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Research Paper

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The illustrative case of the HYBRIT fossil-free steel production initiative in the perspective of industrial symbiosis and convergence

This article attempts to bridge the gap between the concepts of Industrial Symbioses (IS) and Industrial Convergence (IC) by arguing that the two concepts can jointly help to understand the role of industrial structures and value chains that embody transformation processes through which technologies evolve in response to transformation pressure. On one hand, IS with a focus on inter-firm collaborations and resource exchange has become a useful framework to understand and capture the mechanisms that foster sustainable industrial and technological development, while on the other hand IC has been used to analyze technological development that blurs traditional borders between firms in terms of innovations and business development. However, although interrelated the two concepts have been discussed separately. This paper is using the HYBRIT initiative as an illustrative case of a climate change mitigation and as such a "flagship" project in Sweden in an effort to replace the traditional blast furnace technology as the core unit processing technology in steelmaking. It is advocated that whilst many aspects of the conceptual models of IS and IC appear to be congruent with the on-going HYBRIT eco-industrial transformation process, the overall impression is that in future eco-industrial transformations, it could be of interest to develop and deploy a more specific transformation model adapted and capturing unique process-industrial conditions for product and process innovation.

1 Introduction

Industrial transformation processes are often characterised by the presence of both opportunities and challenges on actors that are structurally interconnected as argued by Dahmen (1950) more than half a century ago. As industries become increasingly interconnected, the traditional boundaries that delineate sectors are blurring, giving rise to a complex web of relationships that transcend company and industrial borders (Heo and Lee, 2019). Often, existing inter-industrial collaboration serves as a catalyst for synergistic efforts, fostering the exchange of knowledge, expertise, and resources across diverse sectors (Geum et al., 2016). This interconnectedness not only expedites the diffusion of technological advancements but also promotes the emergence of novel solutions to multifaceted common problems (Kim et al., 2015). In the context of climate change mitigation, where the imperative for rapid and profound solutions is paramount, inter-industrial collaboration has received heightened importance (Elia et al., 2020). The interconnected nature of industries from different sectors thus allows for co-creation of innovative technologies and

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new corporate strategies that can address complex and common challenges associated with climate change. In this context, the two notions of Industrial Symbiosis (IS) (2012; Chertow, 2000) and Industrial Convergence (IC) (Bröring, 2010) have been proposed to capture potential implications for environment management and innovations.

This paper discusses IS and IC in the context of the process industries. Whilst both IS and IC can take place on a technology, corporate, and sectoral level (Curran and Leker, 2011), opportunities for IS on all levels may incentivize IC as well, and vice versa. Although different sectors of the process industries (e.g. chemical, steel, pulp & paper) share several characteristics related to their production systems and conditions for product- and process innovation, their production system characteristics significantly differ from assembly-based industries (Lager, 2017). The "family" of process industries is thus similar within itself, but dissimilar to other manufacturing industries (Lager and Chirumalla, 2020). In consequence, management of IS and IC in the process industries must not only be adapted to the idiosyncratic process-industrial environment in search of cross-industrial management and sectoral patterns, but individual sectoral experiences can in an organizational learning perspective be shared within this important cluster of industries. IS and IC are today fairly well-articulated and researched concepts. In the emergence of IS and "uncovering" of kernels for Industrial Symbiosis (Chertow, 2007), a profitable physical exchange of materials, energy, and/or by-products in-between companies from different sectors of the "family" of process industries has historically been a major driver (Chertow, 2000). The cause could most likely be grounded in the idiosyncratic process-industrial production system characteristics and associated inherent and contextual conditions for product- and process innovation. ***More specifically, the aim for this article is to review the knowledge base and understanding of the individual areas of IS and IC, and further explore their potential conceptual interrelationships and discuss related industrial cooperation and business opportunities. Moreover, to further explore how they could open up opportunities for sustainable development and novel eco-industrial transformation processes, particularly in a process-industrial context.*** Nevertheless, there seems , so far and to the authors best knowledge, to be a lack of useful eco-industrial transfer models designed and adapted to the specific process-industrial common conditions.

The process industries, being major contributors to greenhouse gas emissions, are facing transformation pressure to reduce their carbon footprints, which largely stems from their energy intensive production systems. The selected illustrative case, the HYBRIT fossil-free steel production initiative, draws on a transformative initiative in Sweden with the goal of producing steel in use of hydrogen in the involvement of 3 collaborating industrial actors, from three different sectors of the process industries. In use of this illustrative case of which we already initially could see relations to both IS and IC conceptual models, we intend to explore and test if and how different aspects of the IS and IC concepts, harmonize with the goals of environmental sustainability and broader company business goals, in an eco-industrial transformation case. Previous studies have analyzed this transformative initiative in use of a multi-level perspective (Öhman et al., 2022; Karakaya et al., 2018) while in this paper we use the lens of IS and IC. We argue that successful management of Industrial Symbiosis (Lombardi and Laybourn, 2012; Chertow, 2007) and its related transformation model(s) should be adapted to the idiosyncratic process-industrial environment in a search of advantageous cross-industrial management constellations and potential novel sectoral patterns. Furthermore, that emerging eco-industrial transformations within the process-industrial landscape, in an IC perspective (Kohut, 2019; Bröring et al., 2006b), is changing traditional sectoral boundaries, which ought to incentivize the studying of the process industries as one importance cluster of industries for the global economy. Apart from this introduction, this paper consists of six other sections. In the subsequent section, we briefly review the literature on the cluster of process industries and IS and IC conceptual models. Section 3 provides the research design and some methodology considerations while in Section 4 we briefly discuss the peculiarities and analyze some tentative characteristics the two industrial transformation models. In Section 5 we deploy those theoretical findings as a framework in the positioning of the illustrative case on both transformation models. The total results are discussed in Section 6, and finally, in Section 7 we conclude the paper and provide some implications and arenas for future research.

2 A frame of reference

2.1 The singularity of the "family" of Process Industries

For companies in the process industries, sustainability is not only emerging as an operational issue, but as a prime driver

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for eco-design of non-assembled products (Lager, 2024), and eco-innovation in general (Karakaya et al., 2014), and below we present a brief overview of the characteristics of the "family" of process industries. In the review of the process industries, both production system and delivered product characteristics are discussed, recognizing that in this group of industries corporate sustainability is not only related to product recyclability, but often to a large extent associated with sustainable production processes (Chirumalla et al., 2023).

One fundamental difference between companies in the "family" of process industries and those in assembly-based industries is that supplied and delivered products in the process industries are materials and not components (Simms et al., 2021; Frishammar et al., 2013); a fact which affects not only the upstream supply chain of incoming materials but also the downstream supply chain of outgoing products (Lager and Blanco, 2010). Because of the strong interrelationship between raw materials, production processes and finished products, successful product innovation needs to take a concurrent view on all these areas (Storm et al., 2013), which makes the development of non-assembled products, in reality, the development of new or improved process technology; the process encompasses the product (Lager and Liiri, 2023; Hullova et al., 2016).

Moreover, in assembly-based industries a new product is usually manufactured in a new production setup, whereas a new production system or technology in the process industries usually is integrated within an existing plant structure (Samuelsson et al., 2015; Samuelsson and Lager, 2019). If a company relies on captive (company-owned) raw materials, the characteristics of incoming materials will not only predispose the selection of unit processes and production system design (Frishammar et al., 2012; Aylen, 2013) but may also influence finished product properties (Linton and Walsh, 2008). Raw material variability will also sometimes influence the production system's receiving capability (Soman et al., 2004), especially in the food industries where raw materials are perishable (Van Donk and Fransoo, 2006).

An interrelationship between product and process innovation is often required for a successful development of non-assembled products in the process industries (Reichstein and Salter, 2006; Hullova et al., 2019), as well as an intimate collaboration with technology and equipment suppliers (Storm et al., 2013; Lager and Frishammar, 2012). Furthermore, the production yield in the process industries is dependent on both raw material characteristics (Finch and Cox, 1988) and production system capabilities. Meanwhile, products manufactured in the process industries are often next to homogeneous substances, but their inner structural characteristics largely determine their functionalities in B2B customers' production systems (Kuwashima and Fujimoto, 2023; Chronéer, 2005). The product innovation time cycles in many sectors of the process industries are often extended to protect customers from unforeseen difficulties (Pisano, 1997), requiring time-consuming pilot-planting or full-scale production trials (Lager et al., 2015; Frishammar et al., 2014). From conceptualization to industrialization, a number of alternative test environments are deployed (laboratory, pilot plants, demonstration plants), each one mimicking to a varying degree a forthcoming production process for a new or improved product (Lager and Simms, 2020; Lager and Liiri, 2023).

Apart from company main product families, there are usually a number of supplementary products that must be produced as a consequence of raw material quality and the production set-up (Lager et al., 2017; Lager and Samuelsson, 2018). A semi-finished product, which also could be denominated as an "intermediate product" (Taylor et al., 1981b; Taylor et al., 1981a), is a product that is discharged from the total production process and marketed and sold to other customers for further refining into other kinds of finished products. Low volumes of semi-finished products can thus be a missed market opportunity, since high volumes of semi-finished products may create interesting outlets for part of the volumes from the company's production system. On the other hand, a co-product is defined as a product that must be produced in association with the production of another kind of product. Both product types can be marketed and sold, but a low number of co-products (low volumes) often makes overall operations easier (Lager et al., 2017). Nevertheless, production levels and quality of semi-finished products and co-products are important product categories especially in the perspective of possible opportunities for Industrial Symbiosis. Finally, a by-product could be defined as a product or material (or non-product) that is an inevitable side effect of a select production process. ***Low production volumes of by-products is generally a favorable production position since many by-products, so far, often have to be turned into waste. However, by-products may generate substantial revenues after dedicated product innovation and marketing efforts possibly in a collaborative endeavor with a partner in a symbiotic relation.***

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2.2 Industrial Symbiosis (IS)

As one important part of the sustainability concept, industrial ecology (Ehrenfeld, 2004), views industrial systems in concert with its surroundings, and in a system perspective search for an optimization of the total material cycle from virgin materials, finished products and recycled products at a process technology, firm, inter-firm, and regional (global) level (Chertow, 2000). As an important part of industrial ecology, Industrial Symbiosis (IS) was earlier defined by (Chertow, 2007: p.313) in her seminal paper as:

Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving 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.

In a critical examination of IS projects in the USA, (Chertow, 2007) later on demonstrated that "uncovering existing symbioses" has had a higher success rate than purposely designed eco-industrial parks (EIP). In order to distinguish IS from general "resource exchange", the criterion for IS was proposed by Chertow to incorporate a minimum of three different organizational entities and minimum two different resources. It was further acknowledged that IS should provide environmental benefits, cannot occur in an individual company but in single industry dominated clusters, as well as in multi-industrial ones. Chertow (2007) further concludes that among drivers for IS endeavors, the most basic one is a desire of profitable business supplemented with regulatory, environmental and social drivers. There are today an abundant number of definitions of IS, which can be regarded as an essentially contested concept similar to the "circular economy" concept (Korhonen et al., 2018), and in an analysis of the above definition, Lombardi and Layburn (2012) have proposed some major redefinitions:

IS engages diverse organizations in a network to foster eco-innovation and long-term cultural change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs, value added destinations for non-product outputs, and improved business and technical processes.

In that respect, the proposed inclusion of eco-innovation by Lombardi and Laybourn (2012) in their novel definition of IS is sound, and they note that eco-innovation not only is a common output from IS but possibly also an important driver. They further conclude that the use of the term "traditionally separate industries" in a definition could restrict the usability of the IS construct, and that the assessment of IS possibilities should be "process based" and generally on a company or "facility level". The development of biomass production processes and related high value products could serve as an example on such emerging new industry segments and products embedded both in the IS and IC concepts (Nuur et al., 2012). Moreover, Lombardi and Laybourn (2012) recognize that company and industry boundaries tend to change over time, which in this article) has been a one incitement for the inclusion of the IC concept (Curran and Leker, 2011). The illustrative case of the development of fossil-free hydrogen-based steelmaking presented in this article can thus serve as an example on such changing industrial boundaries related primarily to the IC concept. Furthermore, Lombardi and Laybourn (2012) propose an exchange of the term "industry" with "organizations" as a broader construct; a suggestion which in a process-industrial perspective could facilitate the inclusion of, industrial intermediaries, suppliers of technology solutions and process equipment in the use of the IS concept. Nevertheless, it is vital to discriminate between IS and IC on a company level and on a sectoral level.

2.3 Industrial Convergence (IC)

The notion of IC refers to the integration of previously distinct industries characterized by separate technologies and markets and is defined by Bröring et al., (2006b: p. 488) as "the blurring of boundaries between formerly distinct industries due to converging value propositions, technologies and markets. IC was initially predominantly studied in the information and communication technologies (ICT) industries (Hacklin et al., 2009; Gambardella and Torrisi, 1998). One of the first studies related to the process-industrial cluster was sectoral convergence in the pharmaceutical, specialty chemical, and food industries (Bröring and Leker, 2007; Bröring et al., 2006a). For example, the emergence of a new converged sector was recognized as a new inter-industry segment, and the convergence was described as a "process", when supply-side convergence (input side) was distinguished from demand-side convergence (market pull). In a follow-up study of Nutraceuticals and Functional Foods (NFFF)/Cosmeceuticals, Curran and Leker (2011) concluded that when coping with increasingly permeable industry boundaries it is necessary to source the essential

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knowledge and experience from beyond one's own factory gate. Moreover, industries would be labeled as "converging", if they (or parts thereof) begin to merge with each other in a new field (Curran and Leker, 2011), and they recognize four levels of convergence in a sequential "convergence process" as: science convergence, technology convergence, market convergence, and, finally, industry convergence.

In a study of the dynamics of the final phase of an industrial convergence process Sick et al. (2019) conclude that convergence can take place with varying intensity and with varying length of the individual phases and could be technological or market driven. If an industry A starts to converge with industry B, a new inter-industry segment C occurs. If A+B=C is phasing out A and B they denominate this substitutive convergence, whilst if A and B remain (A+B=A+B+C) this is denominated complementary convergence, when the "core business" of the converging companies is not threatened (Sick et al., 2019). Geum et al. (2016) developed a taxonomy for industry convergence, including technology enhancer, policy-driven environmental enhancer, new business-driven product-service integrator, and service-integrated social business generator. In conclusion, when two industries converge, the dominant industry logic is subject to significant changes, and established firms need to position themselves adequately in the market, acquire new required competences and increase their awareness of partners (Kohut, 2019) and competitors from vastly distinct fields (Kohut et al., 2020). Indeed, in their analysis of IC in entire U.S. industries, Kim et al. (2015) show that significant transformation is under way in the economy, but industry convergence is not yet prevalent across entire industries. Because of that "early warning systems" are of interest and depending on the different stages (levels) of the convergence life cycle the measures could be number of scientific publications, number of patent documents, and number of newspaper abstracts over time (Bornkessel et al., 2016a). Further studies related to convergence in the process industries include functional foods (Bornkessel et al., 2016b), biotechnology (Aminullah et al., 2015; Aaldering et al., 2019), tablet Sub-sector Industry (Calvosa, 2021).

3 Research design

This article present the research results from one part of a research project related to the on-going industrial transformation process induced by the HYBRIT (Hydrogen Breakthrough Ironmaking Technology) initiative in Sweden.

3.1 Research approach

The research approach and the research process for the whole study has been of an abductive kind, going to-and-fro between theory and the empirical settings (van Maanen et al., 2007; Dubois and Gadde, 2002). Whilst a deductive approach starts with a select theory and hypothesis in a further deduction of new theory for a particular area (Popper, 1983; Popper, 1959) an inductive research approach (Glaser and Strauss, 1967) commences with the researcher's phenomenological perception of the topical area. On the contrary abduction, as a more recent approach in the philosophy of science, arguably is positioned in-between a deductive and an inductive approach (Alvesson and Sköldberg, 2009). Brodie and Peters (2020) argue that conceptual development lies in the heart of abduction and that both input and output from abduction is a successive refinement of concepts. As a foundation for inquiry, abductive research may begin with testing an existing theory, or in the application of a new conceptual framework (Kovacs and Spens, 2005):

Abduction also works through interpreting or re-contextualization individual phenomena within a contextual framework, and aims to understand something in a new way, from a new conceptual framework.

Abduction does not refute previous theoretical pre-conceptions (Alvesson and Sköldberg, 2009), and in a discussion of the alternatives of a "loose and emergent" or a "tight and pre-structured" framework, Dubois and Gadde (2002) suggest the latter since the "tightness" reflects the degree to which the researcher has articulated his "preconception". Moreover, they recommend that the framework should evolve when empirical observations inspire changes of the view of theory and vice versa.

3.2 Development of an integrated theoretical framework

Existing theory is generally the point of departure in case study research (Yin, 1994), and the further development of a theoretical framework will afterwards serve as a guidance in search of supporting relevant empirical evidence. IC and IS are in this study viewed as two related but different industrial concepts. In this study we have selected to use the term "concept" instead of "construct", as a more value neutral term in reference to Gioia (2013), describing or

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explaining a phenomenon of theoretical interest. As such, and even if the concept of IS now has been used over two decades (Chertow, 2000) it is still in a flux, and there are a number of proponents suggesting major redefinitions, see e.g, Lombardi and Layburn (2012). In today's societal interest in sustainability and on-going eco-industrial transformations, different definitions of the IS concept are often used in scholarly publications, and the conceptual clarity unfortunately thus tends to diminish. The topical area of IC is somewhat younger (Bröring et al., 2006b), and, so far, the number of publicans in this area are substantially less, and possibly because of that, the conceptual clarity is yet quite good. However, both concepts are still open for further discussions, improvements, possible extensions, or simplifications, until they can reach the level of a more strictly defined construct. Both concepts are, from different angles and perspectives, related to collaboration, intertwinement or exchange of resources, and even potential mergers between complementary companies on different organizational levels. However, one common denominator for both concepts is that company, and sometimes sectoral boarders, are crossed in use of different industrial transformation models. As a consequence, company internal perspectives on innovation, production technology, and products (and waste) are viewed in an outlook "outside company factory gates" (Curran and Leker, 2011).

In this study, each concept has been tentatively defined in use of a number of different characteristics, and if congregated, they can be regarded as embryos for "intentional definitions" (Foellesdal et al., 1990). However, the concepts are still in flux because of new research findings, and the individual concepts thus tend to still vary in scientific publications. The coherent state-of-the-art of conceptual definitions in academy (and industry), can be viewed as their convergent validity. In use of the publications in the literature reviews in the previous Section 2, a number of characteristics of the two concepts have tentatively been identified and presented in Table 1; Section 4. However, the congruence and clarity of each characteristic in each of the individual concepts varies considerably. Even if the concept of IC is of a fairly recent origin (not yet many publications), this concept appears to be of a fairly convergent nature; the individual characteristics are thus not too difficult to outline. On the contrary, the somewhat older concept of IS seems still to be much more in transition and there is still no general agreement on its inherent characteristics or definition. Concept validity could be described as how well a concept, and its related characteristics corresponds to the property one wish to measure or study. Convergent validity as a sub-type of concept validity, is thus related to how coherent alternative descriptions (definitions) of the individual characteristics (measurables) of a concept are depicted in literature. On the other hand, discriminant validity as a sub-type of concept validity, is related to how individual characteristics (measurables) differ between different concepts. In view and use of the information from the literature review of IS and IC, and in the perspective of a process-industrial context, a number of characteristics of the two different transformation models were tentatively identified. For each concept, each characteristic was further detailed in reference to a select number of references from the literature reviews. The discriminant validity of the IC and IS concepts were afterwards analyzed by the research team.

3.3 Deployment of an illustrative mini case

How well the individual characteristics of the IC and IS concepts could be applicable on an on-going industrial transformation project, that from an outside perspective seemed to share some aspects of both concepts, was afterwards tested as an "illustrative case" in a second step. This supplementary case study was carried out in order to test how well the two different concepts could fit a real-life industrial project. The holistic nature of case studies allows a multidimensional perspective, considering a variety of variables (more variables than cases) that may influence the phenomenon under investigation. This is especially pertinent in the study of innovation processes, where a multitude of factors, ranging from policy frameworks to market dynamics, can shape technological advancements. There are a number of rationales for the selection of a single-case research design and according to Yin (1994) a single-case design is analogues with an experiment; a situation which representatives from the process industries should be rather familiar with. One rationale for the deployment of a single-case design, is when it represents a critical case. The single-case study can then be deployed in order to confirm, challenge, or extend the theory, and in this perspective the theoretical foundations for both IS and IC were considered sufficiently well-formulated. Yin has stated that overall, the single-case design is justifiable under certain conditions where the case represents a critical test of existing theory (Yin, 1994), and Welsch et al. (2011) also recommend the potential use of case studies to challenge, refine, verify, and test theories.

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In use of the theoretical framework, the positioning of the HYBRIT project was thus reviewed and validated in a separate interactive exercise together with one representative from the HYBRIT board of directors (CTO of the SSAB and the HYBRIT champion). Furthermore, and during follow-up interviews with the other three individual members of the HYBRIT board and the previous CTO of the HYBRIT management team, the information related to the HYBRIT relationships with the different concepts were often discussed. The results were afterwards triangulated with published official documents and research reports from the project and the official websites from LKAB, SSAB, and Vattenfall. Moreover, the results were further analyzed by the research team in view of their in-depth knowledge acquired in this total study of the HYBRIT initiative. Even if the empirical results must be considered as tentative, the illustrative case can serve as a preliminary outlook on an on-going eco-industrial transformation process carried out when management lacked previous perspectives from any theoretical model and lacking knowledge of either of the IS and IC conceptual models.

4 A discriminant analysis of the IC and IS concepts

4.1 An integrated analysis of the two concepts

In Table 1, a number of important aspects on both concepts have thus initially been selected. In use of the information in Section 2.2 and 2.3, a number of characteristics of IC and IS have afterward been identified, in reliance of important references. Focusing on the discriminant validity of the two concepts, the research team afterwards tentatively positioned the characteristic of each model in the perspective of how strongly the individual characteristics generally are articulated in the overall definitions and descriptions of each conceptual model in publications. A three-point ordinal scale was selected as: Red = Strongly articulated, Yellow = Articulated to some extent, Green = Usually not articulated at all. The results are presented in a "heat map" for the facilitation of a further analysis of the discriminant validity of the individual concepts.

4.2 A preliminary synthesis of the findings from the discriminant analysis

With regards to the aspect of "eco-efficiency and sustainability targets", this is usually strongly articulated in most IS studies, and even if this generally not has been the driver so far for IC, it can certainly be so in the future. The second aspect of "openness for new collaborative partners after initiation of the collaboration", is also strongly articulated and sought for in IS, whilst in IC it is neither common nor advisable, but could yet be a possibility. In the perspective of "the physical location (proximity) of collaborating partners", it is articulated sometimes in IS, but is not a necessity with regards to the conceptual model of IC. "The diversity of collaborating partners" aspect is articulated to some extent in both concepts, and possibly even stronger in IC. There is, however, a rather big difference between the two concepts with regards to "the organizational structure between collaborative partners", and for the IS conceptual model a network structure is a necessity, whilst the organizational mode of operation must be contingent on project characteristics in IC. The characteristic "corporate product, process, or systemic innovation activities" differs strongly in-between the two concepts, and whilst this is the predominant driver for IC, it is not so in IS, even if new conceptual re-definitions this is emerging as a more significant aspect. In the perspective of "corporate profitability and business opportunities", this is a common ground for both concepts, even if it naturally is more strongly articulated in IC. The last but not least characteristic "corporate organizational configurations and corporate boundaries", and a to some extent often a final outcome from IC, this is not at all a desired outcome in IS, but certainly one for IC. In section 6.1 these findings will be further discussed.

5. The illustrative case of HYBRIT fossil-free steel production initiative

5.1 Introducing HYBRIT initiative

The HYBRIT initiative is one out of a large number of initiatives aiming at the development of future fossil-free steel making process routes. This initiative brings together 3 large and historically important industrial sectors in Sweden: LKAB, a state-owned mining company established in 1890 in the rich iron fields of northern Sweden which currently is producing a major part of the EU iron ore raw material. SSAB, established 1978, is a global steel producing

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Table 1 A tentative analysis of eight characteristics of the IC and IS conceptual models, in use of a simplified "heat map" (Red = Strongly articulated; Yellow = Articulated to some extent; Green = Usually not articulated at all).

Conceptual models Model characteristics	Industrial Convergence (IC)	Industrial Symbiosis (IS)
Eco-efficiency and sustainability targets	Sustainability and eco-innovation are not necessarily drivers or targeted output. (Bröring et al., 2006b), (Aminullah et al., 2015); (Geum et al., 2016)	Strong focus on sustainability and as a tool for innovative green growth. Exchange of by-products rather common but not generally nowadays a necessity. (Chertow, 2007; Chertow, 2000)
Openness for new collaborative partners after initiation of the collaboration	Usually a "closed" system with a few numbers of select complementary collaborating partners. (Sick et al., 2019); (Bröring et al., 2006b)	Usually very "open" systems and with a desired inclusion of a growing number of collaboration partners. (Ashton, 2008); (Lombardi and Laybourn, 2012; Chertow, 2007)
The physical location (proximity) of collaboratinga partners	The physical location of collaborative partners is not usually of a major importance, but a proximity could diminish the mental distance among partners. (Bröring et al., 2006b)	Traditionally (but not necessary today) a strong focus on geographic proximity, especially if material, transport costs or energy are important aspects for the industrial network (Chertow, 2007); (Lombardi and Laybourn, 2012)
The diversity of collaborating partners	Usually partners from different industrial sectors and sometimes from an already existing supply/value chain. (Curran and Leker, 2011)	Traditionally partners from separate industrial sectors but a gradual transition into an acceptance of similar partners is today also common. (Chertow, 2000), (Chertow, 2007);(Lombardi and Laybourn, 2012);(Paquin et al., 2014);
The organizational structure between collaborative partners	Generally, a company-to-company emerging collaboration developing into a more strategic alliance among partners with complementary capabilities. (Bröring et al., 2006b); (Aaldering et al., 2019)	Generally, an emerging network structure with a large number of independent collaborative partners. (Chertow and Ehrenfeld, 2012); (Walls and Paquin, 2015);(Korhonen et al., 2004); (Posch et al., 2011)
Corporate product, process, or systemic innovation activities	Collaborative product and/or process innovation (sometimes radical) is generally the initial driver for collaboration. (Hacklin et al., 2009); (Bröring et al., 2006b)	Traditionally, innovation was not necessarily a prerequisite for establishing a collaboration, but incremental innovation is often a necessity. (Boons et al., 2013); (Lombardi and Laybourn, 2012); (von Malmborg, 2007)
Corporate profitability and business opportunities	A profitable business/market outcome is always the overall target (with equally distributed financial gains). (Bornkessel et al., 2016a)	Traditionally a "competitive advantage" (profitability) has been central (less costs for waste disposal is certainly also an attractive target). (Boons et al., 2013); (Paquin et al., 2014; Paquin et al., 2015); (Chertow and Lombardi, 2005)
Corporate organizational configurations and corporate boundaries	The final successful outcome is usually new industrial boundaries. (Gambardella and Torrisi, 1998); (Sick et al., 2019); (Bornkessel et al., 2016b)	New corporate structures or boarders are usually a rare outcome. (Boons, 2008); (Walls and Paquin, 2015); (Lombardi and Laybourn, 2012)

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company in Sweden, while Vattenfall is a state-owned utility company producing electricity, partly from hydropower in Sweden. This initiative is thus a collaboration between three Swedish companies from three different sectors of the process industries and is formally set-up as a Joint Venture. HYBRIT stands for "Hydrogen Breakthrough Ironmaking Technology" and thus includes three actors and incorporate a diversity of core-businesses, production technologies, and products. The initial role of the LKAB group was as a supplier of the primary raw material (direct reduction pellets), SSAB a steel processing company, and Vattenfall a supplier of "green" electricity. The HYBRITE initiative is a still on-going long-term industrial transformation process presently formally governed by a Board of Directors including one representative from each of the three different actors. Nevertheless, many operational development activities have so far been predominately carried out in use of the combined resources from the different mother companies, whilst final industrialization activities to a large extent will be carried out within each of the mother company operational organizations. In consequence, there are a multiple of organizational boundaries within the HYBRIT initiative, including the organizational interfaces between the HYBRIT initiative and each mother company, and the boundaries in-between each individual mother company organization.

5.2 Positioning the HYBRIT initiative on the IS and IC conceptual models, in use of the theoretical framework developed in Section 4

In use of the previously developed theoretical framework in Table 1, the HYBRIT initiative has been positioned on the IC and IS conceptual models in Table 2. The individual characteristics that are valid for the HYBRIT initiative have been marked with bold text in both conceptual models.

In view of the results in Table 2, only the two characteristics "eco-efficiency and sustainability targets" and "corporate profitability and business opportunities" in the IS conceptual model are coherent with the HYBRIT initiative. Nevertheless, the HYBRITE initiative follow the recommended 3 - 2 Chertow (2007) recommendations for at least three entities and two resources, since it includes three actors from different industrial sectors and two materials (electricity and pellets). In reference to Wittgenstein's concept of "family resemblance" (Wittgenstein, 1953), a concept or a construct must not necessarily share all characterizing attributes to be considered as a member of a "family", since few family members generally do. However, the HYBRIT initiative share a large number of IC characteristics, and position very well on the IC conceptual model with six out of eight characteristics and could certainly be regarded as an IC of a kind.

On the other hand, the outcome from the HYBRITE initiative is not of a traditional IC kind. In view of the present LKAB and SSAB intra-organizational supply-chains, one could characterize both the pellet product and the upcoming sponge iron product as semi-finished or intermediate products; a rather common situation in long process-industrial supply chains (Lager and Blanco, 2010). In consequence, and in view of the different outcomes from the IC conceptual model in Section 2.3, **the HYBRIT case is neither a "substitutive" or "complementary" convergence, but an industrial transformation that could be denominated as a "configurative" convergence, when an industrial boarder is relocated in a novel inter-organizational supply chain.**

Even if only two of the IS characteristics relate to the HYBRIT initiative, the authors would not hesitate to include the HYBRITE initiative as an IS in accordance with the Lombardi and Laybourn (2012) re-definition. Moreover, since those two characteristics often today are considered as two of the most essential attributes in the IS concept. This is also in accordance with the Kalundborg Industrial Symbiosis Institute definition of IS as *a collaboration between different industries for mutual economic and environmental benefit* (Posch et al., 2011: p.424).

6 Discussion

6.1 The discriminant analysis of the two conceptual models

In conclusion, and in view of all characteristics, the two concepts IC and IS appears to be rather different since a red color in one concept often has a green or yellow color in the other concept. The individual colorings also distinguish the use of IC as a more "market driven" conceptual model, whilst the IS concept more "sustainability driven". One can further envision that traditional technology and market drivers for IC, in the future will be complemented, or possibly even partly replaced, by emerging environmental drivers for convergence. This could emphasize the necessity of knowledge sharing on a process (technology) level, a facility level, and firm level, and even on an overall sectoral level.

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Table 2 A tentative positioning of the HYBRIT initiative on the IC and IS conceptual models, in use of the theoretical framework and heat map presented in Table 1. The individual characteristics that are valid for the HYBRIT initiative have been marked with bold text in both conceptual models.

Conceptual models Model characteristics	Industrial Convergence (IC)	Industrial Symbiosis (IS)
Eco-efficiency and sustainability targets	Sustainability and eco-innovation are not necessarily drivers or targeted output. (Bröring et al., 2006b), (Aminullah et al., 2015); (Geum et al., 2016)	**Strong focus on sustainability and as a tool for innovative green growth. Exchange of by-products rather common but not generally nowadays a necessity. (Chertow, 2007; Chertow, 2000)**
Openness for new collaborative partners after initiation of the collaboration	**Usually a "closed" system with a few numbers of select complementary collaborating partners. (Sick et al., 2019); (Bröring et al., 2006b)**	Usually very "open" systems and with a desired inclusion of a growing number of collaboration partners. (Ashton, 2008); (Lombardi and Laybourn, 2012; Chertow, 2007)
The physical location (proximity) of collaborating partners	The physical location of collaborative partners is not usually of a major importance, but a proximity could diminish the mental distance among partners. (Bröring et al., 2006b)	Traditionally (but not necessary today) a strong focus on geographic proximity, especially if material, transport costs or energy are important aspects for the industrial network (Chertow, 2007); (Lombardi and Laybourn, 2012)
The diversity of collaborating partners	**Usually partners from different industrial sectors and sometimes from an already existing supply/value chain. (Curran and Leker, 2011)**	Traditionally partners from separate industrial sectors but a gradual transition into an acceptance of similar partners is today also common. (Chertow, 2000), (Chertow, 2007);(Lombardi and Laybourn, 2012);(Paquin et al., 2014);
The organizational structure between collaborative partners	**Generally, a company-to-company emerging collaboration developing into a more strategic alliance among partners with complementary capabilities. (Bröring et al., 2006b); (Aaldering et al., 2019)**	Generally, an emerging network structure with a large number of independent collaborative partners. (Chertow and Ehrenfeld, 2012); (Walls and Paquin, 2015);(Korhonen et al., 2004); (Posch et al., 2011)
Corporate product, process, or systemic innovation activities	**Collaborative product and/or process innovation (sometimes radical) is generally the initial driver for collaboration. (Hacklin et al., 2009); (Bröring et al., 2006b)**	Traditionally, innovation was not necessarily a prerequisite for establishing a collaboration, but incremental innovation is often a necessity. (Boons et al., 2013); (Lombardi and Laybourn, 2012); (von Malmborg, 2007)
Corporate profitability and business opportunities	**A profitable business/market outcome is always the overall target (with equally distributed financial gains). (Bornkessel et al., 2016a)**	**Traditionally a "competitive advantage" (profitability) has been central (less costs for waste disposal is certainly also an attractive target). (Boons et al., 2013); (Paquin et al., 2014; Paquin et al., 2015); (Chertow and Lombardi, 2005)**
Corporate organizational configurations and corporate boundaries	**The final successful outcome is usually new industrial boundaries. (Gambardella and Torrisi, 1998); (Sick et al., 2019); (Bornkessel et al., 2016b)**	New corporate structures or boarders are usually a rare outcome. (Boons, 2008); (Walls and Paquin, 2015); (Lombardi and Laybourn, 2012)

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6.2 Positioning the HYBRIT case in the perspective of the two conceptual models

The creation of the HYBRIT initiative was in reliance of a previous close customer supplier business relationship between LKAB and SSAB, and their close geographic proximity. The illustrative case thus support the view that Industrial Symbiosis often is facilitated by such contextual situations (Chertow, 2007). In use of the IC lens, the initial HYBRIT initiative could certainly initially be regarded as a "blurring" of industrial boarders (Bröring et al., 2006a). **Nonetheless, the final outcome of the HYBRIT initiative will certainly not be a "blurred" industrial boarder but a new well-defined corporate interface, within a novel fossil-free industrial supply/value chain from mine to metal.** In such a perspective, the IC definition is thus more of a characterization of the "industrial convergence process", than the characterization of its final outcome. In view of the organizational, and transformational operational procedures related to the HYBRIT case, the Joint Venture organizational solution is experienced to have fostered a fast development route which most likely could not have been possible with an "open" organizational network structure commonly deployed in IS Science Parks. On the other hand, such a "closed" Joint Venture could be dysfunctional in search of a more "open innovation" culture in future eco-industrial transformations.

6.3 A discussion of the industrial usability of the IS and IC conceptual models, in the perspective of future eco-industrial transformations in the process industries.

Whilst many aspects of the conceptual models IS and IC appear to be congruent with the on-going HYBRIT eco-industrial transformation process, the overall impression is that in forthcoming future eco-industrial transformations in a process-industrial context, it could possibly be of interest to develop and deploy a more specific transformation model. Because of that, the research team has dusted off and reviewed a rather early, but less utilized and configurated transformation model named the Development Block model (DB).

The Development Block (DB) concept was early introduced by Eric Dahmén (1950), who went beyond stylized facts and analyzed the mechanisms of industrial transformations. According to Dahmén, transformation processes necessities the evolution of both positive (opportunities) and negative (challenges) transformation pressures on stakeholders to find solutions (Dahmén, 1998; Dahmén, 1950). The positive transformation pressures are mitigated by the evolution of DBs which encompass interconnected sectors that play a pivotal role in industrial transformation and innovation processes. Thus, the synergy between sectors within DBs where advancements in one sector catalyze growth in another, creates a self-reinforcing cycle of a transformation process. In the context of climate change mitigation, the DB concept could be of interest to further explore and develop as recently discussed by (Chizaryfard et al., 2020). DBs are clusters of industries and sectors that exhibit characteristics of vertical and horizontal relationships that spur technological innovation and fostering development. These sectors are not isolated; they are interlinked, with advancements in one sector often benefiting others, creating a dynamic network of economic progress. The concept of Development Blocks could tentatively be defined as: *A Development Block (DB) is a cluster of industries (sectors) that are interlinked in vertical (or horizontal) synergetic relationship, when an advancement in one industry often benefit others, spurring technological development and innovation.* We believe that it could also be of interest to develop and discuss this conceptual model not only on sectoral, but also on a corporate level.

6.4 Theoretical contribution and aspects of generalization

Purposeful sampling (Patton, 1990; Palinkas et al., 2015) is commonly deployed if an extreme or unique case is selected (Ridder, 2017), and if rarely observably phenomena are investigated, and in reference to Corley and Goya (2011: p. 12) "theory is a statement of concepts and their interrelationships that shows how and/or why a phenomenon occurs". The main theoretical contribution from this study is the discriminant analysis of the related conceptual models and their potential use in eco-industrial transformation in a real-life process-industrial context. In a single case study it is not possible to make statistical generalizations of the research findings, and such a research design is furthermore less adaptable to theoretical generalizations than multiple-case research design (Yin, 1994). The research results can thus not be the foundation for discussing the transferability of the research findings but must provide sufficient contextual information to the readership to determine if this is reasonable. Such a contextual information is what Geertz (1973) name a "thick description". The presentation of the illustrative case is not as such an in-depth case study but

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provide sufficient contextual information for the reader to judge the external relevance of the case (Siggelkow, 2007).

7. Conclusions, implications, and suggestions for future research

The industrial landscape across the globe is undergoing a paradigm shift driven by the necessity to transform towards sustainable modes of production and consumption. These transformation processes often take place at the intersection of technological evolution and across industrial sectors and it is imperative to dissect and understand the intricate dynamics that characterize such transformative processes and their further advancements. The amalgamation of diverse technologies across industrial sectors are by and large underpinned by the presence of symbiotic relationships that influence industrial and technological trajectories. The convergence of once disparate or related sectors not only accelerates technological advancements but also open-up unprecedented possibilities for cross industry collaborations, novel business models, and reconfigured inter-and intra-industrial value chains. The establishment of symbiotic relationships within industrial ecosystems may be argued to amplify the resilience and adaptability of the overall system as this interconnectedness cultivates an environment conducive to sustainable growth, where the success of one entity contributes synergistically to the progress of others. It is from this context that this paper has put a fossil-free initiative aimed at producing steel in the context of the two conceptual models of IS and IC.

It is concluded that the two conceptual models are different, with regards to driving forces, partner structures, and organizational configurations. Nevertheless, both models related well, in an overall perspective, to the select real-life eco-industrial transformation case, pin-pointing a potential need to utilize both models into the development of a specific conceptual model adapted to the process-industrial contextual situation and to the intrinsic nature of product- and process innovation characteristics (Lager, 2024). In the illustrative case the three companies did not rely on any theoretical IC or IS frameworks or models, but jointly set up their organizational framework utilizing their inherent long-term experience of the development of primarily new process technology. Even so, one could suspect that the availability of a firmer foundation and theoretical framework, possibly could have been beneficiary in guidance of their still on-going innovation journey.

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