Kalundborg Industrial Symbiosis: Circular Strategy in the Light of Mutualism

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The Kalundborg industrial symbiosis serves as an excellent example of inter-organizational collaboration, showcasing the principles of industrial ecology and the circular economy. Since the 1960s, local companies have developed a network of material and energy exchanges, turning waste and by-products into reusable resources in a mutually beneficial system. This model not only reduces waste and greenhouse gas emissions but also results in substantial savings in energy and raw material costs. Key participants in this symbiosis include companies such as Novo Nordisk, Novozymes, and Statoil, alongside the Asnæs power plant. These organizations exchange flows of heat, steam, gypsum, and biomass, creating an integrated network where one company's waste becomes a resource for another. The industrial symbiosis has significantly lowered CO_2 emissions and saved millions of cubic meters of water, as well as tons of residual materials annually. This research note highlights that trust and inter-organizational collaboration are essential to the success of this circular economy model, while recognizing that its application in other regions will require adjustments tailored to local conditions.

Keywords: circular economy, industrial ecology, industrial symbiosis, inter-organizational collaboration, Kalundborg (Denmark), mutualism, supply chain

INTRODUCTION

Widely publicized and analyzed in numerous industrial ecology studies due to its global reputation, the Kalundborg industrial symbiosis is in the town of Kalundborg, Denmark, approximately 120 kilometers west of Copenhagen. The town has a population of around 20,000 and is one of the few year-round ports at this latitude. The concept behind industrial symbiosis is relatively simple: it allows companies to synergistically utilize each other's residues, waste, and by-products, sharing and reusing resources to reduce procurement costs and minimize waste emissions (Bourg & Erkman, 2017). This system can be described as a closed-loop or circular model, aiming for the efficient and effective use of shared resources. In practice, the symbiosis developed "organically" (Jacobsen & Anderberg, 2005), starting in the early 1960s through a series of mutually beneficial economic and environmental agreements between neighboring industries. The first exchange occurred in 1961, when the Asnæs coal-fired power plant, now converted to biomass, began supplying surplus heat to the local municipality for residential heating. This initiative represents early awareness of environmental concerns, predating the widespread integration of sustainability into corporate practices (Thomas *et al.*, 2022).

Over time, these agreements evolved into a structured network of material and energy exchanges, which was officially formalized in 1972 as an industrial symbiosis. This is understood as an ecosystem where companies and organizations within a region collaborate to utilize each other's by-products, waste, energy, and resources. Since then, the Kalundborg industrial symbiosis has been an undeniable success, establishing itself as one of the most successful examples globally and highlighting the potential of collaborative resource management in a specific area. By 2024, the network includes not only the municipality of Kalundborg but also 20 public organizations and private companies. Among the most prominent participants are Novo Nordisk (a pharmaceutical company specializing in diabetes treatments), Novozymes (a biotechnology company focused on enzyme and microorganism production), Statoil (an oil refinery), Asnæs Power Station, Gyproc (a plasterboard manufacturer), RGS 90 (a waste treatment company), and Bioteknisk Jordrens (a company specializing in the biological treatment of contaminated soil).

The Kalundborg industrial symbiosis can be regarded as a model for the collaborative management of material resources among multiple supply chain members. However, the existing academic literature offers relatively few studies on how geographical and organizational specificities have contributed to its success. My investigation aims to address part of this gap by exploring the concept of mutualism, derived from the life sciences (Davison, 2020). This approach enhances our understanding of the dynamics of inter-organizational cooperation within the Kalundborg industrial symbiosis, while also highlighting potential co-dependencies between stakeholders and the logistical challenges that this unique industrial ecology model must overcome. Methodologically, the study relies on secondary data sources, including published books, journals, and websites, with careful selection of materials identified by other researchers as credible, particularly those frequently cited in related studies on industrial symbiosis.

This exploratory research note analyzes the Kalundborg industrial symbiosis in three stages, focusing on the mutualistic nature of exchange relationships formalized within an industrial park. The first section provides an overview of the concept of industrial symbiosis as an extension of industrial ecology, tracing its historical development and spontaneous implementation in Kalundborg from the 1960s, and its formalization in 1972. The second section examines the economic and environmental benefits of this innovative model, highlighting key material and energy exchanges that have reduced greenhouse gas emissions, conserved local resources, and generated significant cost savings. At the same time, it addresses the well-known limitations of mutualism. Finally, the third section discusses the challenges of expanding the industrial symbiosis model more broadly, emphasizing the critical role of inter-organizational collaboration between private and public stakeholders.

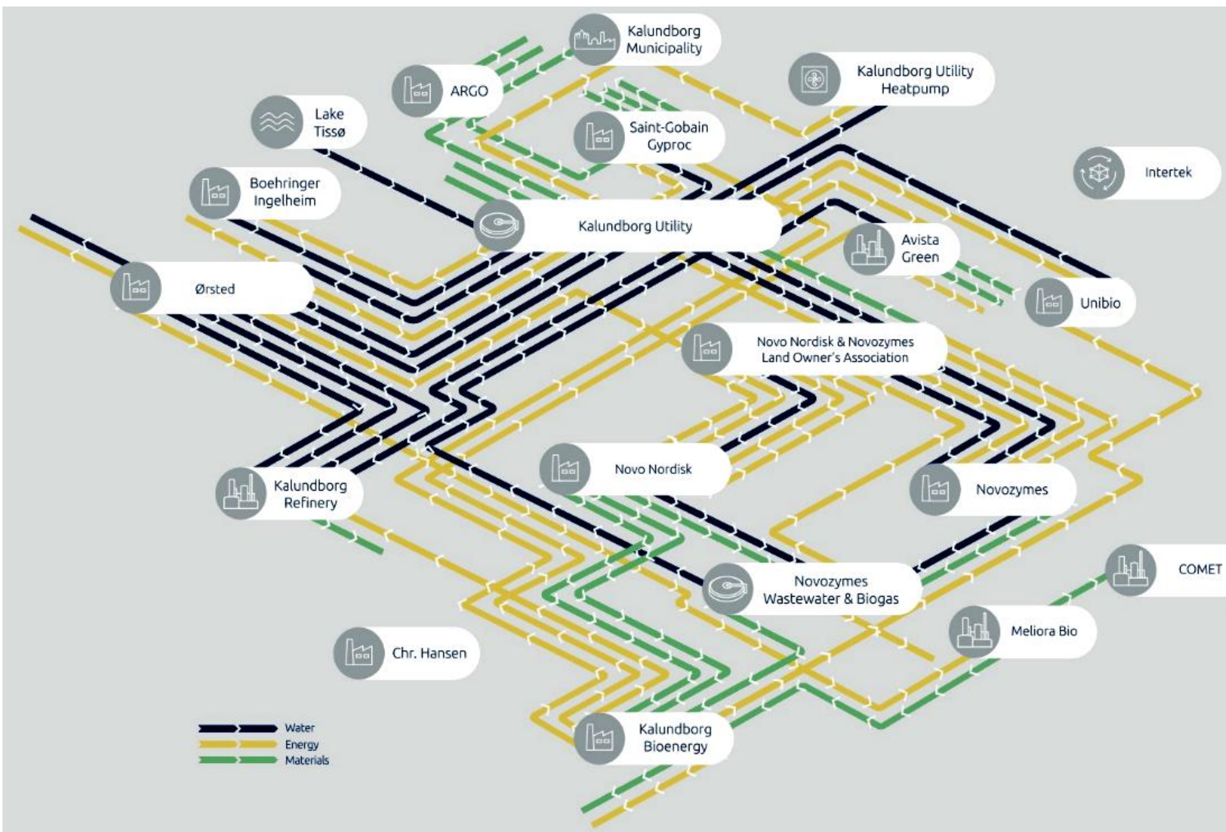
Economic and Environmental Issues

The Kalundborg industrial symbiosis is built upon interconnections between value chains, forming what can be described as a "value chain network" (for a literature review, see Neves *et al.* [2020]). Aligned with the principles of the circular economy—like energy clusters (Pego, 2021)—this network operates on a key industrial principle: the by-products and waste streams from industry X can serve as inputs for industry Y, thereby reducing the environmental impact on a given region. The primary exchanges within the Kalundborg industrial symbiosis, which operates on a mutualistic basis, involve both energy and materials:

- In terms of *energy exchanges*, the Asnæs power plant supplies steam to the Statoil refinery, Novo Nordisk, and the municipality of Kalundborg. This steam is used in various processes, including heating, cooling, and other industrial operations. Additionally, surplus heat from the power plant is distributed to Kalundborg's district heating system, serving local homes and businesses.
- In terms of *material exchanges*, gypsum, a by-product of sulfur removal at the Statoil refinery, is provided to Gyproc to produce plasterboard. Novo Nordisk supplies bio sludge, a by-product of its pharmaceutical manufacturing, to local farms, where it is used as a nutrient-rich fertilizer. Lastly, fly ash and clinker from the Asnæs power plant are utilized in road construction and cement production, reducing the need for virgin raw materials.

The two types of exchanges demonstrate how Kalundborg's industries have developed a system that minimizes waste and conserves resources (see Figure 1). This approach yields substantial environmental benefits for both the participating companies and the wider community (Gulipac, 2016). Firstly, by transforming waste into resources, the symbiosis has significantly reduced the amount of waste that would otherwise be sent to landfills or require costly recycling processes. Secondly, the efficient use of energy and materials within the network has led to a reduction in greenhouse gas emissions: the reuse of surplus heat and steam reduces the demand for additional energy production, which has, in turn, cut CO_2 emissions—estimated to have decreased by 80% since 2015. Thirdly, the reuse of water within the value chain network helps conserve local resources, which is especially critical in regions where water scarcity poses environmental challenges, and excessive freshwater extraction can cause degradation.

FIGURE 1
THE KALUNDBORG INDUSTRIAL SYMBIOSIS



Source: Kalundborg Symbiosis (2024).

The economic benefits of the Kalundborg industrial symbiosis are equally significant, impacting both upstream and downstream operational performance (Jacobsen, 2006). Companies involved in the symbiosis have realized substantial cost savings through reduced needs for raw materials, energy, and waste disposal. For example, utilizing waste heat and steam has lowered energy costs for several companies, enhancing their competitiveness. A lifecycle analysis conducted for Kalundborg Symbiosis in 2020 revealed that the industrial symbiosis generates annual savings of over three million cubic meters of groundwater and 62,000 tons of recycled residual materials. Additionally, by converting waste into marketable products, such as gypsum for plasterboard, companies have created new revenue streams. These economic benefits are complemented by social advantages: the symbiosis supports local employment by sustaining a vibrant industrial base in Kalundborg and creates jobs requiring skilled labor to operate and maintain the complex exchange network.

Strengths and Weaknesses of Mutualism

As the planet confronts the challenges of climate change, resource depletion, and environmental degradation, the principles underlying the Kalundborg industrial symbiosis are more pertinent than ever. Transitioning to a circular economy—where waste is minimized, and resources are reused—requires innovative models that can be scaled up. In this context, the advent of digital technologies presents new opportunities to optimize resource flows, manage exchanges, and enhance efficiency within the value chain networks characteristic of industrial symbiosis. However, the effectiveness of these technologies will be limited without two critical elements: political support to promote cross-utilization of residues, waste, and by-products, and a "short mental distance" between decision-makers involved in the network (Branson, 2016). Understanding the conditions that enabled the Kalundborg industrial symbiosis to flourish on a mutualistic basis will be crucial for the global adoption and success of this industrial ecology model.

The Kalundborg industrial symbiosis is frequently cited as a quintessential example of success in the field of industrial ecology. Several positive aspects justify this recognition: the valorization of by-products and waste, optimized use of natural resources, significant reduction in CO_2 emissions, and its global exemplarity. More broadly, Kalundborg stands out as a success story because it integrates economic performance, energy efficiency, and positive environmental impact, serving as an inspiring model for other regions. Notable examples include the Kawasaki industrial symbiosis in Japan, the Guayama industrial symbiosis in Puerto Rico, and the Kalundborg Ecopark industrial symbiosis in Malaysia, which was directly inspired by the Danish case. The diversity of these examples suggests that the approach may be universally applicable, though this hypothesis remains subject to further discussion, as noted by Boons & Janssen (2005).

Despite its economic and environmental successes, the Kalundborg industrial symbiosis raises several questions about its generalizability as a disruptive industrial ecology model. A major concern is the high level of dependency it creates, as the symbiosis relies heavily on the continuous operation of key participants, particularly the Asnæs power plant and the Statoil refinery (Valero *et al.*, 2012). Any significant changes in their operational cycles could potentially disrupt the entire network. While the current system may be relatively stable, shifts in market conditions, environmental regulations, or technologies could necessitate substantial adaptations—an essential condition for maintaining the symbiosis's sustainability. Moreover, although the Kalundborg model has been successful locally, replicating it in other regions or on a larger scale may be challenging. Variations in geography, industrial composition, and regulatory environments can significantly impact the feasibility of applying the same model elsewhere.

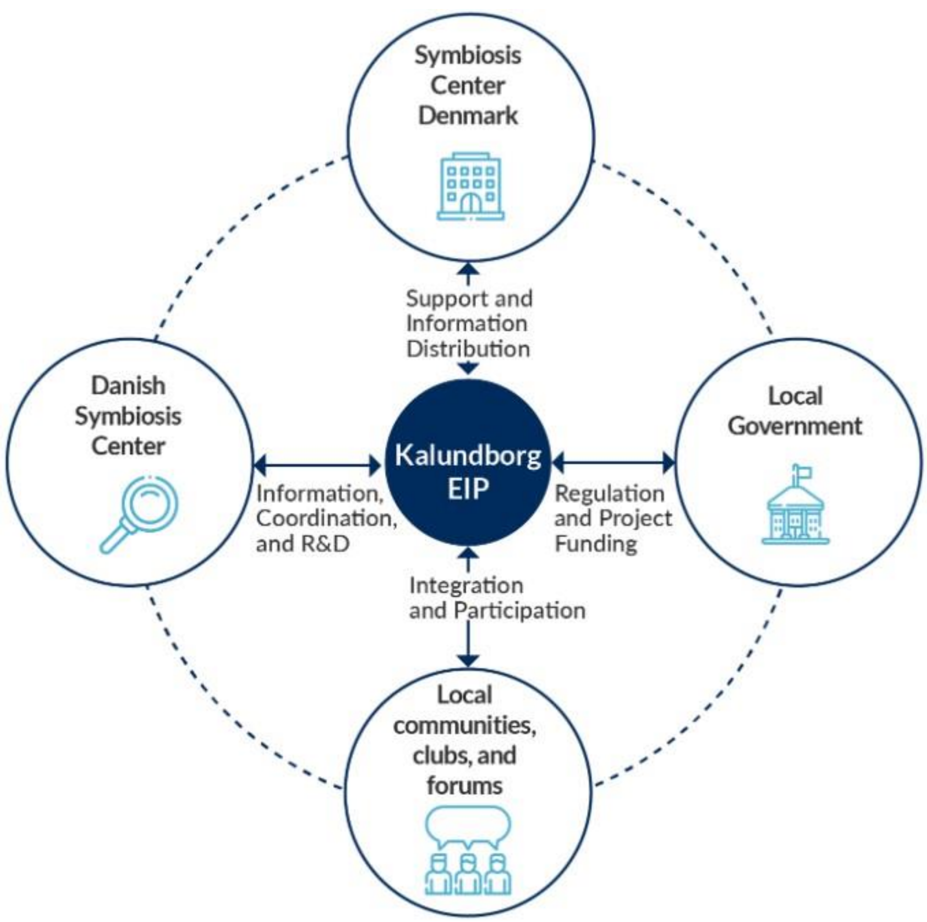
It is also crucial to highlight that the mutualism underpinning the Kalundborg industrial symbiosis faces threats from four internal factors (Gibbs & Deutz, 2007; Bronstein, 2015). Firstly, the high degree of interdependence among stakeholders creates significant vulnerability: if one participant encounters difficulties, the entire value chain network could be disrupted. Secondly, substantial initial investments—both in time and financial resources—are required, leading to high switching costs due to the fixed locations of production units, which hinder rapid redeployment. Thirdly, variations in product lifecycles, production capacities, and strategic objectives among the companies involved can create imbalances that may advantage or disadvantage certain stakeholders. Fourthly, while mutualism aims to optimize resource use, it can introduce excessive complexity in managing the logistical flows of materials, energy, and waste, potentially reducing the overall efficiency of the value chain network.

Collaborative Governance Mechanisms

The Kalundborg industrial symbiosis offers a crucial lesson for developing circular economy models: collaboration between industries, businesses, and political authorities is essential. Such collaboration can foster innovative solutions that benefit all stakeholders and advance broader sustainability goals. However, it is important to consider the specific context, as the success of industrial symbiosis depends heavily on local conditions, such as the types of industries present, the availability of resources, and the regulatory environment (Oughton *et al.*, 2023). In other words, attempts to replicate the Kalundborg model are likely to fail without careful contextualization and a progressive approach to building the value chain network. Allowing time for inter-organizational trust to develop gradually will help prevent opportunistic behavior, such as withholding information crucial for the functioning of the industrial symbiosis, as theorized by Williamson (1985).

This confidence ultimately translates into a collective commitment to the project, fostering a strong sense of collaborative governance among local companies, the municipality, and residents (see Figure 2, from Faria *et al.* [2021]). In the case of the Kalundborg industrial symbiosis, there is a clear convergence between industrial development and community well-being. According to Valentine (2016), true collaboration has been achieved due to an environmental mindset, opportunities for all stakeholders, mutually beneficial initiatives, and performance needs that drive proactive problem-solving. For example, biotech companies like Novozymes and Novo Nordisk contribute their residual biomass to Kalundborg Bioenergy, a biogas plant operated by Bigadan. This biogas is refined into natural gas by removing carbon dioxide and hydrogen sulfide, which greatly benefits the environment and residents. The resulting biomethane is distributed to local companies such as Gyproc, Unibio, and the Statoil refinery, as well as to end consumers via the national gas grid, providing economic benefits. Despite the absence of a central authority to steer the value chain network, the Kalundborg industrial symbiosis effectively manages decision-making without significant difficulties.

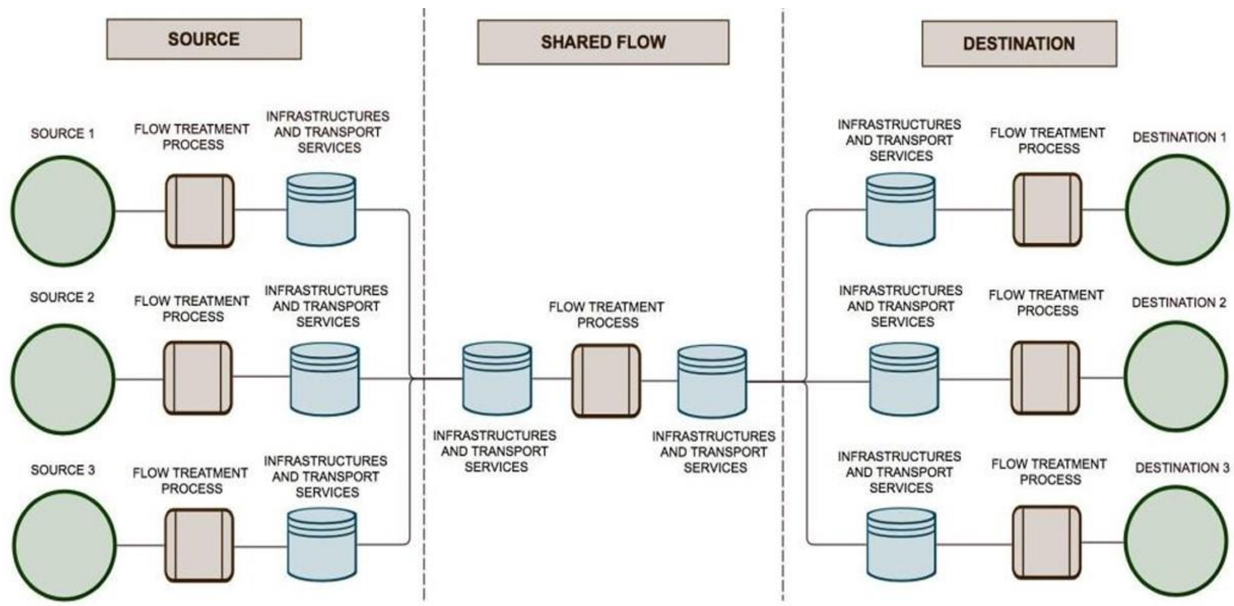
FIGURE 2
THE KALUNDBORG EIP GOVERNANCE



Source: Faria et al. (2021).

It would be misleading to assume that the companies involved in industrial symbiosis operate outside the bounds of economic rationality, particularly with a focus on supply chain performance (Ruiz-Puente & Bayona, 2017; Turken & Geda, 2020). Figure 3 illustrates the supply chain within the context of industrial symbiosis. Unlike a traditional linear supply chain (extraction, production, distribution, consumption, waste), industrial symbiosis emphasizes recycling, reuse, and valorization of by-products and waste. In terms of governance, this approach prioritizes collaboration to reduce both raw material costs and environmental impacts. Managing logistical operations in this framework entails precise synchronization of flows and stocks, with careful attention to the quality, quantity, and timing of material transfers. Industrial symbiosis thus presents a twofold challenge: first, by-products or waste used as raw materials can vary in quantity and quality, complicating logistical planning and necessitating ongoing adjustments to meet requirements; second, ensuring the traceability of material and energy flows is crucial for maintaining efficiency and regulatory compliance. This requires advanced information systems capable of tracking and analyzing data from diverse sources in real time.

FIGURE 3
A SUPPLY CHAIN PERSPECTIVE OF INDUSTRIAL SYMBIOSIS



Source: Ruiz-Puente & Bayona (2017).

All industrial symbioses face similar supply chain performance constraints, which ultimately affect the profitability of the value chain network and its governance. For example, Gyproc established its operations in Kalundborg to take advantage of the refinery's low-cost waste gases and subsequently negotiated a supply of gypsum from the Asnæs power plant, which produces it by extracting sulfur dioxide from flue gases. This arrangement allowed Gyproc to avoid importing gypsum from Spain. The town authorities play a crucial role in fostering collaboration, creating a legal and financial environment conducive to the project. They also contribute to financing; for example, the pipeline that transports steam from the power plant to the refinery was funded by the town authorities, enhancing the district heating network for residents. Collaboration between companies and local stakeholders is a key factor in the success of the Kalundborg industrial symbiosis, particularly in adopting innovative and sustainable solutions. Regular forums are held to facilitate the exchange of information and best practices, and decision-makers actively support the development of industrial symbiosis through their networks (Domenech & Davies, 2011).

DISCUSSION AND CONCLUSION

The implementation of mutualism is pivotal in developing sustainable supply chains by fostering close collaboration between companies and organizations to optimize resource use. This approach leads to a significant reduction in the environmental impact of manufacturing activities while delivering substantial economic benefits. In terms of logistical management, mutualism promotes the optimization of material, energy, and information flows, thereby alleviating pressure on ecosystems and reducing costs related to transportation, storage, and waste management. Additionally, mutualism enhances traceability within supply chains and helps meet increasing regulatory demands for sustainability (Grant *et al.*, 2022). Essentially, mutualism transforms traditional, linear, and resource-intensive supply chains into circular, collaborative systems that facilitate the exchange, reuse, and recycling of waste. From this perspective, mutualism is a crucial element in the analysis of industrial ecology as an interdisciplinary field that explores interactions between industrial systems and the natural environment. Industrial ecology aims to design industrial systems that function like natural ecosystems, where the waste of one entity becomes a resource for another, thereby supporting a circular production model.

The Kalundborg industrial symbiosis serves as a prominent example of industrial ecology, demonstrating the environmental and economic benefits that arise from a collaborative, circular approach to resource management. Evolving organically since the 1960s, this model is founded on the exchange of materials and energy among various companies in the area, leading to substantial reductions in waste, greenhouse gas emissions, and the conservation of local resources. The benefits of the Kalundborg industrial symbiosis are considerable. By optimizing the use of by-products and waste streams, it has not only reduced costs for participating companies but also generated new revenue streams. The model's success is largely attributed to the trust and collaboration among stakeholders, fostering innovations and solutions that benefit the entire community, both economically and environmentally. This success is partly because the stakeholders are not direct competitors in the market but rather complementary links in different supply chains, creating "vertical synergies." The research note aims to address a gap in the literature, as there are relatively few studies that adopt a mutualistic perspective on industrial symbiosis.

Knight *et al.* (2014), for example, propose comparing mutualistic versus competitive interactions within Marshallian industrial districts, which can be viewed as a form of industrial symbiosis. However, their approach is conceptual rather than managerial. Zhang *et al.* (2015) examine sulfur flows in China's Shandong Lubei eco-industrial park using ecological network analysis. While they highlight the potential of mutualistic relationships, their focus is on a utility intensity matrix designed to theoretically conceptualize a system of preferences between exploitation, control, competition, and mutualism. Similarly, Niu *et al.* (2023) adopt a "mutualistic view" to evaluate the symbiotic relationship between industrial development and the environment, using mathematical modeling to propose improved symbiotic coordination. These studies are of significant academic interest as they underscore the relevance of a mutualistic approach to industrial symbiosis. However, they do not address organizational specifics—including governance mechanisms—that influence the success of these systems and are crucial for assessing the degree of reproducibility of various implementations globally.

Indeed, the generalization of the Kalundborg industrial symbiosis is problematic, as noted early by Ehrenfeld & Gertler (1997). The mutual dependence—or co-dependence—among the key participants in the value chain network inherent in mutualism raises concerns about the resilience of the symbiosis to potential market disruptions or political changes (Chopra & Khanna, 2014). Another significant challenge is the difficulty in replicating industrial symbiosis in different regions of the world. Variations in geographical specificities, production system structures, and regulatory environments make it challenging to directly transpose the model without substantial adaptations. In this context, the future of industrial symbiosis, both in Kalundborg and globally, may depend on the further integration of digital technologies. These technologies have the potential to optimize resource flows, manage exchanges, and enhance the efficiency of value chain networks. For example, real-time tracking systems and resource management platforms could improve coordination among companies, reduce losses, and maximize vertical synergies.

The successful implementation of industrial symbioses requires long-term planning and a deep understanding of local dynamics. This involves accurately assessing available resources, identifying potential partners, and raising stakeholder awareness about the importance of cooperation and mutual trust. In this regard, the Kalundborg industrial symbiosis provides a valuable model for advancing towards a widespread circular economy. The insights gained from it highlight that inter-organizational collaboration, supported by collective commitment and mutual confidence, is crucial. The future of industrial ecology, therefore, hinges on a contextualized approach, guided by effective public policies that maximize economic and environmental benefits while ensuring the resilience and sustainability of value chain networks. As Masson-Delmotte (2024) emphasizes, drawing from numerous examples in his work with the IPCC, this often involves navigating a complex landscape of competing interests among decision-makers. Nevertheless, the Kalundborg industrial symbiosis stands as a significant milestone in industrial ecology, offering promising prospects for a more sustainable future.

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REFERENCES

Boons, F., & Janssen, M. (2005). The myth of Kalundborg: Social dilemmas in stimulating eco-industrial parks. In Jeroen, C.-J., & Janssen, M. (Eds.), *Economics of industrial ecology: Materials, structural change, and spatial scales* (pp. 235–247). Cambridge (MA): The MIT Press.

Bourg, D., & Erkman, S., Eds. (2017). *Perspectives on industrial ecology*. London: Routledge.

Branson, R. (2016). Re-constructing Kalundborg: The reality of bilateral symbiosis and other insights. *Journal of Cleaner Production*, *112*, 4344–4352.

Bronstein, J. (Ed.) (2015). *Mutualism*. Oxford: Oxford University Press.

Chopra, S., & Khanna, V. (2014). Understanding resilience in industrial symbiosis networks: Insights from network analysis. *Journal of Environmental Management*, *141*, 86–94.

Davison, A. (2020). Biological mutualism: A scientific survey. *Theology & Science*, *18*(2), 190–210.

Domenech, T., & Davies, M. (2011). Structure and morphology of industrial symbiosis networks: The case of Kalundborg. *Procedia–Social & Behavioral Sciences*, *10*, 79–89.

Ehrenfeld, J., & Gertler, N. (1997). Industrial ecology in practice: The evolution of interdependence at Kalundborg. *Journal of Industrial Ecology*, *1*(1), 67–79.

Faria, E., Caldeira-Pires, A., & Barreto, C. (2021). Social, economic, and institutional configurations of the industrial symbiosis process: A comparative analysis of the literature and a proposed theoretical and analytical framework. *Sustainability*, *13*(13), Article No. 7123.

Gibbs, D., & Deutz, P. (2007). Reflections on implementing industrial ecology through eco-industrial park development. *Journal of Cleaner Production*, *15*(17), 1683–1695.

Grant, D., Trautrims, A., & Wong, C.-Y. (2022). *Sustainable logistics and supply chain management: Principles and practices for sustainable operations and management* (3rd ed.). London: Kogan Page.

Gulipac, S. (2016). Industrial symbiosis: Building on Kalundborg's waste management experience. *Renewable Energy Focus*, *17*(1), 25–27.

Jacobsen, N. (2006). Industrial symbiosis in Kalundborg, Denmark: A quantitative assessment of economic and environmental aspects. *Journal of Industrial Ecology*, *10*(1-2), 239–255.

Jacobsen, N., & Anderberg, S. (2005). Understanding the evolution of industrial symbiotic networks: The case of Kalundborg. In Jeroen, C.-J., & Janssen, M. (Eds.), *Economics of industrial ecology: Materials, structural change, and spatial scales* (pp. 313–336). Cambridge (MA): The MIT Press.

Knight, C., Penn, A., & Hoyle, R. (2014). Comparing the effects of mutualism and competition on industrial districts. *Physica A: Statistical Mechanics & Its Applications*, *416*, 541–557.
Masson-Delmotte, V. (2024). *Face au changement climatique*. Paris: CNRS Editions.
Neves, A., Godina, R., Azevedo, S., & Matias, J. (2020). A comprehensive review of industrial symbiosis. *Journal of Cleaner Production*, *247*, Article No. 119113.
Niu, K., He, W., & Qiu, L. (2023). Symbiosis coordination between industrial development and ecological environment for sustainable development: Theory and evidence. *Sustainable Development*, *31*(4), 3052–3069.
Oughton, C., Anda, M., Kurup, B., Hamadi, M., & Ho, G. (2023). KIC4: A four-dimensional model for industrial symbiosis. Validation with key stakeholders. *American Journal of Industrial & Business Management*, *13*(12), 1456–1485.
Pego, A.-C. (2021). Business model for a circular economy based on Portuguese offshore energy cluster. *Technium Social Sciences Journal*, *19*, 499–505.
Ruiz-Puente, C., & Bayona, E. (2017). Modelling of an industrial symbiosis network as a supply chain. *Proceedings of the 5th International Conference on Sustainable Solid Waste Management*. Athens, 1–14 (CD-Rom).
Sapp, J. (1994). *Evolution by association: A history of symbiosis*. Oxford: Oxford University Press.
Thomas, J., McMurtrey, M., & Rebman, Jr., C. (2022). Supply chain sustainability: A must have for today's competitive business environment. *Journal of Strategic Innovation & Sustainability*, *17*(2), 38–45.
Turken, N., & Geda, A. (2020). Supply chain implications of industrial symbiosis: A review and avenues for future research. *Resources, Conservation & Recycling*, *161*, Article No. 104974.
Valentine, S. (2016). Kalundborg symbiosis: Fostering progressive innovation in environmental networks. *Journal of Cleaner Production*, *118*, 65–77.
Valero, A., Usón, S., & Costa, J. (2012). Exergy analysis of the industrial symbiosis model in Kalundborg. *Proceedings of the 25th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*. Perugia, 406–416.
Williamson, O. (1985). *The economic institutions of capitalism: firms, markets, relational contracting*. New York: The Free Press.
Yoon, C., Moon, S., & Lee, H. (2022). Symbiotic relationships in business ecosystem: A systematic literature review. *Sustainability*, *14*(4), Article No. 2252.
Zhang, Y., Zheng, H., & Fath, B. (2015). Ecological network analysis of an industrial symbiosis system: A case study of the Shandong Lubei eco-industrial park. *Ecological Modelling*, *306*, 174–184.