså medlemmerne i vores forening. Og så er vi jo udmærket klar over, at vi også skaber noget værdi på anden vis, fordi vi faktisk også noget af det, vi producerer fra de her reststrømme faktisk også sendes ud I kan vi sige I byområdet, kan vi sige eller i kommunen? Så Det er den her urban industrisymbiose vi også arbejder inde i. Det er ikke noget, Vi har målt på. Det kommer vi til at gøre, fordi den udvikling vi ser nu, er, at, hvor vi tidligere sagde, at proximity altså nærhedsprincippet var altafgørende, at det skulle være tæt på. Det skal det også helst. Men, men der hvor Vi er nået til nu, så ser vi faktisk at Vores tilgang Og nogle projekter, Vi har i støbeskeen kigger ud på noget som har langt større, kan vi sige rækkevidde i geografi også, så Vi er ude og snakke. Regionalt er vi tænker symbioser nu. Så det kommer vi til at inddrage i den måde, vi kommer til at tænke på. Men for at vi skulle hjælpe os selv, når vi skulle prøve at lave noget LCA, så måtte vi sige, hvordan så det ud altså hvis vi tager in reference og siger hvis vi nu ikke havde lavet de her symbioser. Så havde vi i stedet for brugt olie jo, men naturgas måske så Vi har været Sådan prøver at være realistiske fordi verden har udviklet sig. Nu klipper vi så de her strenge og så har vi set hvordan min stedfar.[Aner ikke hvad han siger her] Hvad er så forskellen? Så på den måde har vi prøvet at sætte grænser op, når Vi har sagt hvad er det så for en effekt. Hvad er det for en værdiskabelse vi har her i forhold til, hvis vi bare har ladet tingene kører, og så er det svært at sætte tal på, fordi Det er det også har gjort her. Det er, at Vi har gjort os selv konkurrencedygtige, så Vi har jo øget eksportværdien. Virksomhederne har slet ikke haft det så svært under krisen i 2008 og frem som andre havde. Jeg tror det er det eneste sted i Danmark der faktisk var vi havde den højeste vækst på det tidspunkt faktisk.

Q: Jeg tænker altså nu her i fremtiden, hvor du sagde at i vi fokuserer mere på regionalt plan går i så også fra den meget koncentrerede i symbiose i Kalundborg til ligesom at foreningen også udvider sig?

PM: Fokus går ikke væk fra den lokale, slet ikke, men for at styrke den lokale, så skal vi faktisk kigge ud og tænke regionalt måske national international nogle gange. Fordi det vi ikke har kunnet realisere. Det er blandt andet Sådan noget som overskudsvarme. Og vi kan jo ikke bruge mere varme. Vi producerer overskudsvarme. Vi kan ikke bruge det selv lokalt, så vi må kigge ud i den større geografi og netop, hvad der sker nu på naturgasområdet. Jamen, det giver rigtig god mening at snakke fjernvarme længere væk, fordi Vi har alt det varme her. Der er jo byer, som jo skal omstille fra naturgas, og det synes de måske ikke de havde travlt, men Det har de så nu [Red: Ukraine]. Så der på den måde, så kan vi være med til at hjælpe den her omstilling, og så bliver det ikke bare et lokalt anliggende. Det skaber selvfølgelig værdi lokalt i Kalundborg, men det skaber i særdeles også værdi for hvor vi sender det hen, men for Danmark som helhed og egentlig også for EU. Så det begynder at have en afsmittende effekt, men Det er jo stadigvæk de lokale virksomheder, som vi primært har for øje og Vi har jo langt har vi også andre nye spændende projekter på vej, som er direkte altså mellem virksomhederne stadigvæk lokalt. Men Det er andre typer symbioser, som vi kigger ind i. Så bare lige for at dreje den der formulering lidt så kigger vi ud, men Det er fordi vi skal ud og skabe de der nye forretningsmodeller, og det skal vi gøre i et stører partnerskab. Og så vil jeg godt lige sige at ja. Vi har før kun haft kernemedlemmer. Vi er gået fra kun at haft medlemmer i symbiosen og så sad man og var med i bestyrelsen, fordi man udviklede en strøm. Nu har vi et ekstra medlem niveau som hedder associeret medlem. Hvor man kan blive medlem, hvis man arbejder hen imod og realisere symbiose samarbejder med os, og Det kan være det, endda vokser endnu til at sige, jamen, så er det videns partnere. Det er ikke til at vide, hvordan det udvikler sig. Men vi har meget fokus på at sige kig lidt væk fra den lidt gammeldags måde. Vi har kigget på samarbejde til og se Der er også meget behov for så meget viden og mange kompetencer og Det sektorkobling og Det er alle mulige typer virksomheder og alle mulige teknologier. Og hvis det skal løftes, så skal vi have det nyeste fra viden intuitioner, universiteter, eksperter inden for udstyr og måleudstyr. Og vi understøtter også uddannelse i lokalområdet. Jo her inden for de sidste 4 år har vi skabt 5 nye uddannelser og Det er ellers ikke noget, Vi har kunnet Kalundborg. Men Det er blandt andet også med stærkt forlede af hjælp fra industrien og deres efterspørgsel ikke og være med til at understøtte det, så på den måde er vi ved at omdefinere. Hvordan vi vil arbejde, fordi vi kan se, at vi, Vi har behov for, at vi kan meget mere, Vi skal. Vi skal inkludere andre elementer, også andre typer partnere for bedst og kan realisere den værdi der ligger

Q: Er det noget i gør proaktivt? Eller kommer virksomhederne til jer?

PM: Det er jo begge veje, men jeg vil sige Det er blevet så stærkt et brand nu, så vi faktisk er ved at blive løbet lidt over enden af virksomheder som er i Kalundborg eller på vej ind i, eller vækster. For eksempel Sådan noget som el gas og varme. Det skal alle virksomheder sådan set bruge alt efter, hvad virksomhedstype Det er ikke, så Det er jo nogle ressourcer, Der er tryk på. Så der prøver vi jo at være proaktive og finde løsninger og snakke med de eksisterende virksomheder. Hvis der kommer rigtig mange og gerne vil være en del af brandet og være en del af økosystemet, fordi de kan se i deres forretning, så kan de faktisk blive mere ressourceeffektive produktive også måske bliver mere synlige på verdensmarkedet og udvikle deres bæredygtigheds profil ved faktisk at lokalisere sig til lignende virksomhed i Kalundborg. Så lige nu der, der har vi simpelthen ikke nok industribyggegrunde. Og vi har pres på ressourcerne, og Det er jo ikke noget, Vi har tænkt for bare 3 år siden. Bare som et eksempel så skal Novo over de næste 3 år bygge 3 nye fabrikker.

Det er 17 milliarder de ligger i lille Kalundborg. Og der er altså også udenlandske virksomheder som noget officielt at noget er ikke officielt. Så der bliver virkelig pres på det er den her value proposition. Vi har arbejdet på i lang tid. Vi ikke troede, vi kunne få lov at presse igennem og sjovt nok havde vi et projekt, der hed det dansk symbiose Center og det er Region Sjælland, der finansieret, og spurgte "Hvorfor kan vi ikke levere på det her nu?" Det var et projekt på 4 År og der var vores argumentation altså det tager jo tid. Men jeg skal love for, at nu sparker det altså ind. Vi har prøvet at sælge det på. Ikke bare biotek. Og vi har en havn, også noget infrastruktur, men fordi Vi har symbiose og helt rigtigt grønne forretningsmodeller, så eksploderer det lidt. Det er sgu svært at håndtere. Men Det er jo netop fordi vi så har kigget ud og så kommer det ind så nogle gange skal vi gøre ingenting vi. Skal nærmest lade være, andre gange, så vil vi gerne prøve at være strategiske i selv at være opsøgende på at få det her til at ske så det. Det var lang snak rundt om det, men Det var fordi. Ja der er mange ting, Der er sket. Noget har vi selv været med til at påvirke andet sker bare fordi der sker den altså hele klimadebatten ikke? At Vi er presset på ressourcer. Det er jo også med til at drive det hen imod den type. Kan vi sige virksomheder eller forankring af eksisterende, men også udviklingen af nye tiltag, som egentlig taler i den dagsorden, Vi har haft længe i vores lokalområde ikke så ja, Det er nu det sker.

Q: Jeg har et meget lavpraktisk spørgsmål og det er simpelthen hvordan? Hvad er foreningen du taler om? Nu talte du også lige om symbiosecenteret, før der var et projekt. Altså når Jeg har siddet og læst litteratur om Kalundborg symbiosen så lyder det som om, I hvert fald for litteraturen. Den videnskabelige litteratur, at symbiose centeret er en instans, der faciliterer. Altså hvad er facilitatoren for det? Igennem mange år forstår jeg det rigtigt, eller er det et projekt?

PM: Vi har jo hele tiden haft aktiviteter for at facilitere det her, men har været forskellige tilgange. I og med hvordan har vi været organiseret? Det har været Virksomhederne selv der startede, så de har jo selv bare kørt det også. Indtil det begyndte at blive faciliteret af en konsulent, der ligesom har været her indtil prøve at drive eller anden form for Sekretariatsfunktion, og det ender så med at kommunen tager rollen på sig. Så bliver der sendt sekretariatschef der. Som jo, så er ansat i kommunen. Det er dér, Vi har sekretariat, og der fortsætter, vi så og bliver mere bevidste om faciliteringen. Og så får vi igennem det et regionalt symbiose Center program 4 år Og i forlængelse af det et nationalt fordi vi går for lokalt regionalt til nationalt for at se, fordi man fra nationale side gerne ville prøve at afsøge den mulighed. Så Det har Været programmer, men Hele tiden være faciliteret lokalt af kommunens og erhvervslivets, Folk, men primært kommunen og Der er det så Vi her for 2 år siden har flyttet. De personer og den facilitering ind i foreningen helt tæt ind på, så Det har hele tiden været facilitering. Ja, men Det er jo så skulle finansieres af sted, så derfor har vi måttet kalde det et eller andet. Hvad skal vi sige en konsulent, der vil høre ind? Så har det været foreningen, hvor man så har haft kommunen som medspiller. Og så har vi så søgt midler til at drive det og opskalere aktiviteterne. Forske lidt i det. Og lave samarbejder og netværk ude i verden, så det det regionale, det nationale Center program. Hvilket har udmøntet i, at Vi har samlet denne reorganisering og bliver klogere siger, Det er Sådan her, vi opererer lige nu, så Det har været facilitering hele Vejen fordi Vi skal Huske på det her, Det er ikke os, Det er ikke Mig der skaber det her. Det der skabes. Det er jo forretningsmodeller, der etableres på baggrund af det. Vi prøver at koble ind i den almindelige forretning. Virksomhederne laver det samme 2 eller flere, så de realiser bare forretning sammen i stedet for at optimere deres egen forretning, så gør de det partnerskab, så virksomheder og 2 eller flere realisere nye ting som giver mening først og fremmest økonomisk, så også økonomisk og så samfundsøkonomisk og så alt det andet med den værdi, de skaber branding og innovation og Sådan noget, men Det er facilitering altså, samtale, dialog, møder, diskussioner. Åbne op og dele, kigger på muligheder være innovative og alt det her. Som virksomhed, men som virksomhed i et partnerskab, og Det er så dér, man finder mulighederne pludselig ikke. Så Det er det her med at mødes tale sammen, innovere til muligheder og prøve at realisere det og sige giver det her giver mening, så pre-feasibility studier et feasibility studier proof of concept bla bla bla ind mod og implementere, simpelthen lave kontrakter På, at nu gør vi det her, og I skal Love at Vi har det her tilgængelige de næste 15, 20 år Så forhandler vi pris ved, at tredje, fjerde, femte. Et eller andet ikke? Der er mange Måder at gøre det på, men Det er faktisk. Business as usual, men hvor vi prøver at være fødselshjælper til at gøre dem opmærksomme på, når de har travlt med deres drift, at de også lige skal huske at. Og kigge ind i de her hjørner, og måske vi matcher dem lige op med at skal mødes med den her teknologileverandør. Og Det er der brug for, for ellers så kører de bare tilbage til business as usual og producerer som de plejer. De skal forstyrres.

Q: Nu ved jeg ikke hvor godt et kendskab du har til ISN, men hvis du skulle give et bud på hvor langt er industriel symbiose nord så i at være en etableret symbiose på niveau med Kalundborg, altså at de på helt begynderstadiet eller er de deroppe hvor at man godt kan begynde at facilitere og ret hurtig opnå end modenhed ligesom den i Kalundborg.

PM: Jeg kender ikke hvor det er I står nu. Jeg ved I har gjort rigtig meget for at kortlægge og mappe, og I har lavet gennem flere projekter prøvet at finde enkelte symbioser og noget er mere sådant potentiale og kortlægge, end Det har været realiseret, ikke? Så på den måde er jo faktisk rigtig, rigtig langt og måske har kan vi sige, at det måske endda endnu bedre kommunikeret, og så er det system for det nu der også lavet den her hjemmeside for at forstå Lucia hun lige gav mig et link til hvor der faktisk blev beskrevet nogle ting. Men det er en ting, for der kan vi gøre rigtigt meget, men det der er vigtigt, det er at få aktørerne i tale og få dem til at forstå og få dem til at mødes og etablere den her kommunikation. Det har samarbejdende dialog som en helt naturlig del af deres forretning.

Q: Så at skabe en identitet?

PM: Jaaa altså en fælles identitet i det, men det skal falde ind som en Kultur i deres virksomhed, det skal blive en del af deres DNA, og det kan du ikke bare gøre sådan her, selvom du har en dejlig hjemmeside. Det kræver jo, at du løbende uddanner og modner virksomheden og virksomhedens ansatte. Det er også noget med, hvem er det at du ansætter i din virksomhed hvor meget af det du deler og deltager du i? Videns udveksling og sådan nogle ting. Vi skal have et overskud på flere niveauer. Det siger vi også i Vores re branding. Altså det her. Det går det surplus. Det overskud ikke bare på, altså en strøm du deler, men også du skal have et overskud i faktisk at kigge udad for at kunne vinde noget, ikke? Og du skal have overskud i at investere noget tid og nogle mandetimer i at mødes med andre, snakke muligheder og også fejle, men også turde investere menneskepenge i og ændre din virksomhed, en produktion eller opdatere den ikke? Der er mange ting i det, som man skal ville hinanden, og det gør man først og fremmest ved, at man vælger at mødes og tale sammen og deler. Og så derudaf skal der så ske. Det skal man gøre løbende. Det nytter jo ikke noget man holder en flot stor konference i år. Og så mødes man en gang næste år, så er det det, og Det er det, Der er problemet med projekter. I har en levetid. Vi har penge til at gøre det, men så må man slippe dem, og derfor har vi valgt at holde fast I forening strukturen, hvor Der er en lille smule penge i hvert fald til en person gennem medlemskab gebyrer, som man hele tiden har en person, som ligesom kan holde fast i det. Og så er der selvfølgelig også nogle kompetencer i, så det er skrøbeligt med én person, men den måde vi arbejder med advisory board nu, så har vi jo rigtig mange dygtige folk ude i virksomhederne, som jo er en del af vores sekretariat organisering, fordi de sidder i advisory board innovation board og har realiseret deltager i bestyrelsesmøder og så videre så videre, ikke? Altså man kan gøre rigtig meget flot på skrivebordet i projektet, men det der noget med at holde fast I det her og få skabt den har samarbejdskultur, den her dialog, og også får beskrevet de gode ting, man så har realiseret som man vidste var symbioser og kunne blive det, eller det som man gjorde og ikke vidste var symbiose, men som faktisk er det. Så sige, jamen, vi kan jo godt ikke. Det er ikke bare Kalundborg og i Østrig eller i Sverige eller hvor pokker Det er... Vi har faktisk allerede gjort det, vi har bare ikke kaldt det symbiose, men Det er jo faktisk det her, Vi har gjort lige her og gør nu, så det giver god mening det, er også symbiose, og så virker det lige pludselig meget mere opnåeligt. Og ikke så kompliceret og farligt, hvis man bare tager den samme tilgang med at vi bare kigger på det som en forretningsmodel, men man kigger på hinanden som samarbejdspartner. Men altså der er mange elementer i det der til at få det til at ske, så der er mange ting man skal have moden indenfor.