DEGREE PROJECT

Unlocking the Potential of AI-driven Circular Business Model Innovation

A case study of an industrial symbiosis

Björn Tomas Minde
Niklas Bäcklund

Industrial and Management Engineering, master's level
2023

Luleå University of Technology
Department of Social Sciences, Technology and Arts

[This page intentionally left blank]

ABSTRACT

Purpose – This study aims to explore and provide empirical insights into AI-driven circular business model innovation (CBMI) in industrial symbiosis. In doing so, it addresses the knowledge gap regarding how industrial companies can use AI to amplify circular business models and facilitate AI-driven circular innovation.

Method – A thematic analysis was used in the study to answer the research questions. It was based on 32 interviews with informants from five companies conducting an AI innovation initiative and experts, as well as two site visits, four project meetings and 61 company documents.

Findings – The analysis showed how AI can amplify an industrial symbiosis and uncovered three principles and symbiotic facilitators for AI-driven CBMI in an industrial symbiosis. The principles and symbiotic facilitators were combined in a coevolutionary alignment framework for AI-driven CBMI in industrial symbioses.

Theoretical contributions – This study contributes to prior literature by (1) depicting how AI changes business models and amplifies an industrial symbiosis, where past research only had conceptualised it; (2) identifying principles that describe how AI-driven CBMI should be approached; (3) uncovering three symbiotic facilitators that create conditions for successful AI-driven CBMI; and (4) conceptualising a coevolutionary framework based on the principles and symbiotic facilitators for aligning the innovation efforts between partners in industrial symbioses.

Practical contributions – Managers in industrial symbioses can use this study to comprehend how AI can improve resource flows and the significance of efficient data sharing in collaborative AI-driven innovation. Moreover, it provides a framework to assist companies in aligning innovation initiatives among partners in order to succeed with AI-driven CBMI.

Limitations of the study – The study focused on five companies involved in an AI innovation initiative in one specific industrial symbiosis. As a result, the findings' generalisability may be limited, and validating these findings in other industrial symbioses and different industrial ecosystems or partnerships would thus be interesting for future research.

Keywords: Artificial intelligence; Circular business model; Circular business model innovation; Circular economy; Industrial symbiosis

ACKNOWLEDGEMENT

This study is a master's thesis by Björn Tomas Minde and Niklas Bäcklund. It is the final part of our master's degree in Industrial Engineering and Management with a specialisation in Innovation and Strategic Business Development at Luleå University of Technology.

We want to express our gratitude towards everyone that has made this work possible. First, we thank our supervisors at Luleå University of Technology, Milad Kolagar and David Sjödin, for their exceptional expertise, guidance, and support. They were instrumental in improving the quality of our work and showed a keen interest in our research.

Second, we are deeply grateful to our company supervisors, Han Yu and Chuan Wang, who provided unwavering support and feedback, even though our subject matter was unfamiliar to them and Swerim AB. Without their enthusiasm, this project would not have been possible.

Third, we sincerely thank our Luleå University of Technology classmates for their invaluable feedback. Their constructive comments and suggestions significantly aided us in refining and improving the quality of our thesis.

Fourth, we greatly appreciate the EnVisA project members for their generous assistance and willingness to support us.

Last but not least, we would like to acknowledge Vinnova Sweden's innovation agency, which funded the EnVisA project (Dnr: 2020-03397), and Swerim AB, who coordinated the project.

We could not have achieved this success without everyone's help and contributions.

Luleå, June 2023

Björn Tomas Minde

Niklas Bäcklund

TABLE OF CONTENT

1 INTRODUCTION

Sustainability is increasingly becoming a strategic priority for industrial companies (Ritala et al., 2018). Businesses must change radically to address the climate crisis, and circular economy is recognised as a critical concept for reducing waste and pollution without sacrificing economic prosperity (Geissdoerfer et al., 2017; Lieder & Rashid, 2016; Olhoff & Christensen, 2022). The goal of a circular economy is to move from a linear (take-make-dispose) to a regenerative economy that replaces the "end-of-life" concept with processes to reuse, recycle, or recover resources and reduce waste (Ellen MacArthur Foundation, 2012). McKinsey estimates that in Europe, 44% of material value – i.e., €78 billion – is lost annually due to inefficient use of steel, plastics, and aluminium (Enkvist et al., 2022). This loss highlights the significant value that circular economy can bring to industries, society, and the environment.

Many scholars link a successful industrial transformation towards a circular economy with digitalisation (Bressanelli et al., 2022; Liu et al., 2022; Neligan et al., 2022; Parida et al., 2019). In particular, researchers have recognised the potential of Artificial Intelligence (AI) to enhance circularity by identifying patterns and trends, forecasting future demand and supply, and automating processes (Chauhan et al., 2022; Kristoffersen et al., 2020). These capabilities unlock several opportunities, including circular business operations; circular product, component, and material designs; and infrastructure optimisation to facilitate circular resource flows (Ellen MacArthur Foundation, 2019). Yet, succeeding with an AI-driven circular economy transformation is far from given, and many companies fail to realise the potential value.

Although AI technology can enable a circular economy in various industries, simply investing in intelligent infrastructure is insufficient to fully harness the potential value (Sjödin & Vinit, 2021). Achieving successful circular economy adoption on an organisational level requires industrial companies to innovate their business models, as this allows for the systemic shift needed in the core logic of businesses (Suchek et al., 2021). A circular economy system demands the creation of new Circular Business Models (CBM), which use as few resources for as long as possible while maximising value extraction (Geissdoerfer et al., 2020). Additionally, fully leveraging AI necessitates rearchitecting business models and establishing an AI-driven company at its core (Iansiti & Lakhani, 2020). Thus, Circular Business Model Innovation (CBMI) is essential to benefit fully from AI, which entails rethinking how to create, deliver, and capture value in order to improve circularity.

Industrial symbiosis is an example of an industrial ecosystem comprised of CBMs that can benefit significantly from AI, in which waste or by-products from one company are used as input by another nearby company (Chertow, 2000; Fraccascia et al., 2019; Neves et al., 2020). For example, matching demand and supply in an industrial symbiosis can be aided through AI-enabled forecasting, improving recycling and resource efficiency (Kristoffersen et al., 2020; Liu et al., 2022). The interest in digital technologies and industrial symbiosis has grown significantly in recent years as researchers, policymakers, and practitioners increasingly recognise its potential to foster more sustainable and competitive industries (Berg et al., 2020; European Commission, 2020; Neves et al., 2020). The literature, however, on AI-enabled CBMI is still in an emergent phase (Chauhan et al., 2022), and the industrial symbiosis perspective has yet to receive much attention. As a result, we identify three main research gaps in the AI, CBMI, and industrial symbiosis literature.

First, there is a need to develop a deeper understanding of how AI can enhance existing industrial symbioses or enable new ones. AI has the potential to significantly increase the circularity of industrial symbioses by predicting future supply and demand and automating operations (Kristoffersen et al., 2020). However, to our knowledge, no empirical research has yet been conducted to demonstrate how AI can amplify an industrial symbiosis. Furthermore, in a recent multiple-case study by Järvenpää et al. (2021), the companies in one industrial symbiosis claimed they saw no value in gathering data from processes but paradoxically thought that waste forecasting would be extremely helpful. This example highlights the need to elevate industrial companies' understanding of the benefits of AI in order to foster the adoption of AI-enabled industrial symbioses and other CBMs.

Second, a better understanding of how to perform AI-driven CBMI is needed. Recent studies show that digitalisation is a crucial driver and success factor for CBMI (Geissdoerfer et al., 2022; Neligan et al., 2022; Parida et al., 2019). Nevertheless, CBMI driven by digitalisation faces several difficulties regarding collaboration, competencies, and data (Antikainen et al., 2018). AI introduces additional hurdles, such as a lack of trust in AI, misunderstandings of AI's capabilities, and complexity that hinders interpretability and transparency (Reim et al., 2020). CBMI is also a complex challenge in and of itself, in which companies face barriers, such as resistance to change, difficulty obtaining management buy-in, and lack of resources, knowledge, or competencies (Geissdoerfer et al., 2022; Guldmann & Huulgaard, 2020; Tura et al., 2019). Therefore, understanding how to overcome the organisational challenges that arise from AI and CBMI is vital for successful AI-driven CBMI.

Last, more insights are needed into how various actors should be involved in AI-driven CBMI activities. Previous research recognises that many industrial companies struggle with CBMI because it requires innovation affecting the entire industrial ecosystem (Geissdoerfer et al., 2022; Guldmann & Huulgaard, 2020), including a complete reconfiguration of value chains, key partnerships, and customer relationships (Geissdoerfer et al., 2020; Kanda et al., 2021). An industrial symbiosis, for instance, relies on partner collaboration to achieve any value realisation (Baldassarre et al., 2019; Chertow, 2000). In addition, despite a paucity of research, AI-driven transformation of ecosystems appears to necessitate business model innovation focused on customer co-creation, ecosystem collaboration, and reconfiguration of partnerships (Kolagar et al., 2022; Sjödin et al., 2021). As a result, industrial symbioses must thoroughly understand how to promote the alignment, coordination, and collaboration needed to realise the potential of AI-driven CBMI.

Against this background and considering the impact, expected benefits, and challenges of AI and CBMI, it is both theoretically and practically relevant to research AI-driven CBMI in industrial symbiosis. This study aims to address these three research gaps by exploring the following research questions (RQ):

RQ1: How can Artificial Intelligence amplify the circularity of an industrial symbiosis?

RQ2: How can Artificial-Intelligence-driven Circular Business Model Innovation be facilitated in an industrial symbiosis?

By examining these questions, we hope to assist and encourage industrial companies in their efforts to adopt AI and carry out CBMI. This study explicitly intends to demonstrate how AI can amplify the realisation of economic, social, and environmental value in an industrial symbiosis and to provide insights into overcoming the challenges of AI-driven CBMI.

The findings show that AI can amplify the circularity of industrial symbiosis but that business model innovation is critical. This study contributes several ways to the literature on industrial symbiosis and AI-driven CBMI. First, we depict AI's potential to amplify the circularity of an industrial symbiosis. Second, it provides initial insights into principles for AI-driven CBMI. Third, it concretises how to create conditions for facilitating AI-driven circular innovation of an industrial symbiosis. Finally, it presents a coevolutionary framework demonstrating how to align AI-driven circular innovation of input and output business models within industrial symbioses.

2 THEORETICAL BACKGROUND

This section gives a theoretical background for comprehending AI-driven circular business model innovation in the context of industrial symbiosis. It is divided into three subsections: (1) Understanding industrial symbiosis, (2) AI-Enabled circular business model & industrial symbiosis, and (3) Towards AI-Driven Circular Business Model Innovation.

2.1 Understanding industrial symbiosis

Industrial symbiosis is a concept that promotes a circular economy by increasing the resource efficiency of industries. Baldassarre et al. (2019) argue that implementing an industrial symbiosis promotes local and worldwide environmental, economic, and social growth. According to Chertow (2000), an industrial symbiosis "*engages traditionally different industries in a collective approach to competitive advantage involving the physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity*" (p. 313). In other words, it is an industrial ecosystem in which circularity principles such as waste restoration, reduction, and avoidance are the primary value-creating activities (Geissdoerfer et al., 2020; Kristoffersen et al., 2020; Neves et al., 2020).

Different industrial symbioses demand various levels of coordination among actors, affecting how value is created and captured from waste (Fraccascia et al., 2019). For instance, an industrial symbiosis within a company requires no coordination, as with Guitang Group, which produces sugar and diversifies its products by utilising its waste to create pulp, paper, alcohol, cement, alkali, and fertiliser (Zhu et al., 2007). On the other hand, an industrial symbiosis with several actors needs a high level of coordination between partners (Fraccascia et al., 2019). An example is the industrial symbiosis in Kalundborg, where five companies have developed a web of symbiotic interactions involving solid waste, water and energy exchanges (Jacobsen, 2006). Industrial symbioses can vary depending on whether a central actor is required to establish, manage, or govern the collaboration, with some industrial symbioses emerging naturally and others requiring a central actor (Fraccascia et al., 2019).

According to Fraccascia et al. (2016), an industrial symbiosis consists of two main business models: one for producing waste and one for using waste. Waste-producing companies can adopt an internal exchange model by utilising the by-product within the organisation or an external exchange model where other businesses use the waste. For waste-using companies, there are three possible models for recycling: input replacement – less virgin input used for the same output; co-product generation – enhancing current business and product portfolio by adding at least one new product; and new product generation – creating an entirely new product and business.

Indeed, we argue that an external-exchange industrial symbiosis should be viewed as a collection of CBMs centred on partnership collaboration. Following Geissdoerfer et al. (2020), we define CBMs as "*business models that are cycling, extending, intensifying, and/or dematerialising material and energy loops to reduce the resource inputs into and the waste and emission leakage out of an organisational system"* (p. 7). This definition emphasises four generic strategies for creating CBMs: (1) *Cycling* – reusing, remanufacturing, refurbishing, and recycling materials and energy within a system; (2) *Extending* resource loops – products use time is prolonged through durable and ageless design, marketing promoting extended usage, maintenance, and repair; (3) *Intensifying* resource cycles entails maximising the utilisation of a product through solutions such as sharing economy; and (4) *Dematerialising* – providing the functionalities of a product without hardware through substitution with service and software solutions. Even though all circular strategies can be applied to enhance an industrial symbiosis, at its core, it is a cycling strategy (Bocken et al., 2016; Geissdoerfer et al., 2020).

2.2 AI-enabled circular business model & industrial symbiosis

Digitalisation presents new opportunities for CBM adoption in industrial companies by offering new avenues for sustainable and profitable practices. AI, in particular, is typically seen as the pinnacle of digitalisation because of its enormous value-adding potential (Brock & von Wangenheim, 2019). Digitalisation is "*the use of digital technologies to innovate a business model and provide new revenue streams and value-producing opportunities in industrial ecosystems"* (Parida et al., 2019, p. 12). Digital technology fundamentally changes how industrial companies can improve productivity, increase growth, add customer value (Björkdahl, 2020), and configure business models to create, deliver, and capture value (Iansiti & Lakhani, 2014). As a result, aiding the implementation of innovative and disruptive CBMs previously thought only to be conceptual (Neligan et al., 2022; Neri et al., 2023; Rosa et al., 2020).

For industrial symbiosis, digitalisation is a critical enabler to optimise resource and knowledge exchange among partners, which are essential to improve recycling and implement more complex symbiotic systems (Colla et al., 2020; Kristoffersen et al., 2020; Liu et al., 2022). For example, connected sensors can support human decision-making by enabling real-time tracking, monitoring, and controlling of resource flows, leading to optimised utilisation of materials (Ingemarsdotter et al., 2019; Kristoffersen et al., 2020; Rosa et al., 2020). In addition, digitalisation can ease information sharing between diverse industries, e.g., digital platforms, which could help businesses identify new ways to interchange resources across sectors and match supply and demand (Liu et al., 2022). Increasing human-machine interaction also improves workplace conditions, and thus digitalisation can improve the economic, social, and environmental aspects of industrial symbioses (Scafà et al., 2020; Sjödin et al., 2018).

AI further amplifies digitalisation's disruptive potential by allowing systems to use sophisticated analytics, learn, generalise beyond known data, and perform tasks independently (Iansiti & Lakhani, 2020). AI is an overarching term for technologies and methods that make systems capable of performing human-like cognitive functions, including learning and reasoning (Ellen MacArthur Foundation, 2019). This study does not focus on specific AI technology but always refers to AI as the often-used term *"strong"* AI, meaning that methods such as Machine Learning and Deep Learning are used. Hence, we construe AI as a *"system's ability to interpret external data correctly, to learn from such data, and to use those learning"* (Kaplan & Haenlein, 2019, p. 17). There are several ways that AI can improve or enable CBM strategies:

- *Cycling* – AI can enhance cycling by forecasting future material flows and improving product end-of-life strategies (Kristoffersen et al., 2020). For example, vision-based AI can improve waste management by distinguishing between materials enabling automatic waste audits, sorting of materials, and sorting of mixed waste, enhancing the amount of recycled material and processing efficiencies (Martinez et al., 2022; Nañez Alonso et al., 2021).
- *Extending* – AI-enabled condition-based and predictive maintenance can significantly extend the lifespan of products (Liu et al., 2022). For instance, Rolls-Royce offers an AI-enabled maintenance service, leveraging data from hundreds of sensors on each aircraft engine to predict future maintenance needs, minimise delays caused by gas turbine defects, and extend utilisation time between repairs (Lee et al., 2019).
- *Intensifying* – AI can benefit the sharing economy by improving trust, resource and price matching, and understanding participants' preferences and attitudes (Chen et al., 2022). As an example, Volvo Construction Equipment utilises AI to mitigate risks and intensify utilisation in their heavy equipment rental, leasing, or performance-based contracts, through improved pricing and demand prediction, predictive maintenance, and intelligent inventory management (Sjödin & Vinit, 2021).

- *Dematerialising* – leveraging AI is often vital to amplify software's dematerialising potential through improved resource optimisation (Neri et al., 2023). For example, General Electric deploys sensors and AI to enhance wind turbines' maintenance, performance, and utilisation, enabling power companies to increase their power-production capacity without adding more hardware (Iansiti & Lakhani, 2014).

Kristoffersen et al. (2020) propose a framework highlighting how an enhanced ability to analyse data can enable and amplify CBMs. Moving from mere data collecting to data analysis with AI generates better *Knowledge* and *Wisdom* regarding resource utilisation, leading to increased resource efficiency and productivity potential. Increased *Knowledge* provides diagnostics of how and why something happened to a resource and discoveries of more efficient utilisation methods. Enhanced *Wisdom* enables predictive capabilities to optimise future resource usage and prescriptive measures unlocking dynamic and automated resource management. In other words, implementing AI further increases the ability to make sense of data, allowing new ways of harnessing value and enabling CBMs (Chauhan et al., 2022; Kristoffersen et al., 2020; Liu et al., 2022).

Although empirical literature is limited on AI application in industrial symbioses, we find several potential benefits. AI can strengthen decision-making in industrial symbioses by providing the proper actor with more relevant and timely information (Bressanelli et al., 2022; Chauhan et al., 2022). Mainly through automating data collection and integration from different sources, e.g., partners' inventories and schedules, and anticipating changes and alerting for upcoming value chain issues (Kristoffersen et al., 2020). For example, in a multiple-case study by Ranta et al. (2021), an industrial company employed AI to forecast waste availability and demand for refined goods. The forecasts helped them manage their value chain to avoid needless warehousing and potential shortages, boost revenues and decrease expenses while closing resource flows.

AI can also enhance material exchange and recycling processes by detecting improvement opportunities through patterns and trends; automating and developing more data-driven methods; and improving waste sorting using machine vision (Liu et al., 2022). For instance, mixed e-waste can be separated automatically with AI, allowing a complete value extraction through recycling individual parts (Ellen MacArthur Foundation, 2019). Thus, AI may enable industrial symbiosis based on recycling streams of mixed buy-products that previously were too difficult or expensive to sort. Furthermore, AI can identify and explore novel waste-to-resource matches and potential company pairings (Kristoffersen et al., 2020; Liu et al., 2022). In conclusion, the potential of AI for industrial symbiosis is significant, both in terms of amplifying current symbiotic systems and enabling new ones.

2.3 Towards AI-driven Circular Business Model Innovation

There is also a need to understand how implementing AI for circularity drives the transformation and innovation of industrial companies' business models in industrial symbioses. A business model describes the *"design or architecture of the value creation, delivery, and capture mechanisms"* a company employs (Teece, 2010, p. 172), typically visualised as a triangle (See Figure 1). In other words, it outlines the system of a company's activities and how they are linked to satisfy the market's perceived needs (Amit & Zott, 2012). The concept differs from strategy in that it represents how a company currently does business with customers and partners, whereas strategy describes how it aims to function in the future (DaSilva & Trkman, 2014). Hence, continuously innovating a company's business models is essential for executing business strategy and, thus, implementing or enhancing circular strategies through AI (Geissdoerfer et al., 2020; Zott et al., 2011).

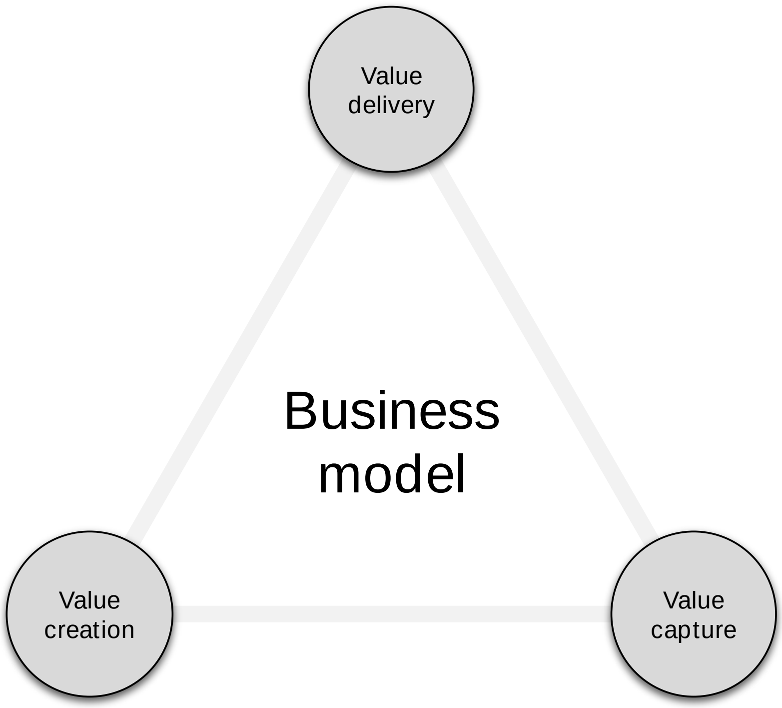

Figure 1. Business model triangle visualisation.

Business model innovation involves either: making changes to components or their interconnections in an existing business model; or crafting new business models that utilise novel methods to create, deliver, and capture value – e.g. for a startup or new business unit of a company (Osterwalder & Pigneur, 2010; Teece, 2010). Like Amit & Zott (2012), we argue that business model innovation includes both radical and incremental innovation because even slightly adjusting a business model can enhance a company's performance. The only difference between CBMI and business model innovation is that the primary goal is conceptualising and implementing CBMs (Geissdoerfer et al., 2020). Consequently, we interpret CBMI to involve creating entirely new CBMs or improving the circularity of existing ones through radical or minor adjustments to the value creation, delivery, and capture methods.

Following this understanding, we investigate AI-driven CBMI in industrial symbiosis through the perspective of how utilising AI for circular strategies affects companies' value-creation, delivery, and capture mechanisms. Even though the topic of AI and CBMI is novel, we draw some preliminary assumptions from the research on business model innovation, CBMI, and AI.

Value creation relates to how a business creates its value proposition, which is the benefit that a company's product or service promises to provide to the customer (Teece, 2010). A company builds its value proposition through partnerships, key activities, and resources (Osterwalder & Pigneur, 2010). Since AI relies on large data sets, securing high-quality data is essential to reap the benefits of AI (Reim et al., 2020). As a result, data management (i.e., data collection, storage, integration, and security) and AI management become central activities in an AI-enabled CBM to acquire and utilise the data resource (Brock & von Wangenheim, 2019; Kristoffersen et al., 2020). These activities also require knowledgeable individuals, who may be internal staff or partners (Iansiti & Lakhani, 2020). Thus, partnerships, key activities, and needed resources are all potentially impacted by AI-driven CBMI in industrial ecosystems (Kanda et al., 2021; Kolagar et al., 2022; Linde et al., 2021).

Value delivery involves establishing operational processes and activities to deliver the promised value (Teece, 2010). One propitious use case for AI is decision support to optimise the circularity of business operations (Kristoffersen et al., 2020). Although ensuring that an AI solution provides value to the users is critical, companies frequently overlook the value-delivery aspect of digital solutions (Linde et al., 2021). Indeed, developing processes to ensure the adoption of AI applications and data delivery between partners seems to be essential aspects of AI-driven CBMI in industrial ecosystems (Geissdoerfer et al., 2022; Kolagar et al., 2022; Reim et al., 2020).

Value capture refers to how business configure their cost structures and revenue models to convert value creation into profits (Teece, 2010). In an industrial symbiosis, AI can optimise waste flows between partners, which entails changing revenue or cost structures (Kristoffersen et al., 2020). Nevertheless, individuals' distrust of AI can make them less willing to use it, resulting in diminished value capture of a tool (Reim et al., 2020). An example of how AI can alter value capture is Volvo Construction Equipment's use of AI to enable revenue models like rental, leasing, and performance-based contracts (Sjödin & Vinit, 2021). However, companies frequently fail to assess how digital opportunities may alter cost and revenue structures as well as how value should be distributed among actors, preventing them from capturing value (Åström et al., 2022; Linde et al., 2021). Thus, ensuring and aligning value capture for the entire industrial ecosystem in collaborative AI-driven CBMI appears critical (Åström et al., 2022; Kanda et al., 2021; Kolagar et al., 2022).

In conclusion, AI has significant potential to amplify the circularity of industrial symbioses and drive CBMI in partner companies. Despite this, many challenges and uncertainties confront this transformation, with no research insights to guide the way forward. Accordingly, this paper aims to extend the literature on AI-driven CBMI in industrial symbiosis. The study's method, findings, and contributions are described in the following sections.

3 METHOD

This section outlines the methods employed to achieve the purpose of this study, including the research approach and the choice of research context. It also describes the data collection and analysis procedures and measures to enhance the study's quality.

3.1 Research approach

To explore AI-driven CMBI and how AI can amplify industrial symbiosis, we conducted a case study of an AI innovation initiative in a symbiosis. Because prior studies were lacking, we chose an inductive research approach to understand the informants' context and perceptions in order to create a theory on what was happening (Saunders et al., 2007). Our study aimed to uncover new findings in a novel research area, forcing us to gather insights from the data. Hence, the study was exploratory, relying on data to predict and explain behaviour (Saunders et al., 2007). Additionally, the research questions and theoretical background were revised several times to ensure that everything relevant to the study was discovered. Throughout the study, we also used prior literature to guide our investigation. Overall, this approach allowed us to work iteratively with data collection and analysis to describe a real-world phenomenon as precisely as possible.

3.1.1 Case selection

To answer the research questions, we conducted a single case study on an ongoing AI innovation initiative within an industrial symbiosis based on a steel manufacturer's waste gases (see Figure 2 for illustration). The AI initiative's goal was to optimise the use of waste gases in the symbiosis by forecasting future supply, thereby improving circularity by reducing the reliance on oil to safeguard operations. In particular, the AI helped LuleKraft's operators make decisions regarding burning gases and oil to generate heat and electricity, as they previously had no prediction of future waste gas availability. The initiative included three symbiotic companies: SSAB (steel manufacturer), LuleKraft (energy producer), and Luleå Energi (energy utility company), as well as two AI developers: Data Ductus (software engineering company) and Swerim (research institute).

Figure 2. Energy-system industrial symbiosis based on waste gas in Luleå, Sweden.

We considered this case suitable to answer the research questions because (1) the initiative was conducted in the context of industrial symbiosis; (2) AI was being implemented; and (3) it was evident that a successful initiative demanded partners to change how they conduct business in the symbiosis. Moreover, the collaboration between the partners and external AI experts gave us a broad set of knowledge for the data collection to create a comprehensive picture of the situation.

3.2 Data Collection

We collected primary data through 32 interviews in three waves (see Table 1) and participated in four project meetings and two site visits, one at LuleKaft and one at SSAB (see Table 2). Secondary data was also gathered from informants and external sources. Additionally, observations and informal discussions took place in the offices at Luleå Energi, LuleKraft, SSAB, and Swerim. The data collection occurred between January and June 2023.

During the interviews, both were present. One of us interviewed while the other took notes and asked follow-up questions as needed. We switched roles during each interview to reduce the impact of one person's bias (David & Sutton, 2016). All interviews were also recorded so we could analyse thematical and re-listen to what was said, except for one due to technical issues.

Table 1. Interviews and informants.

ID	Role of informant	Time (min)	Transcribed words	Type
	Wave one explorative interviews			
I1	Production Engineer at Luleå Energi*	42	5 080	Video
I2	Production Manager at LuleKraft*	200	24 134	F2F
I3	Senior Data Scientist, Data Ductus*	20	0	F2F
I4	(1) Process Engineer Manager and (2) Production Manager at LuleKraft*	97	12 422	Video

I5	Energy Coordinator at SSAB⋆	50	6 267	Video
Wave two semi-structured interviews				
I6	Senior Data Scientist at Data Ductus⋆	54	9 766	Video
I7	Ex. Project Leader & Data Scientist at Swerim⋆	37	4 663	F2F
I8	Project Leader & Data Scientist at Swerim⋆	60	6 597	F2F
I9	Data Scientist at Data Ductus⋆	39	5 044	Video
I10	Distribution Manager, District Heating, at Luleå Energi	40	8 252	F2F
I11	Production Manager, District Heating, at Luleå Energi	44	7 020	F2F
I12	Senior Researcher & Manager at Swerim⋆	57	7 025	F2F
I13	Production Engineer at Luleå Energi⋆	56	7 151	Video
I14	Energy Coordinator at SSAB⋆	65	7 820	Video
I15	CEO at LuleKraft	74	10 361	F2F
I16	Production Manager at LuleKraft⋆	48	6 781	F2F
I17	Process Engineer Manager at LuleKraft⋆	39	4 169	Video
I18	Production Engineer at Luleå Energi⋆	63	9 764	Video
I19	(1) IT Service Delivery Manager, (2) IT Customer Delivery Manager, (3) IT Coordinator, and (4) IT Service Delivery Manager at SSAB	66	10 471	F2F
I20	Production Manager at LuleKraft⋆	37	4 806	Video
I21	Production IT Manager at SSAB	31	3 621	Video
I22	Operations Engineer at LuleKraft	42	6 237	F2F
I23	Operator at LuleKraft	46	4464	F2F
I24	Operations Engineer at LuleKraft	44	5023	F2F
Wave three validation interviews				
I25	Senior Researcher, industrial symbiosis expert, at Swerim	61	–	F2F
I26	Production Engineer at Luleå Energi⋆	85	–	F2F
I27	Senior Researcher, data sciences & circular economy expert at RISE	69	–	F2F
I28	Senior Project Leader, digital-driven industrial symbiosis & circular economy expert at RISE	64	–	F2F
I29	Production Engineer at Luleå Energi⋆	67	–	Video
I30	Process Engineer Manager at LuleKraft⋆	68	–	F2F
I31	Production Manager at LuleKraft⋆	64	–	Video
I32	Energy Coordinator at SSAB⋆	41	–	Video

⋆ Member of the AI initiative

3.2.1 *Wave one – understanding how AI can amplify an industrial symbiosis*

In the first wave, we sought to fully understand the AI initiative and how AI can amplify an industrial symbiosis. This wave included two steps: (1) informal discussions and secondary data gathering and (2) conducting exploratory interviews.

Wave one began with informal discussions with the project leader and one team member of the AI initiative. Subsequently, we collected secondary data from the project leader and partners and searched for relevant external documents (e.g. partners' websites). The internal documents included presentation slides, project documents, recordings of past presentations, spreadsheets and other documentation from the companies and the initiative; external documents comprised annual reports, company websites, macro data, and master's theses on the industrial symbiosis.

The second step of the data collection involved creating a guiding questionnaire (See Appendix A based on our insights from step one and business model theory (e.g., Osterwalder & Pigneur, 2010; Teece, 2010). Then we conducted five exploratory interviews with initiative members from each company in the industrial symbiosis to understand each company's point of view. In these interviews, we asked numerous follow-up questions to deepen our understanding.

3.2.2 *Wave two – uncovering how to realise value from AI in industrial symbiosis*

In the second wave, our primary goal was to uncover how companies in an industrial symbiosis can realise the value of AI. Additionally, we used it to validate and supplement our findings from wave one. To achieve this, we interviewed 19 individuals who were either involved in the initiative or affected by the implementation of AI. We conducted follow-up interviews with those from wave one and selected additional informants using snowball sampling and recommendations from our supervisors at Swerim.

All our interviews were semi-structured, combining a predetermined set of open questions with the ability to ask follow-up questions (Saunders et al., 2007). This approach allowed us to explore specific themes and responses in greater depth and tailor the interviews to match the informants' areas of expertise better. Our interview questionnaire was developed based on wave one and the theoretical background (See Appendix B). Because of the inductive approach, we iteratively updated the questions throughout this wave as collected data enlightened us. Also, each interview began with us presenting the illustration from the first analysis to validate and supplement it.

3.2.3 Wave three – validating findings

We conducted eight interviews in the third wave to validate the findings from analysis two. To gain various perspectives, we decided to interview core members from the innovation initiative and external experts. The interviews were conducted by thoroughly examining the data structure and framework from analysis two together with the informants. Additionally, we showed and explained the illustration in section 4.1 to informants not involved in the initiative to ensure they understood the context.

3.2.4 Parallel data collection

Parallel to the data collection wave one and two, we attended and took notes during four project meetings and two site visits. We attended project meetings to observe partnership collaboration, gain a deeper understanding of the context, aid further data collection, and validate our findings. The site visits helped us better understand the informants, context, and partners' business models. See Table 2 for a more in-depth explanation of the purpose of each occurrence.

Table 2. Project meetings and site visits.

ID	Participants	Location	Duration	Goal of attending
		Project meetings		
PM1	7 Project Members	Luleå Energi	210 min	Understand the initiative and gather data. The meeting dedicated 20 minutes to our research.
PM2	7 Project Members and 3 x AI PhD students	Swerim	240 min	Discuss and supplement initial findings from data collection wave one. The meeting dedicated 30 minutes to our research.
PM3	7 Project members and 3 x AI PhD students	LuleKraft	220 min	Validate the first analysis and discuss the initial findings from data collection wave two. The meeting dedicated 30 minutes to our research.
PM4	5 Project members 3 x AI PhD students	SSAB	210 min	Validate the second analysis; it occurred after all wave two interviews. The meeting dedicated 30 minutes to our research.
		Site visits		
SV1	CEO as a guide & four Operators	LuleKraft	60 min	Comprehend how LuleKraft generates hot water and electricity from waste gas and what engineers and operators do; it included 20 min unplanned group interview in the operator room.
SV2	Guide & Operators	SSAB	180min	Understand SSAB's core business and how it relates to the industrial symbiosis.

3.3 Data analysis

We conducted three distinct data analyses throughout this study. The first aimed to answer RQ1; the second sought to answer RQ2 and confirm the findings of analysis one; and the last validated the results of analysis two.

3.3.1 Analysis one – answering RQ1

The first analysis mainly aimed to answer RQ1. Our analysis was iterative, meaning we revisited previous findings and revised conclusions based on new data. Initially, we used informal discussions and 61 secondary data to create an illustration and a table depicting the business model changes needed by AI (see Appendix C for the specific data used).

The five semi-structured exploratory interviews were then thematically analysed using the steps outlined in analysis two to improve the initial illustration and table. We focused on quotes describing the industrial symbiosis, business model changes and benefits brought about by the AI initiative. Business model theory assisted us in identifying first-order categories and second-order themes for business model changes (e.g., Osterwalder & Pigneur, 2010; Teece, 2010). We also used the interviews from data collection wave two to validate and further enhance the analysis (see Figure 3 for the final data structure and Appendix D for representative quotes). Finally, we ran a Monte Carlo simulation to quantify the CO_2 and cost benefits of using AI to amplify the symbiosis (see Appendix E). This mathematical random sampling method enabled us to calculate numerical results despite the uncertainty (Kroese et al., 2014).

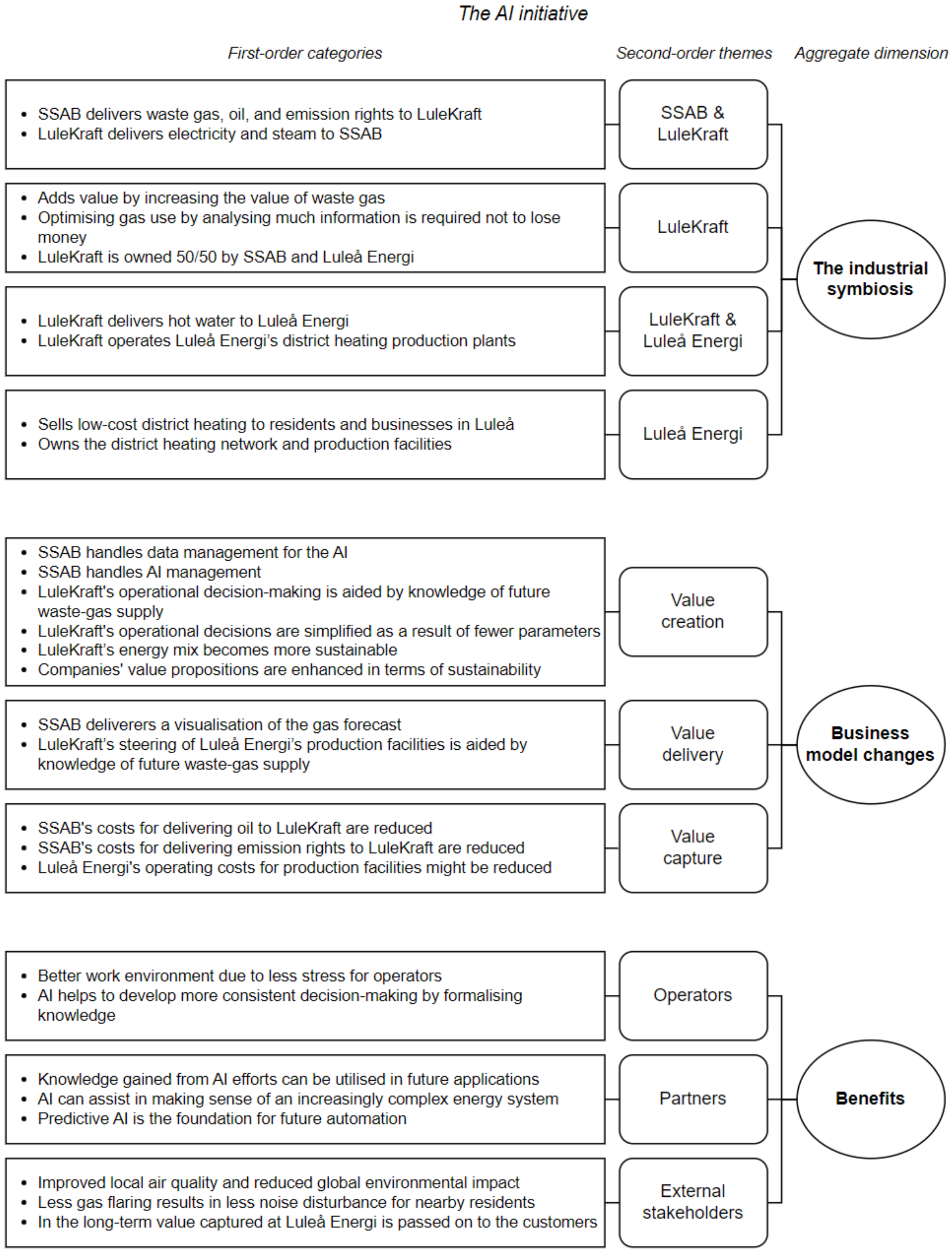

Figure 3. Data structure analysis one.

3.3.2 Analysis two – answering RQ2

The primary goal of the second analysis was to answer RQ2, but it also assisted in answering RQ1. In contrast to analysis one, where we developed themes based on theory, every step in our second analysis approach was data-driven and inductive. The analysis included gathered data from 24 interviews, four project meetings, and two site visits. We performed all steps iteratively and did steps 1-3 simultaneously with data collection wave two to gain insights that would guide further data collection (Saunders et al., 2007). We conducted a thematic analysis based on Braun and Clarke's (2006) five-step process, with one added step:

Step 1: Familiarise ourselves with the data. First, we read each transcript carefully while listening to the interview to ensure a thorough understanding of the context and meaning of the data.

Step 2: Generating initial codes. After reading through each interview, we generated the initial codes using open coding, which resulted in 917 initial codes. First, one researcher identified and labelled relevant quotes in the transcript, and then the other reviewed the labelling and added more codes as needed. At last, we discussed all the codes before extracting them into our analysis document.

Step 3: Building the initial data structure. We sorted our initial codes by identifying similarities and grouping them into broad themes using different levels of headings in a Microsoft Word document. Our inductive approach allowed us to construct data structure directly from the data. Initially, we organised the initial codes under broad subjects, making combining them into first-order categories and making sense of the data easier. Then we built the data structure with a bottom-up approach by grouping the first-order categories into themes. Finally, the second-order themes were grouped into aggregate dimensions.

Step 4: Reviewing the data structure. After creating the initial thematic analysis, we reviewed it by determining whether the individual quotes formed coherent first-order categories. As a result, certain codes were removed. Then we looked at whether the categories fit together to form second-order themes and made any necessary changes if we discovered issues within the categories or themes. Finally, we ensured the themes were assigned to an appropriate aggregated dimension. This process was repeated until we were confident that our changes would not significantly improve the data structure.

Step 5: Defining and naming dimensions. The fifth step was an iterative process to identify the essence of each second-order theme and aggregated dimension. First, we discussed the meaning of each theme and dimension to form a coherent understanding, and then we wrote a description. This process also enhanced our analysis by correcting logic errors in the data structure and strengthening the names of our categories, themes, and dimensions. At last, we met with our supervisors from the Luleå University of Technology to further refine and validate our thematic analysis. The final data structure included 46 first-order categories, 16 second-order themes, and six aggregated dimensions (see Figure 4 and Figure 5), representing quotes for each first-order category are presented in Appendix F.

Step 6: Constructing the framework: The last step entailed visually linking the aggregated dimensions and describing their meaning in a framework. The business model triangle served as the foundation for the visualisation. Then, based on our gathered knowledge from the data, we visualised the interconnectedness of the aggregated dimensions and described what they imply together.

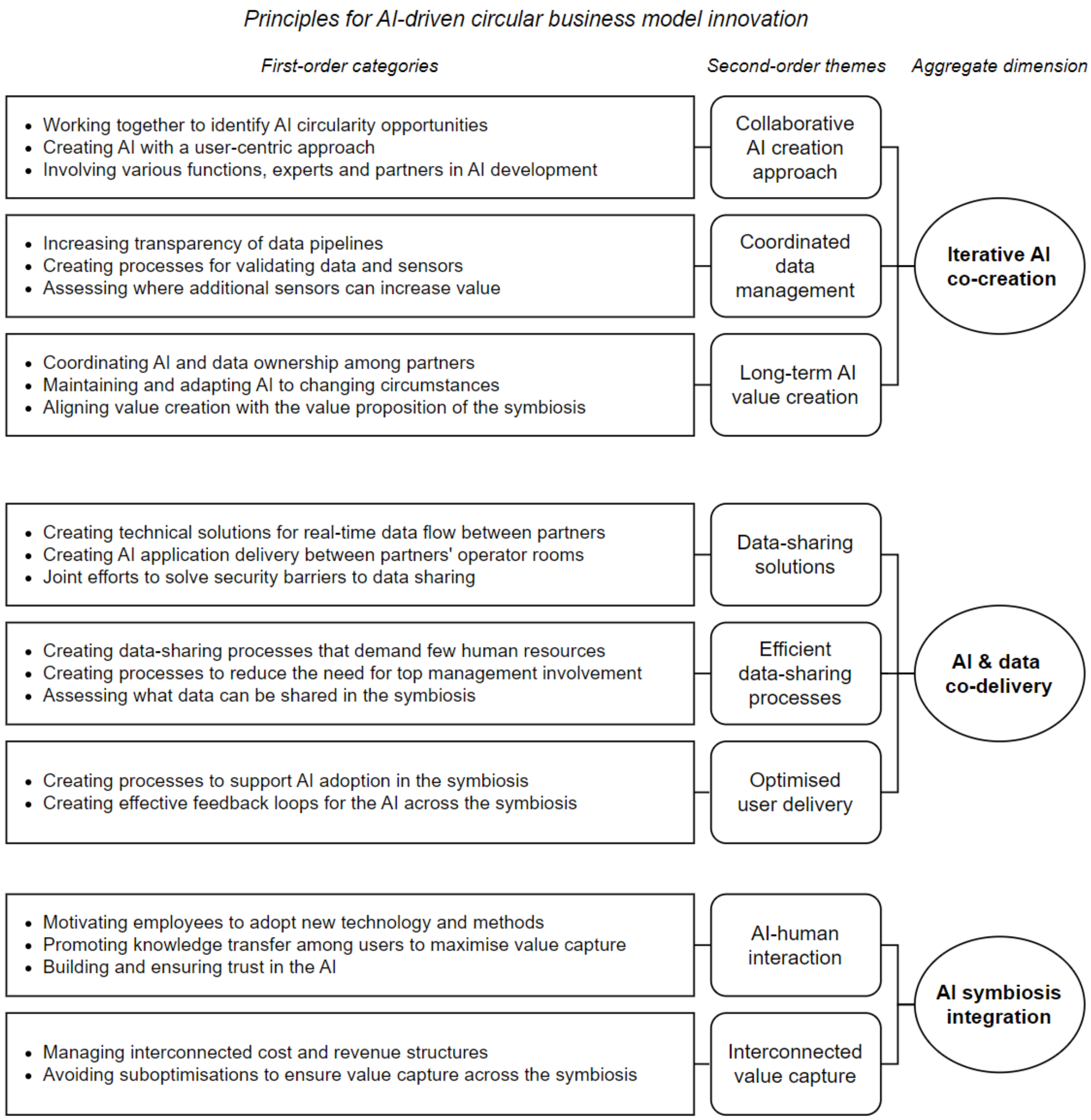

Figure 4. Data structure analysis two (1 out of 2).

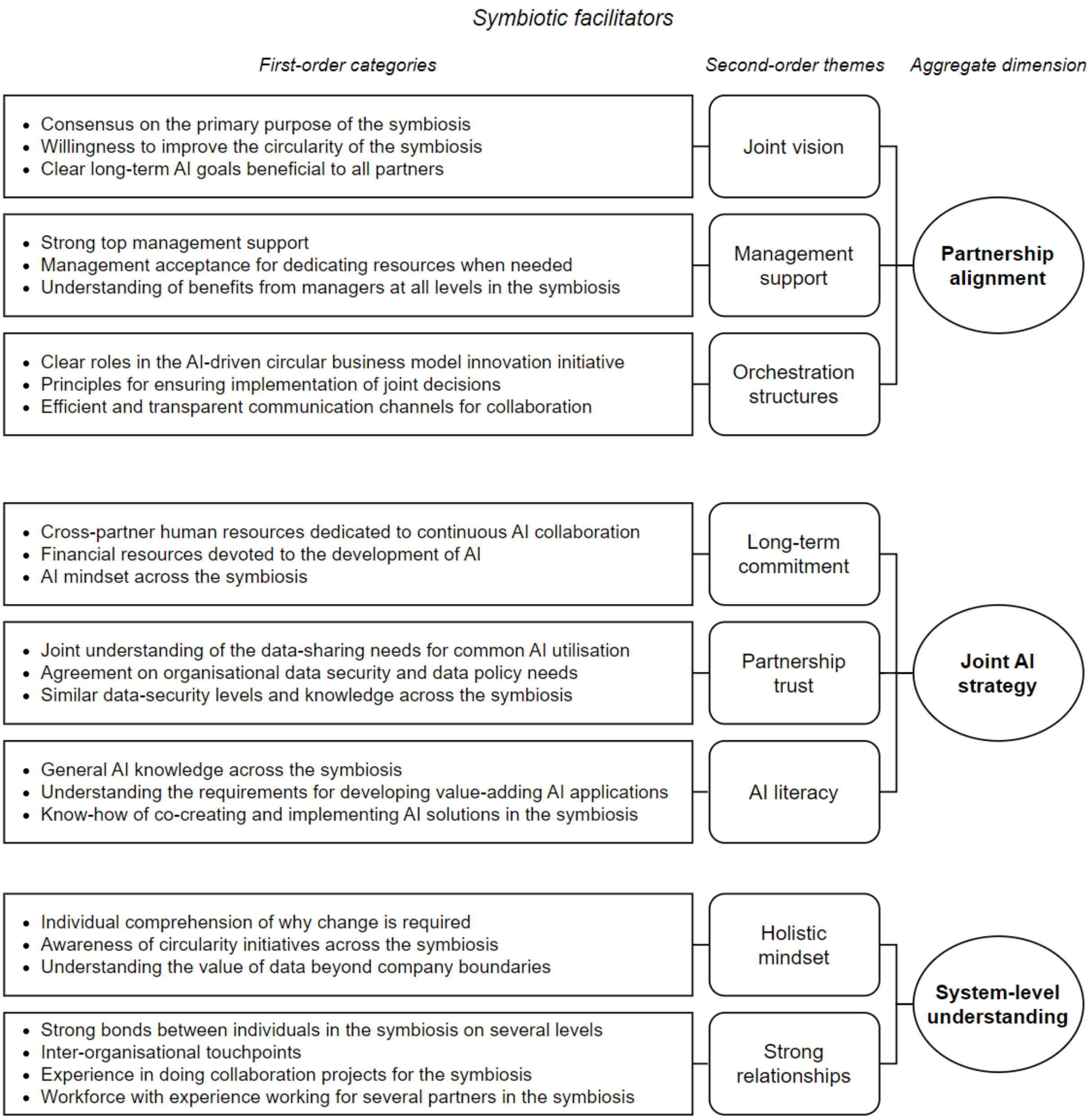

Figure 5. Data structure analysis two (2 out of 2).

3.3.3 Analysis of validatory interviews

In the last analysis, the purpose was to validate our second analysis. We, therefore, focused on the informants' interpretations that presented alternative perspectives and ideas to our findings. Hence, we utilised notes and interview recordings to compare what informants said regarding the findings. No severe flaws were discovered, and only minor adjustments were made to first-order categories. For example, *"strong bonds between individuals in the symbiosis"* was clarified by adding *"on several levels"*. By doing this, we also enhanced our understanding of the overall data, significantly improving our framework.

3.4 Quality improvement measures

According to Lincoln and Guba (1985), four criteria influence a qualitative study's trustworthiness: credibility, transferability, dependability, and confirmability. As we conducted our research, we considered all of these elements to ensure the validity of our data interpretation and increase the trustworthiness of this study.

Credibility measures how accurately the results reflect the real world (Lincoln & Guba, 1985). According to Shenton (2004), there are 14 different provisions researchers can make to improve credibility, and of these, we used triangulation, frequent debriefing sessions, and peer scrutiny of the research project. We triangulated our data by comparing it to previous research and the data itself, where we had diverse informants. Throughout the study, we had frequent debriefing sessions with our supervisors, five times at Luleå University of Technology and weekly at Swerim. Our supervision meetings focused on discussing and planning our research project, presenting findings, and seeking advice on improving the study. Peer scrutiny was carried out in four seminars, with four peers providing feedback on our report at each meeting.

Transferability is the degree to which research findings can be generalised or applied to different contexts (Lincoln & Guba, 1985). In qualitative research, it is hard to achieve high transferability with a single study (Shenton, 2004). Although we interviewed individuals from different companies, which increases transferability, it should be noted that they were all connected to the same initiative. We also provided the context of the study in Section 3.1.1 to assist researchers and managers in using their judgment and experience to determine whether the findings are transferable to their context. The results in Section 4.1, which are descriptive in nature and further explain the context, also add to the transferability of the study.

Dependability gauges how consistent research findings are and how easily they can be replicated over time (Lincoln & Guba, 1985). In this study, we deliberately tried to clearly and transparently describe our methods. This increases dependability by allowing future researchers to replicate our work, even if their results may differ from ours (Shenton, 2004).

Confirmability refers to which extent research findings are grounded in the data rather than the researcher's personal biases, motivations, or interests (Lincoln & Guba, 1985). This study used triangulation and reflexivity to achieve greater neutrality (Shenton, 2004). Triangulation between informants from the case companies and past research also helped us reduce investigator bias. With reflexivity, we tried to be aware that our actions could influence the results, so we followed our research approach guidelines as closely as possible to avoid personal bias.

4 FINDINGS

Based on empirical data from five companies, we have identified how AI can amplify an industrial symbiosis and conceptualised how to realise the value of AI-driven CBMI fully. To untangle successful AI-driven CBMI, we specifically focused on an AI initiative in a waste-gas-based symbiosis. We present these findings in three sections: 4.1 demonstrate how AI amplifies an industrial symbiosis; 4.2 outlines principles for AI-driven CBMI in an industrial symbiosis; and 4.3 describes symbiotic facilitators. Following this presentation, we outline a framework elaborating on how industrial symbioses can ease AI-driven CBMI in section 4.4.

4.1 How AI amplifies the industrial symbiosis

A comprehensive illustration of how the studied AI initiative amplifies the industrial symbiosis is shown in Figure 6. Below the visualisation, the numbers explain the corresponding benefits and AI-driven changes. Using AI to enhance the circularity of the symbiosis demands several modifications to the case companies' business models, which are presented in Table 3. These findings are based on analysis one and the principles from analysis two.

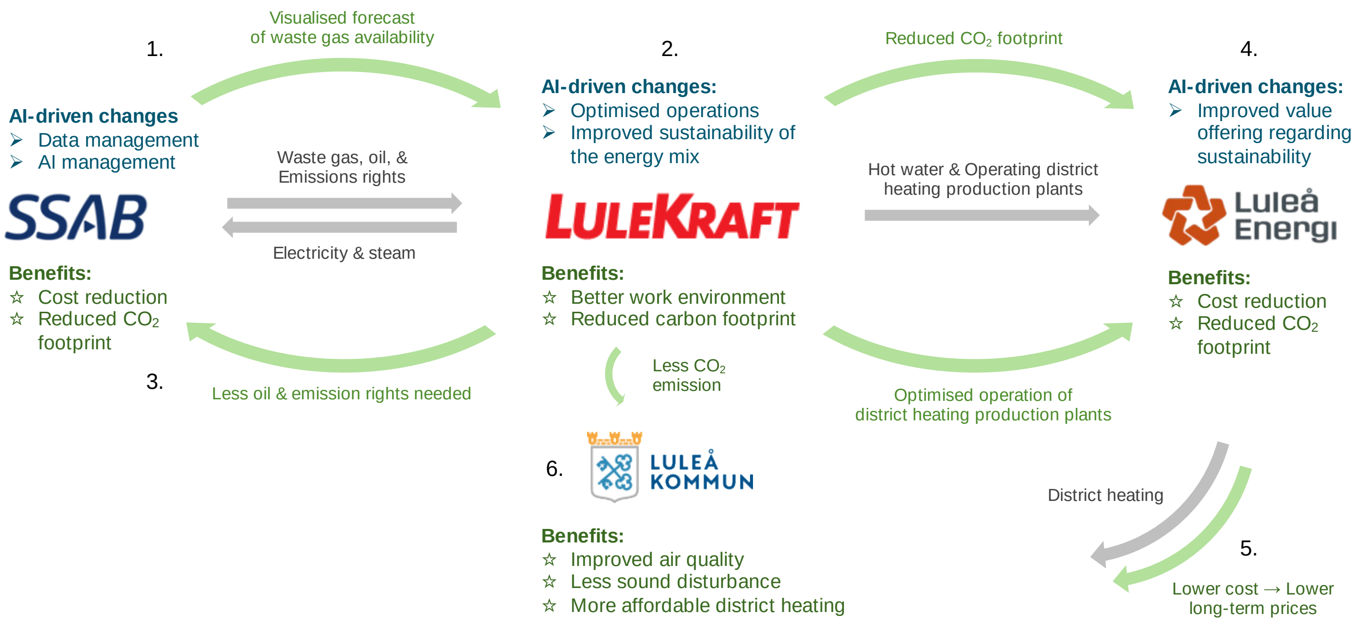

Figure 6. Illustration of how AI amplifies the industrial symbiosis.

1. Added value from SSAB to LuleKraft. Due to security concerns, SSAB will host the AI and deliver LuleKraft a visualised forecast of waste gas availability. Therefore, the AI-driven changes at SSAB will include data management to ensure data quality necessary for accurate predictions and AI management to ensure the system operates as intended.

2. AI-driven changes and benefits at LuleKraft. LuleKraft can then use the forecast to enhance its operations and achieve a more sustainable energy mix for generating hot water and electricity. Ultimately the AI could help to minimise the amount of oil required to safeguard operations when the uncertainty of available gas is high, resulting in lower CO_2 emissions, estimated to be 411 tons (see Appendix E). Additionally, AI optimises operations by predicting future gas supply and reducing the parameters that operators must consider.

3. Added value from LuleKraft to SSAB. Using AI, it is possible for LuleKraft to generate the same amount of electricity and hot water while consuming less oil leading to a reduced carbon footprint for SSAB. This also results in cost savings for SSAB because the amount of oil and emission rights they must cover for LuleKraft decreases (estimated to be 841 thousand SEK).

4. Added value from LuleKraft to Luleå Energi. Since LuleKraft reduces oil usage, the hot water sold to Luleå Energi will have a reduced carbon footprint. In addition, the AI can improve LuleKraft's ability to optimise the operations of Luleå Energi's production plants throughout the city, potentially resulting in cost savings. The lower carbon footprint, in turn, enhances the value proposition of district heating in terms of sustainability, which Luleå Energi's customers value, particularly businesses.

5. Added value from Luleå Energi to Luleå Kommun. Luleå Energ's goal is to eventually pass on their cost savings to customers by reducing prices. As a result, any cost savings generated by AI will ultimately lead to lower district heating prices in the long run.

6. Added value from LuleKraft to Luleå Kommun. As a result of less gas flaring, residents who live close to the steel plant would experience better air quality and less sound disturbance. Moreover, cost reduction for Luleå Energi would mean cheaper district heating in the long term.

Table 3. AI-driven business model changes in the industrial symbiosis.

	SSAB	LuleKraft	Luleå Energi
Value Creation	*Data management:* – Data collection, integration, and delivery to the AI – Data storage needed for training the AI – Sensor calibration to ensure data quality *AI management:* – AI hosting, data maintenance and adding updates – AI knowledge through internal staff or external partners *Value Proposition:* – Greener steel and improved goodwill locally	*Optimised operations:* – Knowledge of future waste-gas supply helps operators optimes operational decision making – Aided current operational decision-making due to less stress and fewer parameters to account for *Improved sustainability of the energy mix:* – More cycling of waste gas – Less oil consumed *Value Proposition:* – Better carbon footprint and improved goodwill locally	*Value Proposition:* – Greener district heating, valued especially by business customers – *Lower long-term prices*
Value Delivery	*Visualised forecast of waste gas availability:* – Deliver visualisation to the control room – Collaborate with operators for correct control room visuals	*Optimised operation of district heating production plants* – Better forecasts improve operators' ability to optimise the production plants owned by Luleå Energi	
Value Capture	*Cost reduction:* – Less oil delivered from SSAB to LuleKraft – Fewer emission rights needed	*Due to business agreements that make SSAB pay for oil and emission rights that LuleKraft uses, all value capture will land in SSAB's pockets*	*Cost reduction:* – Potential cost reduction cost through optimises operations of district heating production plants

4.2 Principles for AI-driven circular business model innovation in an industrial symbiosis

A critical insight from our informants was the need to outline principles for AI-driven CBMI in an industrial symbiosis. Our analysis identified three principles: *Iterative AI co-creation (value creation), ensuring AI delivery (value delivery) and AI symbiosis integration (value capture).* These principles are fundamental business model activities on a general symbiosis level that transcend company borders. Each principle is also primarily associated with one of the three business model elements: value creation, delivery, or capture (visualised in Figure 7).

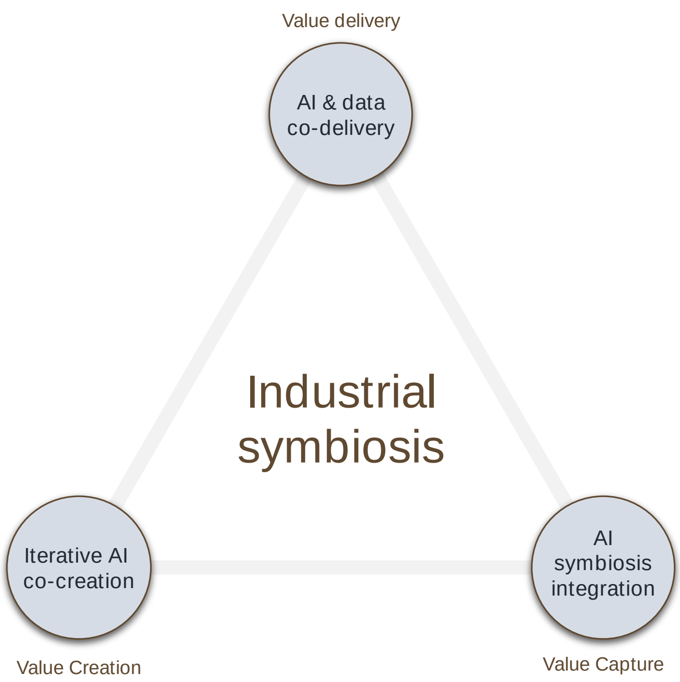

Figure 7. AI-driven CBMI principles with their primary business model component.

4.2.1 Iterative AI co-creation

Iterative AI co-creation focuses on the development of AI that adds value to an industrial symbiosis, laying the foundation for successful AI implementation. This principle is essential for successfully establishing processes that create and sustain value-creating AI.

A collaborative *AI creation approach* is the first key element to creating and implementing AI successfully. Several informants highlighted that working together to identify AI opportunities is essential to ensure innovation that benefits the entire industrial symbiosis. Once partners have identified an opportunity, involving intended users in the development process is vital to ensure that the AI solution adds value and acceptance if it initially does not operate perfectly. During the site visit at LuleKraft, operators exemplified this by showing an initial application interface that had to be rebuilt due to excessive parameters and controls, rendering it unusable. Informants also emphasised the importance of close cross-company collaboration involving various functions and experts to minimise misunderstandings, train AI on the correct data, and streamline AI development. As one data scientist put it:

> *"Many of these projects are same same but different … How do we get data? What is the data quality? Who understands the processes and systems? You also frequently hear various interpretations of these aspects depending on whom you are talking to." (I6)*

The second component is *coordinated data management* to ensure trustworthy and high-quality data across an industrial symbiosis. The data scientists stressed the importance of having transparent data management and pipelines between partners to ensure trust in data needed for AI development. Continuously validating sensor data is also necessary for providing reliable data. Additionally, informants suggested that partners could increase data relevance by identifying areas where new sensors could aid AI creation. The data scientists pointed out that inadequate input data will lead to inaccurate AI output. Consequently, they emphasised the importance of working together to secure high-quality data to build reliable AI, as one data scientist explained:

> *"I mean, if any company wants to implement an AI model, at least they have to know the basic saying garbage in, garbage out." (I9)*

Finally, *long-term AI value creation* is essential for ensuring the value of AI over time. Several informants stated that maintaining the value of innovation initiatives over time is hard, and AI is even more difficult. To address this, informants emphasised the need for partners to evaluate ownership of AI and data to establish accountability for managing data and AI. Maintaining the value of AI necessitates regular maintenance and updates to adjust to real-world changes affecting its predictive abilities. The informants, therefore, underlined the need for companies to allocate resources to adapt and maintain the AI to planned and unforeseen changes in the industrial symbiosis. Furthermore, informants indicated that in the long run, all value creation, including AI, in the symbiosis must be aligned with the end customer's need. The energy coordinator at SSAB described the importance of considering long-term value creation as follows:

> *"But it requires, I believe, a certain level of commitment from someone who feels ownership … What resource will look after this model in the future? Currently, an external party has developed it. If SSAB takes over, someone from SSAB must understand it and be involved in updating, ensuring its proper functioning, and assessing its performance." (I5)*

4.2.2 AI & data co-delivery

AI & data co-delivery highlights the importance of ensuring that the value created in one area is delivered to its intended receiver. The principle underscores the need for seamless and effective application delivery and data-sharing solutions across company borders.

The first essential component is *data-sharing solutions* to handle the data flows required for AI in an industrial symbiosis. Multiple informants highlighted the importance of secure real-time data flow between departments and companies to provide AI with input data. Secure data-sharing is essential to avoid interference with digital production and operator systems. This also applies when delivering AI applications to another partner's operator room. To address this, the IT experts at SSAB recommended a data warehouse to securely integrate all available data and enable sharing across company boundaries. Furthermore, informants underscored that partners should collaborate to develop secure cross-company data-sharing solutions. As one production manager explained, this approach enhances understanding of what each company is comfortable with and potential solutions. Nevertheless, sharing information with partners is not the problem, as clarified by the energy coordinator at SSAB:

> *"There is still this IT security. It is difficult to share data … We have no problem sharing information with people at LuleKraft … But it's a crucial aspect to ensure that the whole system operates safely." (I5)*

A second crucial element is establishing *efficient data-sharing processes* in order to reduce the resources required for sharing data. Several informants explained that data sharing could be challenging in an industrial symbiosis due to the involvement of multiple human and decision-making touchpoints, leading to friction. Informants, therefore, stressed the significance of streamlining data-sharing processes by minimising top management involvement and human resource needs. For example, one manager stated that companies should identify data they can freely share within the symbiosis. With a clear understanding of what data can be shared, top management and human involvement in companies' data-sharing processes can be significantly reduced, as explained by a production manager at Luleå Energi:

> *"Looking at all the data, we might be able to give 80% straight up. Then there's the remaining 20%. Well, you can have 15% of it, but we'd like to keep the remaining 5% … if we don't make a contract with the death penalty if you spread it." (I11)*

The last part is *optimised user delivery* processes to aid the use and adoption of AI tools. The operators at LuleKraft emphasised the importance of clear instructions and adequate training to support their understanding and implementation of new digital tools. AI developers and operators also underlined that efficient feedback processes are crucial for gathering valuable insight to ensure usability and improve the AI once the system runs. For example, one LuleKraft operations engineer stated that efficient and transparent user feedback loops across company borders are beneficial because they speed up updates and reduce potential tensions between companies. Another operations engineer noted:

> *"If I provide feedback, then I expect a response in return. If I don't get any sort of reply, and just throw everything into a black box, and nothing ever comes back. Then I will cease to provide feedback." (I24)*

4.2.3 AI symbiosis integration

AI symbiosis integration addresses value capture for AI-driven CBMI in an industrial symbiosis. This principle concerns how partners should set up policies, processes, and activities to ensure that AI is used to capture its full potential.

To fully capture the value of AI, it is critical to leverage *AI-human interaction*. Informants highlighted that promoting knowledge transfer among users is necessary to create best practices. For example, one data scientist explained that managers could use an AI prediction to formalise knowledge between operating teams by comparing their decision-making based on the model to reduce discrepancies between them. Furthermore, data scientists and practitioners emphasised that lacking trust towards a new tool can hinder its value capture. Hence, suggesting that education and demonstration of functionality would help generate trust towards new AI tools. RISE's AI expert also mentioned that having transparent AI helps. To exemplify, the production manager at LuleKraft said:

> *"It is important before implementing such a system that you test it for quite some time before going live. And then run trials before completely releasing it, to ensure that people trust the model."* (I20)

Another fundamental aspect is recognising the *interconnected value capture* in an industrial symbiosis. One informant highlighted this by stating that certain information crucial for maximising LuleKraft's value capture may also be price-sensitive information for SSAB shares. Informants noted that decisions or innovations made in one company often impact all the other partners. They also underlined the significance of agreements to help manage cost and revenue structures between companies and indicated that it helps to maintain value capture when changes occur. Moreover, informants working within the symbiosis emphasised the importance of considering all partners in operational decisions and AI usage. They also insinuated that transparency and accountability among partners are crucial factors in preventing sub-optimisation. For example, sharing production plans, gas availability information, and economic agreements can enhance transparency and accountability. One operator exemplified the cost structures' interconnectedness from SSAB's point of view:

> *"Gas is flaring. Okay, so LuleKraft must burn oil instead ... which quickly adds up to millions for us. So perhaps we should call in the maintenance guy on overtime, even if it costs us a little extra."* (I22)

4.3 Symbiotic facilitators

Our analysis reveals three crucial interconnected factors that can ease AI-driven CBMI in an industrial symbiosis: *partnership alignment*, *joint AI strategy*, and *symbiosis understanding*. These facilitate the business model reconfiguration required to unlock AI's circularity benefits.

4.3.1 Partnership alignment

Partnership alignment is the foundation for a successful industrial symbiosis that benefits all partners. The interconnected nature of a symbiosis also means that changing one partner's business model often causes ripple effects through partners, especially when implementing AI solutions. Consequently, alignment between all departments and levels across partners is a crucial symbiotic facilitator for innovating a symbiosis utilising AI.

An essential first step for alignment is having a *joint vision* of the future industrial symbiosis. Despite the different main business goals of the companies involved, the symbiosis has thrived for over 40 years. The informants explained that consensus on the primary purpose of the symbiosis has enabled it to evolve and improve over time. Additionally, a strong willingness to improve the circularity of a symbiosis is pivotal for innovation, which LuleKraft is a notable example of. Their dedication has considerably reduced CO_2 emissions in the past ten years through optimised operations and influencing partners to align their processes towards shared CO_2 reduction, as their CEO enthusiastically described:

> *"That's what I tell my men and women. We are already good and take that in. But we can do better. Still, that doesn't mean we're bad. It means we are exceptional. 5 is a pass, and we are at 8.3, which is far above a pass; it's an A+. But you can't give up, can you? You must continue to strive for excellence." (I15)*

In contrast, informants mentioned that it sometimes takes work to motivate workers at SSAB to prioritise circularity improvements within the industrial symbiosis. Nonetheless, informants also recognised the difficulty in engaging personnel in circularity initiatives for the symbiosis if all their performance measures focus on production. Especially if the circularity innovation is not directly related to steelmaking, which accounts for most of SSAB's profits. Informants stressed that partners get on board if they see the innovation's symbiotic and organisational benefits. Therefore, a clear long-term AI goal that benefits all is crucial to align partners. As one manager strongly asserted:

> *"The partnership is about working together. Regardless of what is written on the jacket, the goal is the same. Our goal is to provide added value to all partners." (I2)*

A second important aspect is *management support*. The informants emphasised the need for strong top management support to innovate an industrial symbiosis. Nevertheless, every decision for change does not have to be top-down managed, but it will ease alignment throughout the organisation. Having management acceptance for dedicating resources towards innovation when needed can also aid AI-driven change. Multiple informants said that competition constantly pressures industrial firms to create slimmer organisations, and as a result, resources often must be taken from other core activities. Thus, to motivate resource allocation and management support for an innovation initiative, managers at all levers in the symbiosis must understand the benefits. One manager described it as follows:

"I already have 1,000 post-it notes. What is in it for me? Yeah, but things will improve going forward because of. Then people buy it. ... Explain why they should join." (I16)

Another vital component is *orchestration structures* to ease the collaboration and coordination between partners needed for change. Several informants noted the importance of clear roles in innovation initiatives because aligning the organisations towards a common goal and performing business model innovation becomes more manageable. If a partner perceives its role as unclear, it can result in low motivation and underutilisation of that partner's abilities, ultimately leading to missed opportunities for ideas and solutions. Informants also underlined that structures for implementing joint partner decisions are essential to ensure the alignment of affected parts in the industrial symbiosis. Otherwise, individuals or departments might be unaware of their critical role in implementing a decision or exploring an opportunity.

Furthermore, informants highlighted that orchestrating change demands efficient and transparent communication channels to reduce the risk of delays and misunderstandings. For example, one operator expressed that even internal communication can be challenging. One informant also shared an example of how one department wanted a digital system to solve a production problem. However, further investigation revealed that another department caused it and improved communication saved roughly 1,5 million SEK. Another informant highlighted the importance of efficient communication by playfully describing how different company-based vocabularies can make coordination difficult:

"In companies, you often have your vocabulary. If we speak to the blast furnace at SSAB, they say: yes, but we must stop due to the 'stäjfsen'. Nobody knows what that is. But we also have our language called LuleKraftian, which contains many strange words that don't exist. Although everyone here knows what they mean, and vice versa at SSAB." (I17)

4.3.2 Joint AI strategy

A *Joint AI strategy* focuses on facilitating continuous innovation of an industrial symbiosis. The objective is to create conditions that support the activities needed for AI-driven circular business model innovation. Adopting a long-term approach towards AI development is vital, as successful innovation often comes after several failures. Consequently, AI know-how has to be built over time in a symbiosis by dedicating resources and creating circumstances for continuous AI innovation.

A crucial aspect is a *long-term commitment* towards AI. The informants emphasised that developing AI solutions for an industrial symbiosis necessitates ongoing efforts from cross-partner personnel resources. Therefore, they indicated that a dedicated team of individuals from each company would enable a long-term perspective; team members do not necessarily need to be full-time. This team structure would also help partners overcome the challenge of losing critical competencies due to employee turnover by allowing for a more effortless transfer of responsibilities when employees change jobs. Moreover, informants mentioned that a long-term commitment is necessary to ensure the proper functioning of an AI system. For example, a research project developed an AI to forecast district heating which operators never adopted due to a lack of such commitment. While informants mentioned that the AI initiative did not demand significant new investments, they noted that dedicated long-term financial resources are needed for long-term technical data-sharing solutions, consulting hours, and personnel expenses for taking time away from other activities. Additionally, establishing an AI mindset across the symbiosis is essential to foster the adoption of new methods and employee-generated innovation, as one manager at LuleKraft optimistically exemplified:

> *"You have to be patient. You must involve and engage as many people as possible. So they think this is exciting. A lot is going on, and you're thinking far ahead. What might this mean? What can this bring?" (I17)*

A key issue is building *partnership trust* to aid collaboration for joint AI solutions. Most informants stressed the significance of a widespread understanding of the data-sharing requirements for developing joint AI tools to increase the likelihood of success. The informants also expressed varying opinions on security needs. While some stressed the need for high security to prevent breaches and unauthorised access, others believed concerns about leaked data are exaggerated. One data scientist, for instance, reported difficulty interpreting data sets despite access to extensive information. However, in this case, Luleå Energy provides critical services for society, which raise national security concerns in addition to protecting company secrets. This fact highlights the importance of agreeing on the necessary security levels, having high data-security knowledge, and ensuring similar security levels among partners to increase willingness to share data. One manager pragmatically described the importance of trust in the following way:

> *"If we have three companies, and we are here on the security level (showing high with hand), company B is here (showing lower with hand), and company C is not addressing the issue, they are the weakest link. Then we can't send data to them." (I11)*

Another vital aspect is *AI literacy* among partners since it enables effective communication and collaboration with AI. Informants noted that general AI knowledge about what it can and cannot do is crucial for increasing organisational support for AI development. Additionally, understanding the requirements helps partners evaluate where AI can be adopted based on current conditions and identify necessary changes to enable more opportunities. The informants also noted that know-how regarding co-creation and implementation of AI solutions significantly benefits innovation in the industrial symbiosis. For example, SSAB, LuleKraft, and Luleå Energy utilise various hardware and software solutions in different production areas. Thus, understanding AI, linkage of various hardware and software, energy systems, industrial processes, data from several areas, and effective collaboration with multiple departments and partners are all required for successful AI implementation. Furthermore, the informants emphasised the importance of developing and sustaining a workforce with combined AI and industry knowledge across partners to support long-term innovation, as one manager at LuleKraft described:

> *"When creating a system, it's important to consider the long-term … While a project's progress relies on the project manager and participants, a system's survival should not rely on one person in a single role. It should be natural in the role and clearly described, allowing for easy handover to another person." (I16)*

4.3.3 System-level understanding

System-level understanding is a crucial facilitator for generating novel AI ideas to improve the circularity of an industrial symbiosis. Cross fertilisation between companies and individuals is essential for identifying untapped symbiotic potential. Individuals can also more easily embrace AI-driven CBMI if they understand the bigger picture and the reasons behind an initiative.

A critical component is a *holistic mindset* across partners because innovation in an industial symbiosis often affects individuals and departments that will not benefit directly. Several informants, therefore, underscored that individual comprehension of why change is necessary is vital to create motivation for change. For example, one manager argued against the view that industry workers resist change, stating that most workers simply want to understand the underlying reasons. When employees understand the bigger picture, they can also push back against decisions based on a lack of understanding that demands workers to undertake sub-optimising tasks for the symbiosis. System-level understanding can also be improved by raising awareness of circularity initiatives within the symbiosis by spreading information through, for instance, internal news channels. One informant suggested celebrating successful innovation initiatives by serving a cake in the lunchroom to draw attention to the importance of symbiosis collaboration. Elevated system-level understanding also results in comprehending the value of data beyond company boundaries, which is crucial to foster new ideas for AI applications. One data scientist explained:

> *"Typically, you collect and use data in real-time locally. However, integrating data from several sources, you can lift things to a higher level and, in many cases, refine things and get more value out of it." (I6)*

Another essential aspect is *strong relationships* between partners. All informants acknowledged that strong relationships on several levels are necessary for daily operations and critical for successfully innovating an industrial symbiosis. Thus, they stressed the importance of inter-organisational touchpoints, such as monthly catch-up meetings, site visits, and workshops. Similarly, conducting various partner projects can strengthen relationships, improve collaboration and increase system-level understanding. Additionally, the AI initiative's members mentioned that a workforce with experience from multiple companies develops relational networks that promote inter-company ties and a better understanding of the symbiosis. One data scientist emphasised how grateful they were to have an individual with experience and contacts across the symbiosis:

> *"Thankfully, we have had Björn, who has experience from both SSAB and LuleKraft. So he's seen it from various angles and has been able to explain: Most likely it is because they've done this, and this looks weird because of this, and so on." (I6)*

4.4 A coevolutionary alignment framework for AI-driven circular business model innovation

This section synthesises our findings in a coevolutionary alignment framework for AI-driven CBMI in industrial symbioses (see Figure 8). The informants revealed that AI is a powerful tool to streamline business operations and amplify the circularity of an industrial symbiosis. Despite these opportunities, unlocking the full potential of AI necessitates partnership commitment. The findings propose that efficient coordination and collaboration are vital in identifying opportunities, creating value, delivering value across company borders and capturing value in an industrial symbiosis.

However, carrying out the requisite CBMI that the findings suggest joint AI solutions demands is challenging. For example, all informants highlighted how difficult it was to transfer data between partners. The lifeblood of an AI application is data. Therefore, if data sharing between companies in an industrial symbiosis is not seamless, the value potential of an AI solution is severely limited. Our framework visualises how the principles and symbiotic facilitators are mutually reinforcing and linked in addressing how companies can coevolve to overcome the challenges of AI-driven CBMI. To demonstrate the framework's key insights, we describe three overarching yet connected aspects to unlock the full potential of AI in industrial symbioses.

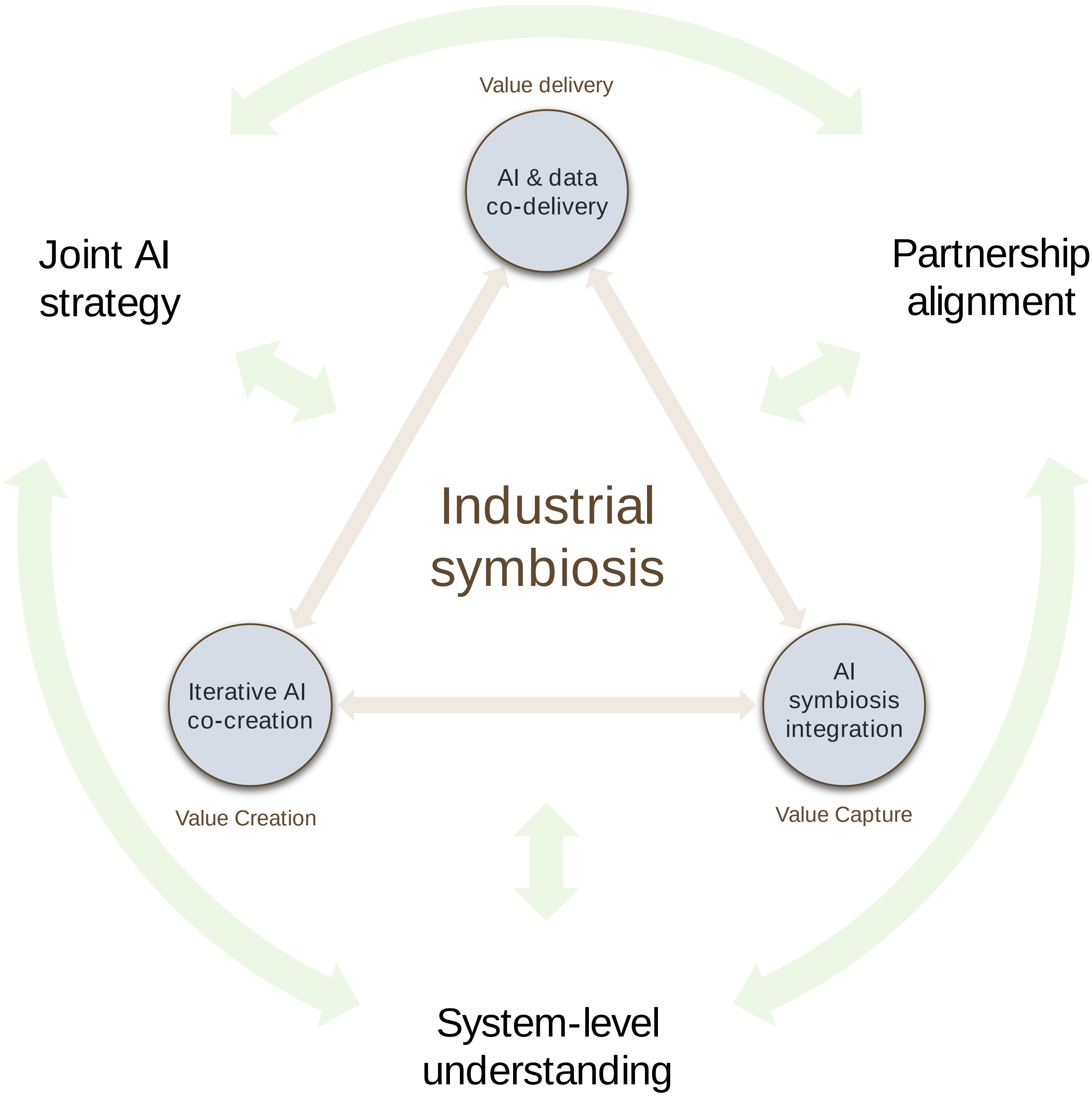

Figure 8. A coevolutionary alignment framework for AI-driven circular business model innovation.

Principles for AI-driven circular business model innovation unlock the potential of AI. Simply developing an AI in isolation is insufficient to innovate and improve the circularity of an industrial symbiosis. Truly leveraging AI goes beyond company borders. Unlocking the full potential of AI in a symbiosis, thus, demands collaboration and coordination of companies' CBMI efforts. At its core, this relies on the following principles: *iterative AI co-creation*, *AI & data co-delivery*, and *AI symbiosis integration*. Applying these principles is an iterative process because they are interdependent and necessitate parallel work.

Ensuring AI & data co-delivery between partners is vital to establish a solid foundation for AI. Without organisational processes and technologies that enable smooth data sharing in an industrial symbiosis, conducting other AI-driven CBMI activities will be impossible. Companies must adopt an *iterative AI co-creation* approach that promotes collaboration, coordination, and transparency between departments and experts across a symbiosis. Our informants emphasised that creating AI is an iterative process that requires input and validation from various sources and departments. Furthermore, partners should consider *AI symbiosis integration* during and after its development to ensure adoption and correct usage in order to not sub-optimise.

Symbiotic facilitators develop stronger bonds enabling partners to innovate as one unit. Our analysis reveals three fundamental interconnected factors that facilitate the adoption of the AI-driven CBMI principles in an industrial symbiosis: *partnership alignment*, *joint AI strategy*, and *system-level understanding*. All symbiotic facilitators are coevolutionary, meaning that improving one will aid the others. Moreover, adopting principles will also support the development of symbiotic facilitators.

Existing inefficiencies and tensions within the partners' relationships will be apparent when applying principles for innovating an industrial symbiosis. Therefore, strong bonds between partners are essential to overcome challenges and promote effective collaboration. This can be achieved by ensuring a *holistic mindset* and fostering *strong relationships* across a symbiosis. Additionally, *partnership alignment* and a *joint AI strategy* will aid the *system-level understanding* and strengthen bonds between partners. Indeed, performing AI-driven CBMI principles as one unit is crucial, which requires efficient collaboration and coordination. This is primarily ensured by having a *joint vision, management support*, and *orchestration structures* but can also be significantly aided by having a *common AI strategy* and *system-level understanding*.

Principles and symbiotic facilitators align AI-driven innovation of output and input business models. Although most informants reported difficulties obtaining a commitment from SSAB for the AI initiative, we contend that the situation is complex and calls for a thorough understanding of multiple data points. In particular, our analysis reveals that aligning symbiotic innovation with the output business model is more challenging than aligning with the input business model.

In this case, LuleKraft plays a crucial role in maximising the value of SSAB's waste gas by serving as a bridge between SSAB and Luleå Energy. As a result, LuleKraft has an innate understanding of the industrial symbiosis and is deeply committed to its enhancement. While Luleå Energy's business model is partly based on the symbiosis, their limited involvement in value-creation activities results in less organisational understanding. For SSAB, however, the symbiosis is a minor business model component, and few individuals are directly exposed to it, resulting in even less organisational understanding and a sense of ownership. Consequently, output-based companies may naturally be less committed to symbiotic innovation, necessitating more efforts from input-based partners to ensure alignment. Undeniably, this underscores the importance of the principles and symbiotic facilitators in aligning AI-driven circular innovation of the business models in an industrial symbiosis (see Figure 9 for visualisation).

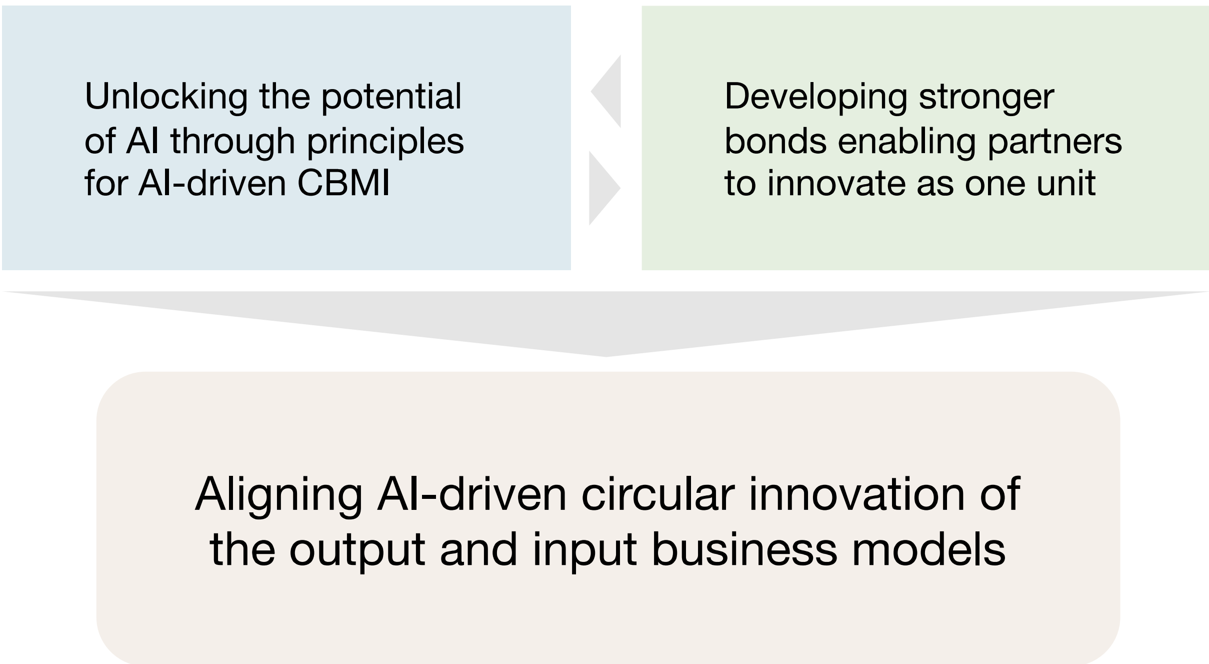

Figure 9. Visualisation of the framework's key insights.

5 DISCUSSION & CONCLUSION

This study sought to increase the understanding of AI-driven CBMI in the context of industrial symbiosis. Given the potential of digitalisation to enable the transition towards circularity in industries and the promising outlook of AI, the area of AI-driven CBMI is underexplored and requires further investigation (Bressanelli et al., 2022; Chauhan et al., 2022; Kristoffersen et al., 2020; Liu et al., 2022; Neligan et al., 2022; Parida et al., 2019). The findings provide empirical insight into conducting AI-driven CBMI of an exchange-based industrial symbiosis. This study demonstrates how AI can amplify circularity and delineate the principles and symbiotic enablers for AI-driven CBMI. Furthermore, it elaborates on the coevolutionary alignment of circular innovation of output and input business models required for successfully amplifying an industrial symbiosis using AI. In doing so, it makes several theoretical and managerial contributions.

5.1 Theoretical contributions

Our study makes theoretical contributions to the literature on AI, CBMI, and industrial symbiosis in four ways. First, it contributes by demonstrating the potential of AI to amplify the circularity of an industrial symbiosis. Previous research has explored the ability of AI to enhance circularity (Chauhan et al., 2022; Kristoffersen et al., 2020). This study takes it further by providing concrete evidence of how AI can forecast and optimise material flows within an industrial symbiosis and supporting previous research that digital technologies improve the work environment (Scafà et al., 2020; Sjödin et al., 2018). Consequently, this study reduces the need for scholars to rely on conceptual assumptions by offering a real-world example of the positive impact of AI.

Second, this study advances the understanding of the principles necessary for AI-driven CBMI. Although past research by Iansiti and Lakhani (2020) emphasises the importance of business models for ensuring AI application in companies, there is still a lack of research exploring the circularity contexts. Sjödin et al. (2021) expanded on this by exploring AI principles required for scaling AI capabilities in a digital servitisation context. Our analysis identifies three principles: *Iterative AI co-creation*, *AI & data co-delivery*, and *AI symbiosis integration*. These principles are vital to unlock the value of AI in an industrial symbiosis and address the organisational and collaborative challenges identified in prior CBMI literature (Antikainen et al., 2018; Geissdoerfer et al., 2022; Guldmann & Huulgaard, 2020; Tura et al., 2019), as well as challenges related to AI implementation (Iansiti & Lakhani, 2020; Reim et al., 2020; Sjödin et al., 2021).

Third, our findings contribute to AI-driven CBMI by being the first study concretising how to create conditions for circular innovation using AI in an industrial symbiosis. Existing research acknowledges the complexity of CBMI, requiring innovation that impacts entire industrial ecosystems (Geissdoerfer et al., 2022; Guldmann & Huulgaard, 2020; Kanda et al., 2021). Furthermore, AI-driven business model innovation presents additional challenges (Sjödin et al., 2021), which indicates that AI-driven CBMI faces several challenges. Our study addresses these challenges of AI-driven CBMI by uncovering three key symbiotic facilitators: *partnership alignment*, *joint AI strategy*, and *system-level understanding*. In line with Sjödin et al. (2021), these findings emphasise the significance of collaboration for effective AI implementation.

Last, we contribute to the industrial symbiosis literature by showcasing how to align AI-driven innovation of input and output business models in industrial symbioses. Kolagar (2022) highlights the importance of business model innovation, collaboration, and alignment for digital transformation in industrial ecosystems. However, more insights are needed regarding AI and various industrial ecosystems, such as industrial symbiosis. We address this gap by presenting a framework grounded in the identified principles and symbiotic facilitators that depicts how to achieve coevolutionary alignment of AI-driven CBMI in industrial symbioses.

5.2 Managerial contributions

AI affects all industries worldwide, and companies generate more data than ever. Still, few can fully harness their data's potential and leverage AI to solve business needs. On top of that €78 billion of material value is lost annually in the use of steel, plastic, and aluminium only in Europe (Enkvist et al., 2022), while industrial symbiosis and digital technologies such as AI are seen as key for creating more sustainable and competitive industries (Berg et al., 2020; European Commission, 2020; Kristoffersen et al., 2020; Neves et al., 2020).

This study increases the understanding of the implications of AI-driven CBMI and its potential for enhancing an industrial symbiosis. This knowledge assists managers in evaluating AI's impact on their businesses, addressing the knowledge barrier identified by Järvenpää et al. (2021), where top management lacked an understanding of data utilisation for AI-enabled forecasting in an industrial symbiosis. Our findings highlight that managers must understand the importance of building a solid data foundation for AI-driven CBMI, including secure, reliable, transparent, and accessible data.

Furthermore, aligning innovation efforts in an industrial symbiosis is essential due to the high interconnectedness. Managers must consider the identified principles and symbiotic facilitators as guiding factors to foster alignment between partners in order to achieve successful AI-driven CBMI. Priority should be given to working with symbiotic facilitators because they remove partnership collaboration barriers and facilitate innovation beyond AI. Subsequently, companies should focus on designing business model innovation activities based on the identified principles. Thus, by leveraging facilitators and adhering to principles, companies can effectively align their innovation efforts and, thereby, successfully unlock the full potential of AI-driven CBMI in an industrial symbiosis.

5.3 Limitations and future research

In this study, we collected data from five case companies operating within an specific industrial symbiosis context, specifically an energy system utilising waste gases from a steel manufacturer to generate heat, water, and electricity. Consequently, the generalisability of the findings may be limited, as industrial symbioses can vary significantly (Fraccascia et al., 2019). Future research aimed at validating these findings in other industrial symbioses and diffrent industrial ecosystems or partnerships would thus be interesting.

Furthermore, we conducted the case study during an ongoing innovation initiative, which missed potential insights due to the absence of long-term implementation data. This means there may be additional insights not captured in this study. Future research could explore the impact of successful AI-driven innovation initiatives to provide a more comprehensive understanding, particularly regarding maintaining the value of AI.

This study's findings are grounded on data from an innovation initiative utilising AI to optimise operations by predicting gas availability in an industrial symbiosis. However, AI offers numerous application areas for organisations (Iansiti & Lakhani, 2020; Sjödin et al., 2021), and several informants in this study identified additional opportunities where AI could enhance circularity and solve business needs. Moreover, informants in the validatory interviews noted that the symbiotic facilitators are essential for all industrial symbiosis innovation efforts. We, therefore, believe that our findings present opportunities for future research to explore the principles and symbiotic facilitators for business model innovation in other innovation or digitalisation efforts of industrial symbioses.

5.4 Conclusion

This study supports previous research that highlights digitalisation as a crucial enabler for the circular economy and particularly emphasises the potential of AI. The study aimed to answer two research questions: (RQ1) *How can Artificial Intelligence amplify the circularity of an industrial symbiosis?* and (RQ2) *How can Artificial-Intelligence-driven Circular Business Model Innovation be facilitated in an industrial symbiosis?* The study answers RQ1 by illustrating how AI can enhance the circularity of an industrial symbiosis and depicting the business model changes needed. Additionally, the identified principles contribute to a more comprehensive understanding of how AI amplifies circularity. To answer RQ2, it characterises principles and symbiotic facilitators and combines these findings into a coevolutionary alignment framework for promoting AI-driven CBMI in industrial symbioses. In conclusion, this study provides initial empirical insights into AI-driven CBMI and clearly demonstrates the need for further research.

REFERENCES

Amit, R., & Zott, C. (2012). Creating value through business model innovation. *MIT Sloan Management Review, 53*(3), 45-49. https://search.proquest.com/docview/963962187

Antikainen, M., Uusitalo, T., & Kivikytö-Reponen, P. (2018). Digitalisation as an Enabler of Circular Economy. *Procedia CIRP, 73*, 45-49. https://doi.org/10.1016/j.procir.2018.04.027

Åström, J., Reim, W., & Parida, V. (2022). Value creation and value capture for AI business model innovation: a three-phase process framework. *Review of Managerial Science, 16*(7), 2111-2133. https://doi.org/10.1007/s11846-022-00521-z

Baldassarre, B., Schepers, M., Bocken, N., Cuppen, E., Korevaar, G., & Calabretta, G. (2019). Industrial Symbiosis: towards a design process for eco-industrial clusters by integrating Circular Economy and Industrial Ecology perspectives. *Journal of Cleaner Production, 216*, 446-460. https://doi.org/10.1016/j.jclepro.2019.01.091

Berg, H., Le Blèvennec, K., Kristoffersen, E., Streè, B., Witomski, A., Stein, N., Bastein, T., Ramesohl, S., & Vrancken, K. (2020). Digital circular economy as a cornerstone of a sustainable European industry transformation. *ECERA European Circular Economy Research Alliance.* https://doi.org/10.13140/RG.2.2.13769.36966

Björkdahl, J. (2020). Strategies for Digitalization in Manufacturing Firms. *California Management Review, 62*(4), 17-36. https://doi.org/10.1177/0008125620920349

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering, 33*(5), 308-320. https://doi.org/10.1080/21681015.2016.1172124

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77-101. https://doi.org/10.1191/1478088706qp063oa

Bressanelli, G., Adrodegari, F., Pigosso, D. C. A., & Parida, V. (2022). Towards the Smart Circular Economy Paradigm: A Definition, Conceptualization, and Research Agenda. *Sustainability (Basel, Switzerland), 14*(9), 4960. https://doi.org/10.3390/su14094960

Brock, J. K., & von Wangenheim, F. (2019). Demystifying AI: What Digital Transformation Leaders Can Teach You about Realistic Artificial Intelligence. *California Management Review, 61*(4), 110-134. https://doi.org/10.1177/1536504219865226

Chauhan, C., Parida, V., & Dhir, A. (2022). Linking circular economy and digitalisation technologies: A systematic literature review of past achievements and future promises. *Technological Forecasting & Social Change, 177*, 121508. https://doi.org/10.1016/j.techfore.2022.121508

Chen, Y., Prentice, C., Weaven, S., & Hsiao, A. (2022). A systematic literature review of AI in the sharing economy. *Journal of Global Scholars of Marketing Science, 32*(3), 434-451. https://doi.org/10.1080/21639159.2020.1808850

Chertow, M. R. (2000). Industrial symbiosis: literature and taxonomy. *Annual Review of Energy and the Environment, 25*(1), 313-337. https://doi.org/10.1146/annurev.energy.25.1.313

Colla, V., Pietrosanti, C., Malfa, E., & Peters, K. (2020). Environment 4.0: How digitalization and machine learning can improve the environmental footprint of the steel production processes. *Matériaux & Techniques, 108*(4), 507. https://doi.org/https://doi.org/10.1051/mattech/2021007

DaSilva, C. M., & Trkman, P. (2014). Business Model: What It Is and What It Is Not. *Long Range Planning, 47*(6), 379-389. https://doi.org/10.1016/j.lrp.2013.08.004

David, M., & Sutton, C. D. (2016). *Samhällsvetenskaplig metod* (1st ed.). Studentlitteratur AB.

Ellen MacArthur Foundation. (2012). *Towards a Circular Economy-Economic and Business Rationale for an Accelerated Transition*. https://ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an

Ellen MacArthur Foundation. (2019). *Artificial intelligence and the circular economy - AI as a tool to accelerate the transition*. https://ellenmacarthurfoundation.org/artificial-intelligence-and-the-circular-economy

Enkvist, P., Klevnäs, P., Westerdahl, R., & Åhlén, A. (2022, Jul 20,). How a 'materials transition' can support the net-zero agenda. *McKinsey Insights.* https://www.mckinsey.com/capabilities/sustainability/our-insights/how-a-materials-transition-can-support-the-net-zero-agenda

European Commission. (2020). *Circular Economy Action Plan: For a cleaner and more competitive Europe*. https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf

Fraccascia, L., Giannoccaro, I., & Albino, V. (2019). Business models for industrial symbiosis: A taxonomy focused on the form of governance. *Resources, Conservation and Recycling, 146*, 114-126. https://doi.org/10.1016/j.resconrec.2019.03.016

Fraccascia, L., Magno, M., & Albino, V. (2016). Business models for industrial symbiosis: a guide for firms. *Procedia Environmental Science, Engineering and Management, 3*(2), 83-93.

Geissdoerfer, M., Pieroni, M. P. P., Pigosso, D. C. A., & Soufani, K. (2020). Circular business models: A review. *Journal of Cleaner Production, 277*, 123741. https://doi.org/10.1016/j.jclepro.2020.123741

Geissdoerfer, M., Santa-Maria, T., Kirchherr, J., & Pelzeter, C. (2022). Drivers and barriers for circular business model innovation. *Business Strategy and the Environment*. https://doi.org/10.1002/bse.3339

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production, 143*, 757-768. https://doi.org/10.1016/j.jclepro.2016.12.048

Guldmann, E., & Huulgaard, R. D. (2020). Barriers to circular business model innovation: A multiple-case study. *Journal of Cleaner Production, 243*, 118160. https://doi.org/10.1016/j.jclepro.2019.118160

Iansiti, M., & Lakhani, K. R. (2014). Digital ubiquity: How connections, sensors, and data are revolutionizing business. *Harvard Business Review, 92.*

Iansiti, M., & Lakhani, K. R. (2020). Competing in the age of AI: How machine intelligence changes the rules of business. *Harvard Business Review, 98.*

Ingemarsdotter, E. K., Jamsin, E., Kortuem, G. W., & Balkenende, A. R. (2019). Circular strategies enabled by the internet of things: a framework and analysis of current practice. *Sustainability, 11*(20), 5689. https://doi.org/10.3390/su11205689

Jacobsen, N. B. (2006). Industrial Symbiosis in Kalundborg, Denmark: A Quantitative Assessment of Economic and Environmental Aspects. *Journal of Industrial Ecology, 10*(1-2), 239-255. https://doi.org/10.1162/108819806775545411

Järvenpää, A. -., Salminen, V., & Kantola, J. (2021). Industrial Symbiosis, Circular Economy and Industry 4.0 - A Case Study in Finland. *Management and Production Engineering Review, 12*(4), 111-121. https://doi.org/10.24425/mper.2021.139999

Kanda, W., Geissdoerfer, M., & Hjelm, O. (2021). From circular business models to circular business ecosystems. *Business Strategy and the Environment, 30*(6), 2814-2829. https://doi.org/10.1002/bse.2895

Kaplan, A., & Haenlein, M. (2019). Siri, Siri, in my hand: Who's the fairest in the land? On the interpretations, illustrations, and implications of artificial intelligence. *Business Horizons, 62*(1), 15-25. https://doi.org/10.1016/j.bushor.2018.08.004

Kolagar, M., Parida, V., & Sjödin, D. (2022). Ecosystem transformation for digital servitization: A systematic review, integrative framework, and future research agenda. *Journal of Business Research, 146*, 176-200. https://doi.org/10.1016/j.jbusres.2022.03.067

Kristoffersen, E., Blomsma, F., Mikalef, P., & Li, J. (2020). The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies. *Journal of Business Research, 120*, 241-261. https://doi.org/10.1016/j.jbusres.2020.07.044

Kroese, D. P., Brereton, T., Taimre, T., & Botev, Z. I. (2014). Why the Monte Carlo method is so important today. *WIREs Computational Statistics, 6*(6), 386-392. https://doi.org/10.1002/wics.1314

Lee, S. M., Lee, D., & Kim, Y. S. (2019). The quality management ecosystem for predictive maintenance in the Industry 4.0 era. *International Journal of Quality Innovation, 5*, 4. https://doi.org/10.1186/s40887-019-0029-5

Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: a comprehensive review in context of manufacturing industry. *Journal of Cleaner Production, 115*, 36-51. https://doi.org/10.1016/j.jclepro.2015.12.042

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry*. sage.

Linde, L., Sjödin, D., Parida, V., & Gebauer, H. (2021). Evaluation of Digital Business Model Opportunities. *Research-Technology Management, 64*(1), 43-53. https://doi.org/10.1080/08956308.2021.1842664

Liu, Q., Trevisan, A. H., Yang, M., & Mascarenhas, J. (2022). A framework of digital technologies for the circular economy: Digital functions and mechanisms. *Business Strategy and the Environment, 31*(5), 2171-2192. https://doi.org/10.1002/bse.3015

Martinez, P., Mohsen, O., Al-Hussein, M., & Ahmad, R. (2022). Vision-based automated waste audits: a use case from the window manufacturing industry. *International Journal of Advanced Manufacturing Technology, 119*(11-12), 7735-7749. https://doi.org/10.1007/s00170-022-08730-2

Nañez Alonso, S. L., Reier Forradellas, R. F., Pi Morell, O., & Jorge-Vazquez, J. (2021). Digitalization, Circular Economy and Environmental Sustainability: The Application of Artificial Intelligence in the Efficient Self-Management of Waste. *Sustainability (Basel, Switzerland), 13*(4), 2092. https://doi.org/10.3390/su13042092

Neligan, A., Baumgartner, R. J., Geissdoerfer, M., & Schöggl, J. (2022). Circular disruption: Digitalisation as a driver of circular economy business models. *Business Strategy and the Environment, 32*(3), 1175-1188. https://doi.org/10.1002/bse.3100

Neri, A., Negri, M., Cagno, E., Franzò, S., Kumar, V., Lampertico, T., & Bassani, C. A. (2023). The role of digital technologies in supporting the implementation of circular economy practices by industrial small and medium enterprises. *Business Strategy and the Environment,* 1-26. https://doi.org/10.1002/bse.3388

Neves, A., Godina, R., Azevedo, S. G., & Matias, J. C. O. (2020). A comprehensive review of industrial symbiosis. *Journal of Cleaner Production, 247*, 119113. https://doi.org/10.1016/j.jclepro.2019.119113

Olhoff, A., & Christensen, J. (2022). *Emissions Gap Report 2022: The closing window.* United Nations Environment Programme. https://wedocs.unep.org/bitstream/handle/20.500.11822/40874/EGR2022.pdf?sequence=1&isAllowed=y

Osterwalder, A., & Pigneur, Y. (2010). *Business model generation: a handbook for visionaries, game changers, and challengers.* John Wiley & Sons.

Parida, V., Sjödin, D., & Reim, W. (2019). Reviewing literature on digitalization, business model innovation, and sustainable industry: Past achievements and future promises. *Sustainability, 11*(2), 391. https://doi.org/10.3390/su11020391

Ranta, V., Aarikka-Stenroos, L., & Väisänen, J. (2021). Digital technologies catalyzing business model innovation for circular economy — Multiple case study. *Resources, Conservation and Recycling, 164*, 105155. https://doi.org/10.1016/j.resconrec.2020.105155

Reim, W., Åström, J., & Eriksson, O. (2020). Implementation of artificial intelligence (AI): a roadmap for business model innovation. *AI, 1*(2), 180-191. https://doi.org/10.3390/ai1020011

Ritala, P., Huotari, P., Bocken, N., Albareda, L., & Puumalainen, K. (2018). Sustainable business model adoption among S&P 500 firms: A longitudinal content analysis study. *Journal of Cleaner Production, 170*, 216-226. https://doi.org/10.1016/j.jclepro.2017.09.159

Rosa, P., Sassanelli, C., Urbinati, A., Chiaroni, D., & Terzi, S. (2020). Assessing relations between Circular Economy and Industry 4.0: a systematic literature review. *International Journal of Production Research, 58*(6), 1662-1687. https://doi.org/10.1080/00207543.2019.1680896

Saunders, M., Lewis, P., & Thornhill, A. (2007). *Research methods* (4th ed.). Pearson Education Limited.

Scafà, M., Marconi, M., & Germani, M. (2020). A critical review of symbiosis approaches in the context of Industry 4.0. *Journal of Computational Design and Engineering, 7*(3), 269-278. https://doi.org/10.1093/jcde/qwaa022

Shenton, A. K. (2004). Strategies for ensuring trustworthiness in qualitative research projects. *Education for Information, 22*(2), 63-75. https://doi.org/10.3233/efi-2004-22201

Sjödin, D., Parida, V., Palmié, M., & Wincent, J. (2021). How AI capabilities enable business model innovation: Scaling AI through co-evolutionary processes and feedback loops. *Journal of Business Research, 134*, 574-587. https://doi.org/10.1016/j.jbusres.2021.05.009

Sjödin, D., Parida, V., Petrovic, A., & Leksell, M. (2018). Smart Factory Implementation and Process Innovation. *Research-Technology Management, 61*(5), 22-31. https://doi.org/10.1080/08956308.2018.1471277

Sjödin, D., & Vinit, P. (2021, Dec 4,). AI-driven circular business models — Leveraging AI for circularity benefits in manufacturing. *Managment of Innovation and Technology, 18*, 10-11. https://mgmt.imit.se/artiklar/ai-driven-circular-business-models/

Suchek, N., Fernandes, C. I., Kraus, S., Filser, M., & Sjögrén, H. (2021). Innovation and the circular economy: A systematic literature review. *Business Strategy and the Environment, 30*(8), 3686-3702. https://doi.org/10.1002/bse.2834

Teece, D. J. (2010). Business Models, Business Strategy and Innovation. *Long Range Planning, 43*(2), 172-194. https://doi.org/10.1016/j.lrp.2009.07.003

Tura, N., Hanski, J., Ahola, T., Ståhle, M., Piiparinen, S., & Valkokari, P. (2019). Unlocking circular business: A framework of barriers and drivers. *Journal of Cleaner Production, 212*, 90-98. https://doi.org/10.1016/j.jclepro.2018.11.202

Zhu, Q., Lowe, E. A., Wei, Y., & Barnes, D. (2007). Industrial Symbiosis in China: A Case Study of the Guitang Group. *Journal of Industrial Ecology, 11*(1), 31-42. https://doi.org/10.1162/jiec.2007.929

Zott, C., Amit, R., & Massa, L. (2011). The Business Model: Recent Developments and Future Research. *Journal of Management, 37*(4), 1019-1042. https://doi.org/10.1177/0149206311406265

APPENDIX A – Interview guide for data collection wave one

The following interview guide is an English translation of the Swedish original.

Intro

- Introducing us
- Ask if we can record
- Can you introduce yourself? Role in the project/company?
- What is the most critical business issue in the EnVisA project that you think we can contribute to?

Project

- What would you say is the purpose of the EnVisA project?
- If the best possible scenario for the project is achieved, what does it mean?
- What is your role in the project?
- What is (the Company)'s role in the project?
- What does (the Company) hope to get out of the project?
- Has (the Company) carried out AI projects before?
    - When, What, & How?
    - Have you been involved in anything?
- What are the difficulties associated with the project?
    - For you?
    - For your company?
    - For others?
    - In the big picture (collaboration/cooperation/symbiosis)
- How do you think the project relates to HYBRIT in the long term?

Solution

- Why is an AI needed?
    - What problems should be solved?
    - What is the bottleneck in the process/energy system?
    - What is the problem in the process/energy systems?
- When everything is implemented, how will the AI solution work?
    - Which companies will use the visualisation?
    - Who will use AI?
    - Who will maintain the AI?
    - Who will own the AI?
- Who owns the data that the AI uses?
    - Do more parties than SSAB contribute data to the AI?
    - How is data collected and delivered to the system?
    - Who is responsible for data collection?

Partnership

- What is the advantage of LuleKraft being jointly owned by SSAB and Luleå Energi?
- How would you describe that your company add value to the symbiosis?
- How would you describe the value that your company get out of the symbiosis?
- Are there more parties involved in LuleKraft than the owners SSAB and Luleå Energi?
- How would you describe the partnership relationship?
    - How integrated are all partners?

    - How much is it a customer/seller relationship?
    - Or do you collaborate closely all the time?
- Will the relationship change if AI implementation is realised? Why, what, how?
- Do you share data between partners today?

How do all business models link together

- Can you describe how each company makes money from the symbiosis?
- As we understand it, Luleå Kraft buys gas from SSAB.
    - How does it work?
    - How is paid?
    - Do they get anything else?
- Luleå Energi buys district heating and electricity from LuleKraft.
    - How is this paid?
    - How does LuleKraft meet the demand of the district heating network?
- SSAB buys steam and electricity from LuleKraft.
    - How is this paid?
- Does only SSAB buy electricity from LuleKraft?

The questions presented above are the ones we started our first interview wave with. These questions, however, changed the most from interview to interview as our understanding grew. As a result, each informant was asked questions about current business models that were unique to them.

APPENDIX B – Interview guide for data collection wave two

The following interview guide is an English translation of the Swedish original.

Intro

- Introducing us
- Ask if we can record
- Can you introduce yourself? Role in the project/company?

What are the value and difficulties

- Presentation of illustration
  - Do you want to add or remove something to the illustration?
  - Are there any other comments you want to make regarding the illustration?
- Do you see any other benefits of the EnVisa project which is not connected to cost reductions or reduced carbon emission?
- Do you see any long-term benefits of EnVisa?
  - Company
  - Industrial symbiosis
- Do you see any difficulties for the AI to create and deliver this value?
  - Short-term
  - Long-term
  - Anything other than Data?

What changes are needed to realise the value of EnVisa

- What changes have been made so far in the various companies and partnerships to get this far in the EnVisa project?
- What changes do you think are needed going forward to realise the value of Envisa fully?
- How have you managed to get this far?

What changes are needed to realise the value of AI

- Based on your knowledge from the EnVisa project, what is generally required to realise the value of AI projects?
- Do activities and processes need to be changed or added? Why, What & How?
  - Change the roles of operators?
  - Change production?
  - Change routines?
  - Change the responsibilities of workers?
  - Change the responsibilities of managers?
- Are there any policies that need and can be changed to facilitate implementation?
- Does mindset need to change in the organisation? Why, What & How?
  - Data-driven mindset?
  - Does the mindset need to change from a linear to a more circular mindset?
  - Is there a need to focus more on end consumers or the stakeholders affected by pollution?
- What abilities and competencies are needed? Why, What & How?
  - Is there a need for training & education?
    - Will the partnership be able to update and manage the AI without DD and Swerim?

- What resources are needed? Why, What & How?
  - Financial?
  - Knowledge?
  - Personnel?

Partnership

- Do existing relationships need to change? Why, What & How?
  - Information sharing?
  - Data sharing?
  - Communication?
  - Cooperation?
- Are new partners required?
- Do other stakeholders need to be involved in change? Why, What & How?
  - Customers
  - Municipalities
- How do you get everyone on board for the innovation of the symbiosis?
  - Is there a need for more commitment from senior managers?
  - Is there a need for more commitment from those who will perform tasks?
- Does the way alignment is created between the partners need to change? Why, What & How?
  - Change payment flows/transactions between partners/customers?
  - Incentive structures?
  - Does SSAB see the benefit?
  - Should SSAB get more money because they deliver a new service to LuleKraft?
- Does the way alignment is created at all levels in the companies need to change? Why, What & How?
  - How do we ensure that everyone does their best to realise the value of AI?
  - Get individuals to feel ownership.
- Do incentives need to change to succeed with innovation in the long term?
- How can you make it easier for your partners to succeed with AI?

Conclusion

- What are the three most important things to consider to increase the chances of success with AI?

APPENDIX C – Secondary data used in the first analysis

Table 1 describes the data used in the first analysis, its purpose, and its source.

Table 1. Secondary data.

Data type	Description	Purpose	Source
9 Annual reports	The three most recent annual reports from the three main companies in the industrial symbiosis.	Understand the companies, their financial situation, and current business models.	Websites of LuleKraft[1], Luleå Energi[2], and SSAB[3], as well as Retriever Business[4].
3 External websites	Information about the energy system, district heating, and sustainability efforts, as well as pricing and marketing to end users.	Understand current business models.	Websites of LuleKraft, Luleå Energi, and SSAB
Macro Data	See Appendix E.	Mainly used in the Monte Carlo simulation, but also improved the understanding of cost structures.	See Appendix E
3 Master thesis	Theses written by Samuel Nordgren (2006), Erik Sandberg (2014), and Anders Hake (2014). Includes technical descriptions of the industrial symbiosis and evaluations of potential enhancements.	Understand the energy system on a technical level and thus the value creation of industrial symbiosis.	Digitala Vetenskapliga Arkivet[5]
12 Project documents (Word/pdf)	The documents provide a detailed description of the AI initiative's planning and past results.	Understand the AI imitative in depth.	Project leader
24 Project PowerPoints	Includes every internal and external PowerPoint presentation. Provides an in-depth look at the short-term challenges and outcomes of the AI initiative.	Understand the changes, challenges, and benefits that AI will bring to the case companies.	Project leader

[1] https://LuleKraft.se
[2] https://www.luleaenergi.se/ars-och-hallbarhetsredovisningar/ars-och-hallbarhetsredovisning-2021/ & https://ar.luleaenergi.se/sv/arsredovisning/2020/
[3] https://www.ssab.com/sv-se/ssab-koncern/investerare/rapporter-presentationer
[4] https://www.retrievergroup.com/sv/business-suite licences through Luleå University of Technology
[5] http://www.diva-portal.org/smash/get/diva2:1027308/FULLTEXT01.pdf, https://www.diva-portal.org/smash/get/diva2:1025677/FULLTEXT02, & http://www.diva-portal.se/smash/get/diva2:1019569/FULLTEXT02.pdf

Data type	Description	Purpose	Source
2 Project videos	Recordings of presentations made for an audience outside of the imitative.	Understanding how the AI imitative is communicated to external stakeholders.	Project leader
3 Quantitative data files	Data regarding cost and revenue structures and emissions.	Understand how AI affects cost and revenue structures and circularity.	LuleKraft, Luleå Energi, Project leader

APPENDIX D – Representative quotes for first-order categories in analysis one

Table 1 presents the quotes that best represent each first-order category for the first thematic analysis. Upon request, we may supply additional quotes that form the basis of our data structure.

Table 1. Representative quotes of analysis one.

ID	Representative quote	First order-category	Second-order themes
	The industrial symbiosis		
I5 I1 I2	We (SSAB) supply... waste gases to be able to produce district heating through LuleKraft. (I5) SSAB reports emission rights for LuleKraft (I1) SSAB then buys the oil for me (LuleKraft). (I2)	*SSAB delivers waste gas, oil, and emission rights to LuleKraft*	SSAB & LuleKraft
I2	They want to get rid of the gas and make money from it, and they mainly want steam and electricity.	*LuleKraft delivers electricity and steam to SSAB*	
I1	So, it is like just a platform (LuleKraft) to somehow increase the value of the gases.	*Adds value by increasing the value of waste gas*	LuleKraft
I1	Now we see that it is Wednesday, they will do this then, then we will get less of this gas and so on so that... As I said, those who sit and operators have quite a lot in their heads when they sit there. A lot to decide on, and make decisions about.	*Optimising gas use by analysing much information is required not to lose money*	
I1	And LuleKraft is a part-owned company between us (Luleå Energi) and SSAB.	*LuleKraft is owned 50/50 by SSAB and Luleå Energi*	
I1	and we (Luleå Energi) buy the hot water from LuleKraft.	*LuleKraft delivers hot water to Luleå Energi*	LuleKraft & Luleå Energi
I2	Yes, we (LuleKraft) optimise the process for Luleå Energi… They had their own production team at Luleå Energi before.	*LuleKraft operates Luleå Energi's district heating production plants*	
I10	It is a safe, stable, and secure supply of heat. The customers should have as little, have to care as little as possible about it, and it should work, and then we have very good prices too... Customers, big and small, should be able to devote themselves to what value they create. If it is a company… or private individuals, they can do other things.	*Sells low-cost district heating to residents and businesses in Luleå*	Luleå Energi
I1	We (Luleå Energi) own the facilities and the boilers... the plants, we own the network.	*Owns the district heating network and production facilities*	
	Business model changes		

ID	Representative quote	First order-category	Second-order themes
I5 I16	we use the data we have at SSAB (I5) Then SSAB will come and fix them, and if it is critical for the calculation to be correct, then you can install double transmitters, and then you can compare it. That makes the system easy today... But it is about safeguarding raw data through calibration and finding maintenance intervals. (I16)	*SSAB handles data management for the AI*	**Value creation**
I16	It is on SSAB's side that they calibrate and verify the values... Because everything must be with them, and it is for IT security reasons that all the software will be with SSAB.	*SSAB handles AI management*	
I16	That is extra value… I think like this. You get the opportunity to make a plan instead of just living in the moment... You have a forecast, and then you have something to rely on.	*LuleKraft's operational decision-making is aided by knowledge of future waste-gas supply*	
I17	Yes, but to get more information to the operators. To understand why we do this or why we do that... It is quite complex as it is today, and we have quite a lot to keep track of. It is not just the process itself, but we have an eye on electricity prices, and we have an eye on how to run the accumulator tank, and we have all our Excel sheets that you have heard about.	*LuleKraft's operational decisions are simplified as a result of fewer parameters*	
I2	If I know 2 hours ahead, there is coke gas. If I am going to start the boiler, I know if there will be gas, then it feels safer to say yes, now we start. I can also know that if I have coke gas, I do not have to add expensive fuels: oil or LPG.	*LuleKraft's energy mix becomes more sustainable*	
I10	Certainly, the customers, especially corporate customers, are aware of this and want as little fossil fuel as possible. So that they are satisfied with this recycled energy, and it is optimised as much as possible. So that I think there is value in showing, above all, that we work on the questions.	*Companies' value propositions are enhanced in terms of sustainability*	
I6	But the only way you can do it is that these models have to be implemented on the SSABS side, and then the result is presented on a screen at LUKAB. So, LUKAB does not get the data directly, but they only get this view of the data presented on their screens.	*SSAB deliverers a visualisation of the gas forecast*	**Value delivery**
I1	And then they say to start the boiler. Then this tool will help. It is for them that we need this forecast so that we help them do the right thing.	*LuleKraft's steering of Luleå Energi's production facilities is aided by*	

ID	Representative quote	First order-category	Second-order themes
		knowledge of future waste-gas supply	
I2	Can you remove oil or LPG and solve the task of burning gas. It is such a huge leverage on the economy because with every drop of oil you lose a lot.	*SSAB's costs for delivering oil to LuleKraft are reduced*	
I1	So there they win. If they can run on their gas at LuleKraft, then SSAB does not have to pay out emission rights for LuleKraft. (1)	*SSAB's costs for delivering emission rights to LuleKraft are reduced*	**Value capture**
I1	We will see that a LuleKraft could get access to a larger proportion of gas or a better optimisation of the gases and, in that way, be able to produce district heating more optimised. Then we would also be able to stop tipping at certain facilities.	*Luleå Energi's operating costs for production facilities might be reduced*	
	Benefits		
I16	Yes, it is a work environment issue. It is actually for the staff. It is a stressful factor not knowing... They could be running five plants or six plants alone... they have to make many decisions, so everything that can be reduced helps them.	Better work environment due to less stress for operators	
I1	And some are very good at seeing that they are now blowing. Now we see that it is Wednesday, they will do this then, then we will get less gas and so on. Those who are experienced operators can read out what we think AI will also be able to tell them to do. That is probably the hope that a new person can then sit behind the levers and get that experience directly from AIn.	*AI helps to develop more consistent decision-making by formalising knowledge*	**Operators**
I1	There are lessons to be learned there… in the Hybrit case, the gases will not be an issue as a heat source... There we will make use of other types of residual energies… So there can always be an optimisation aspect. You can use AI there, so the lessons learned from this project can be applied further.	*Knowledge gained from AI efforts can be utilised in future applications*	
I5	Different parameters come into play, the energy storage, different process solutions, and so on, making it all more complicated.	*AI can assist in making sense of an increasingly complex energy system*	**Partners**
I8	Then from the prediction, we can have smart control. Smart control is based on the prediction and includes the model, so if the prediction model is not good. Then the control will have a lot of errors and bugs.	*Predictive AI is the foundation for future automation*	

ID	Representative quote	First order-category	Second-order themes
I2	We can optimise and get rid of more fossil fuel in Luleå… If you know about the availability of coke gas, you can use coke gas in a more sensible way.	*Improved local air quality and reduced global environmental impact*	**External stakeholders**
I2	It is very disturbing for the nearby residents in Svartöstan. Take summertime. How fun it is to sit in the garden and hear: DUUUUU, it just roars.	*Less gas flaring results in less noise disturbance for nearby residents*	
I10	Instead, we do something smart that reduces costs, and that is if you do not burn fossil oil. It is very expensive. This will also benefit the customers in the long run.	*In the long-term value captured at Luleå Energi is passed on to the customers*	

APPENDIX E – Monte Carlo simulation of cost and CO_2 benefits

Monte Carlo simulation:

Monte Carlo simulation is a mathematical random sampling technique to estimate the possible outcomes of uncertain events[6]. The basic idea is to use randomness to solve problems that, in theory, have deterministic solutions. For example, when calculating financial[7] or sustainability[8] outcomes, Monte Carlo simulation can be particularly beneficial when alternative approaches are time-consuming or impractical.

Purpose:

The purpose of the simulation was to estimate and quantify what the AI could realistically achieve in terms of CO2 and cost savings. Determining how AI will affect the entire industrial symbiosis is difficult because of the complexity of its energy system. As a result, we decided that a Monte Carlo simulation was the best method for simplifying the analysis in terms of parameters and complexity while still accounting for the inherent uncertainty.

The analysis was carried out in collaboration with industrial experts who have worked in the energy system for over 35 years. Consequently, we believe this is the most accurate estimate that can be made now. To improve the estimation further, we recommend tracking the impact of AI for at least 1-2 years.

Method:

First, we used the knowledge gained from data collection wave one, the first two project meetings and site visits to develop a mathematical formulation for cost CO2 and cost savings in the industrial symbiosis, which we then broke down into smaller pieces. After careful consideration, we decided against estimating the potential CO2 and cost savings at Luleå Energi because (1) we realised that savings at their production sites are much more indirect and reliable estimation requires monitoring the AI's effects for some time; and (2) the potential savings are much smaller than those at other companies, making it safer to ignore them in the absence of

[6] Kroese, D. P., Brereton, T., Taimre, T., & Botev, Z. I. (2014). Why the Monte Carlo method is so important today. *Wiley Interdisciplinary Reviews: Computational Statistics*, *6*(6), 386-392. https://doi.org/10.1002/wics.1314

[7] Glasserman, P. (2004). *Monte Carlo methods in financial engineering*. New York: springer. https://doi.org/10.1007/978-0-387-21617-1

[8] de Almeida Guimarães, V., Junior, I. C. L., & da Silva, M. A. V. (2018). Evaluating the sustainability of urban passenger transportation by Monte Carlo simulation. *Renewable and Sustainable Energy Reviews*, *93*, 732-752. https://doi.org/10.1016/j.rser.2018.05.015

accurate data and consider them to be variation in the model that already exists. CO_2 savings at LuleKraft is described by:

$$CO_2\ savings = Oil\ saved * Emission\ of\ oil$$

Cost savings for the industrial symbiosis are described as follows:

$$Cost\ savings = Oil\ cost + Energy\ tax\ cost + Emission\ rights\ cost$$

Which can be further subdivided as follows:

$$Cost\ savings = Oil\ saved\ (Oil\ price + Oil\ tax) + Emission\ price * CO_2\ savings$$

After formulating the logic, we gathered the data required to create all the variables for the simulation. In addition, we took help from the engineers at LuleKraft to estimate the amount of oil saved and to double-check that our data was correct. Table 1 describes all the variables we used in the simulation.

Table 1. Input variables.

Variable	Unit	Description of the variable	Source
Oil saved	GWh/ Year	A continuous random variable with a probability distribution that describes how saving becomes more challenging as time goes on. It is calibrated to a most likely number and has a minimum and maximum savings cap.	Estimated by engineers at LuleKraft
Emission of oil	CO_2 Ton /GWh	A fixed variable representing the amount of CO_2 emitted by burning oil at LuleKraft.	Naturvårdsverket[9]
Oil price	SEK/ GWh	A continuous random variable with a normal probability distribution. Mean = Exponential Moving Average. Std.= ten-year average of the yearly standard deviation.	Investing.com[10]
Oil tax	SEK/ GWh	A fixed variable representing the tax cost of burning oil at LuleKraft.	LuleKraft
Emission price	SEK/ CO_2Ton	A continuous random variable with a normal probability distribution. Mean = Estimated 2023 price by SEB. Std.= ten-year average of the yearly standard deviation.	SEB Group[11] Investing.com[12]

[9] https://www.naturvardsverket.se/vagledning-och-stod/luft-och-klimat/berakna-klimatpaverkan/
[10] https://www.investing.com/commodities/brent-oil-historical-data (Daily 2012/01/03 – 2023/04/03)
[11] https://sebgroup.com/sv/press/nyheter/2022/priset-pa-utslappsratter-far-stor-effekt-i-ar
[12] https://www.investing.com/commodities/carbon-emissions-historical-data (Daily 2022/01/03 – 2023/04/03)

Comment: (a) Although imperfect, we believe that a normal distribution best represents future prices determined by supply and demand.

Last, we used Excel VBA scripts to run the Monte Carlo simulation in Microsoft Excel. We ran a total of 20 000 samples, and the variable from continuous distributions was updated in each instance. The result was then checked by data scientists and engineers from the AI initiative to ensure that the estimates were reasonable.

Result:

Based on our simulation results, we created three scenarios with a 90% confidential interval, as shown in Table 2. The breakdown of cost savings from the base scenario is depicted in Figure 1. Figure 2 presents the results of each run in the simulation.

Table 2. Yearly savings scenarios.

Scenario	Cost savings (thousand SEK)	CO_2 savings (ton)
Best	1 327	637
Base	841	411
Worst	354	186

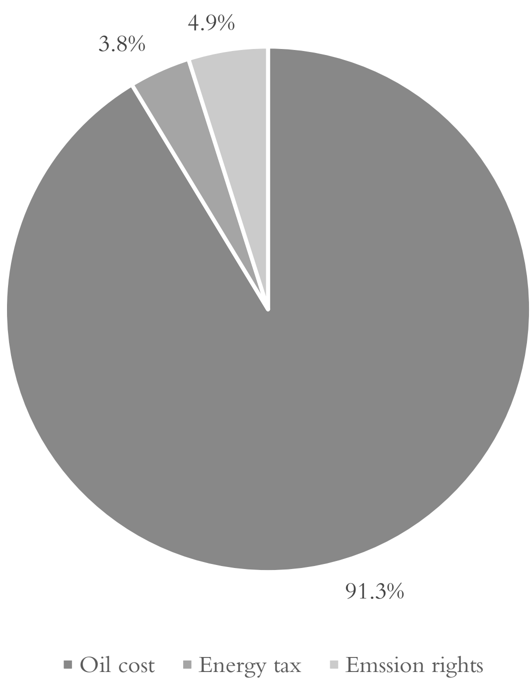

Figure 1. Distribution of savings.

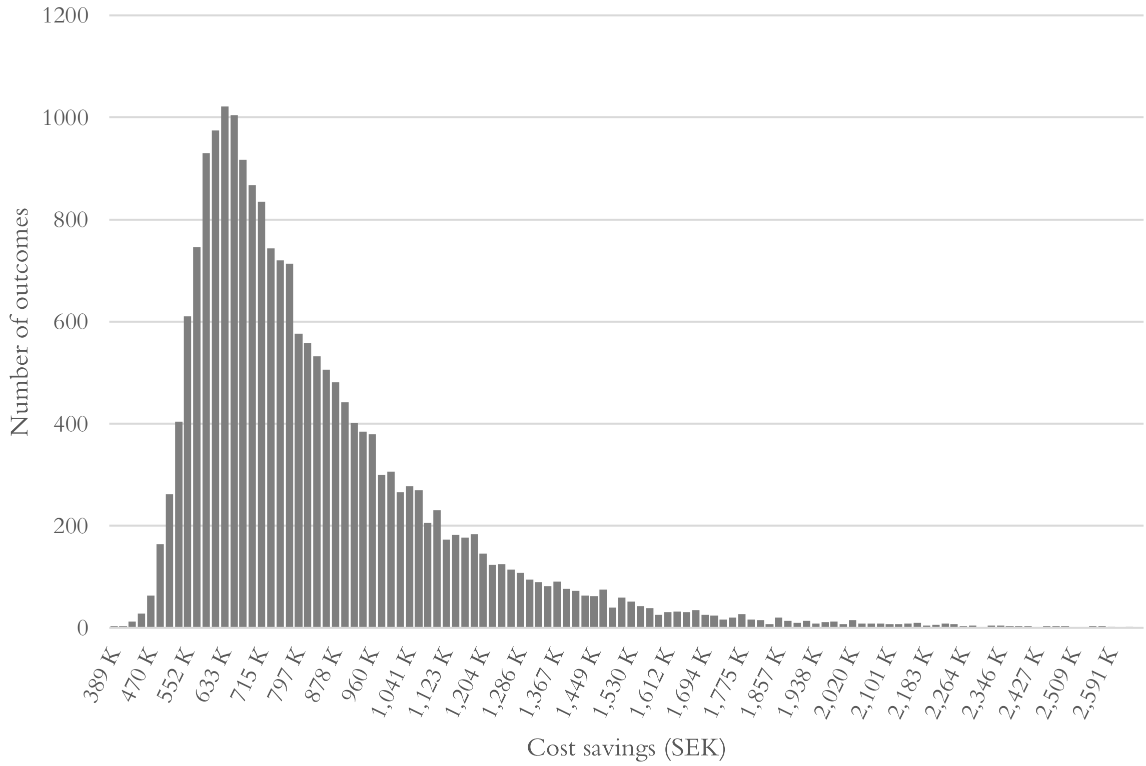

Figure 2. Monte Carlo simulation result.

APPENDIX F – Representative quotes for first-order categories in analysis two

In the complete thematic analysis, most first-order categories have more than ten quotes, with only "*Creating data-sharing processes that demand few human resources*" having four. Table 1 presents the quotes that best represent each first-order category, excluding the ones in the report's findings section. Upon request, we may supply additional quotes that form the basis of our data structure.

Table 1. Representative quotes of analysis two.

ID	Representative quote	First-order category	Second-order theme
Aggregated dimension: Partnership alignment			
I5	Everyone's goal is to use the process gases available from SSAB most efficiently. In essence, this is just a project to improve further the common goals that we already have, I would say.	*Consensus on the primary purpose of the symbiosis*	Joint vision
I10	Yes, so we are participating and cooperating. Then we will see what we can do together, to perform various cooperation programs. We can take the energy accumulator as an example. It is a developed collaboration with LuleKraft and SSAB, which affects our collaboration in a new and good way.	*Willingness to improve the circularity of the symbiosis*	
I13	But the bottom line is to talk to each other. So we get down to an understanding. Talk and settles on some shared vision.	*Clear long-term AI goals beneficial to all partners*	
I7	But it is needed, I think, perhaps at the group level. As I said, this is a way to reduce carbon dioxide emissions for us. We are going to try this.	*Strong top management support*	Management support
I6	This is something you have to invest in. You have to make sure that even those in production and those in line work actually get space or extra resources to be able to participate in the way you expect.	*Management acceptance for dedicating resources when needed*	
I8	I think it is their choice. They have to pay something to put more in, but if they already see the potential... I think it will not be a problem.	*Understanding of benefits from managers at all levels in the symbiosis*	
I16	Yes, but you can earn a lot from that because sometimes it can get a little fuzzy. Yes, now I am on a project there, wonder what I am going to do, is it so important that I come, huh, what is my role? So it is thus a greater probability that people leave the meeting with more than just the next meeting date.	*Clear roles in the AI-driven circular business model innovation initiative*	Orchestration structures

ID	Representative quote	First-order category	Second-order theme
I19	Who is the priority… Who is to decide that this should really be done? Is it up to LuleKraft, or is it up to SSAB?	*Principles for ensuring implementation of joint decisions*	
I6	There are quite a lot of silos. Where you have production, you have IT for themselves, and they do not always talk a lot to each other.	*Efficient and transparent communication channels for collaboration*	
Aggregated dimension: Joint AI strategy			
I16	So then we met, it was in fairly simple forms, and I think we sat together for an hour often at SSAB, and then we discussed how we use waste energies and flaring. But it has died out. It would have been good for the project, so we already had a group.	*Cross-partner human resources dedicated to continuous AI collaboration*	**Long-term commitment**
I13	And that was why it was delayed because the funding was unavailable. No one was really willing to take the investment cost.	*Financial resources devoted to the development of AI*	
I6	How should we use AI in a smart way? How do we collect data? How are we using it?	*AI mindset across the symbiosis*	
I11	Because somewhere, there must be a machine that will use Big Data methods to absorb all the ones and zeros that go into the processes of all three actors.	*Joint understanding of the data-sharing needs for common AI utilisation*	**Partnership trust**
I12	We have three stakeholders. And SSAB has their policy, so they cannot share this data to the cloud or externally. That is a barrier to this work, but it could be solved.	*Agreement on organisational data security and data policy needs*	
I11	Therefore, from a safe point of view, it would be very good if all companies were located here (indicating high up with hands).	*Similar data-security levels and knowledge across the symbiosis*	
I17	Explain a little bit about what AI is and how to use it. I think that will set many gears in motion.	*General AI knowledge across the symbiosis*	**AI literacy**
I6	If you have a slightly better picture of what the conditions are that are needed to be able to run a good project. Yes, an AI or ML project.	*Understanding the requirements for developing value-*	

ID	Representative quote	First-order category	Second-order theme
		adding AI applications	
I14	I think it is about the difficulties of implementing it, that is... to make it live, if you say so, in the real system between SSAB and LuleKraft.	*Know-how of co-creating and implementing AI solutions in the symbiosis*	
Aggregated dimension: System-level understanding			
I7	People said what kind of project is this? And why should we be in this? Why have we joined this? Has it been anchored? Because there were so many people involved.	*Individual comprehension of why change is required*	**Holistic mindset**
I13	You have to pay attention to things... It could be to send a small flasher on the intranet. It does something. Someone is reading it, but it might be good to pay attention.	*Awareness of circularity initiatives across the symbiosis*	
I12	I think SSAB and LuleKraft both need to know what data they deliver. In this case, it will be LuleKraft and Luleå energi. Which data and how are they using it? So then they need to understand to know each other.	*Understanding the value of data beyond company boundaries*	
I18	Take the companies Luleå energi, LuleKraft, and SSAB. It is like a company name on a piece of paper, but in order for something to be done in reality. It is necessary that people talk to each other and so on.	*Strong bonds between individuals in the symbiosis on several levels*	**Strong relationships**
I15	The contact surface with SSAB can be better, and it can be like visits, workshops, and monthly meetings, like just with teams now. It is so simple, so there is a lot to improve on.	*Inter-organisational touchpoints*	
I5	So there has always been a partnership in itself there, but I think the benefit of this project is, in particular, to be able to walk away from ingrained working methods.	*Experience in doing collaboration projects for the symbiosis*	
I15	I have drafted Björn. He has been there, and his contact network at SSAB is good.	*Workforce with experience working for several partners in the symbiosis*	

ID	Representative quote	First-order category	Second-order theme
	Aggregated dimension: Iterative AI co-creation		
I14	Technically speaking, the content of the partnership is changing. And there can be an advantage with a project like this: you get a clear picture for everyone. What can be improved without you knowing about it.	*Working together to identify AI circularity opportunities*	Collaborative AI creation approach
I19	But what do we want, like what do the operators get out of this? What does the company benefit from this? Because it happens so that we do not sit and do fancy stuff that nobody wants.	*Creating AI with a user-centric approach*	
I9	if I am using that data... a discussion has to be made between the person who is producing the data and handling the data and the person who is analysing the data ... I mean we need this data, but how does the data look like or what data you have and what is missing as of now?	*Involving various functions, experts and partners in AI development*	
I9	With how the pipeline works and how the data is being handled. That kind of information was missing, and it was initially quite slow.	*Increasing transparency of data pipelines*	Coordinated data management
I12	The other thing is they are using some sensors, and then there is some damage, which they never fixed. Then it leads to we cannot get the data we want, and if we cannot get the data, then how can we use machine learning?	*Creating processes for validating data and sensors*	
I8	And secondly, to make it work better, I think it may need more sensors. The more sensors, the better. Like it got more information back, and you can have more predictions	*Assessing where additional sensors can increase value*	
I1	Yes, I do not know if LuleKraft can do everything themselves… It might have to be discussed if SSAB should be the owner of the system or the AI then or if it is LuleKraft.	*Coordinating AI and data ownership among partners*	Long-term AI value creation
I8	Rerun and renew and modify the system periodically. This is very important. To modify these systems periodically... You need to ensure it runs and is efficient.	*Maintaining and adapting AI to changing circumstances*	
I10	but this understanding of LuleKraft for the end customers I think could be better	*Aligning value creation with the value proposition of the symbiosis*	

ID	Representative quote	First-order category	Second-order theme
	Aggregated dimension: AI & data co-delivery		
I19	In the project, there is an opportunity to connect to that data warehouse and not have to crawl behind the process firewall to get some data out and then into the mainframe or into some system to get some data out.	*Creating technical solutions for real-time data flow between partners*	Data-sharing solutions
I13	They are discussing a bit, and I think I have touched on that with this picture. For example, SSAB owns the data and is then visualised at LuleKraft. LuleKraft does not own the data. The data is SSAB's and so on.	*Creating AI application delivery between partners' operator rooms*	
I13	How should we share data, and what is secure? What is uncertain? What signals do we have? It was probably one of the issues that SSAB and LuleKraft touched upon quite early.	*Joint efforts to solve security barriers to data sharing*	
I11	And manual work has been done on it, and it is exactly the same thing, and we have to protect sensitive AI data. It can be very time-consuming because then you have to go through it.	*Creating data-sharing processes that demand few human resources*	Efficient data-sharing processes
I21	Then if we get the green light from our management that it is OK to give out this information, that is fine.	*Creating processes to reduce the need for top management involvement*	
I6	Yes, it is production data, and it is like this. How sensitive is it, and who is it that you fear will get hold of this data? But there, it is also like this; when you do not know, it is always safest to say no, instead of actually finding out.	*Assessing what data can be shared in the symbiosis*	
I24	At an early stage, involve the operators to get the operators used to the tool, and the operators can be a little bit involved in the process so that we understand what it means. That it is not just a black box.	*Creating processes to support AI adoption in the symbiosis*	Optimised user delivery
I22	Then towards the external facilities there, it is a little more difficult because it is another company... it takes a little longer. There, it is they who decide how it should look.	*Creating effective user feedback loops for the AI across the symbiosis*	
	Aggregated dimension: AI symbiosis integration		

ID	Representative quote	First-order category	Second-order theme
I10	Yes, it is about creating motivation so everyone feels motivated about what you do. If it is the same at LuleKraft and SSAB, they see the motivation and joy.	*Motivating employees to adopt new technology and methods*	**AI-human interaction**
I6	What I also see with models like this is, in some way, to formalise knowledge. In a model, it has people's decisions or experiences, and you can gain experience from three different shifts instead of only one.	*Promoting knowledge transfer among users to maximise value capture*	
I20	It has to deliver before you release it because otherwise, they roast it. You could have done a good job.	*Building and ensuring trust in the AI*	
I7	If there is not enough gas to fulfil this agreement or the deal where they had promised, then a LuleKraft has to go in and fire with oil. And SSAB has to pay for it.	*Managing interconnected cost and revenue structures*	**Interconnected value capture**
I6	If you can look at trends over a longer period, look forward and backwards, and better understand the business. Not just locally: how do we optimise this process? But instead, how do we get profitability in the entire chain?	*Avoiding suboptimisations to ensure value capture across the symbiosis*	