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Digital Industrial Symbiosis: Theoretical Foundations and Case Study Analysis

Špela Dermol
Pulp and Paper Institute, Ljubljana, Slovenia
Spela.dermol@icp-lj.si

Valerij Dermol
International School for Social and Business Studies, Celje, Slovenia
Valerij.dermol@mfdps.si

Abstract

Industrial symbiosis has emerged as a key strategy in promoting sustainable industrial development by fostering resource efficiency, reducing waste, and improving economic and environmental performance. This paper explores the theoretical foundations of industrial symbiosis, analysing its key characteristics, challenges, and the role of digital technologies in facilitating resource exchanges. The analysis investigates existing industrial symbiosis initiatives worldwide, highlighting best practices and assessing the effectiveness of digital platforms in supporting collaboration. While industrial symbiosis has demonstrated significant benefits, barriers such as financial constraints, regulatory inconsistencies, and data-sharing hesitancy remain challenges to wider adoption. The study identifies gaps in implementation, particularly for small and medium-sized enterprises, and discusses the prospects of emerging technologies, such as artificial intelligence, blockchain, and digital twins, in overcoming these limitations. Future research should focus on empirical assessments of digital tool effectiveness, policy incentives, and sector-specific industrial symbiosis models to enhance global adoption and sustainability outcomes.

Keywords: Industrial Symbiosis, Circular Economy, Resource Efficiency, Digital Technologies, Sustainability, Waste Management

INTRODUCTION

Industrial symbiosis is an increasingly relevant approach in modern industrial sustainability as it promotes resource efficiency, environmental responsibility, and economic viability. The motivation behind this paper lies in understanding how industrial symbiosis has been implemented across various sectors and how digital technologies support its adoption. The research aims to analyse existing industrial symbiosis initiatives, their challenges, and the role of digital tools in facilitating their development. The paper is structured into two main sections. The first part presents the theoretical

foundations of industrial symbiosis, outlining its key principles, benefits, and integration with digital technologies. The second part provides an empirical analysis of industrial symbiosis initiatives by reviewing case studies, EU-funded projects, and digital solutions supporting symbiotic exchanges.

This research was conducted within the framework of the FReINDs and SymbioTech Erasmus+ projects, which focus on advancing industrial symbiosis through digital innovation and sustainable resource management.

INDUSTRIAL SYMBIOSIS: THEORETICAL FOUNDATIONS

Definition and Concept of Industrial Symbiosis

Industrial symbiosis is a sustainability-driven approach where industries collaborate to exchange resources, including byproducts, energy, and water, to enhance efficiency and reduce environmental impact. Unlike conventional waste management, which primarily focuses on disposal, industrial symbiosis emphasises material reuse and resource optimisation within industrial networks. It is crucial in advancing circular economy principles by minimising waste and reducing reliance on virgin materials (Biswas & John, 2022; Patricio et al., 2022).

Key Characteristics of Industrial Symbiosis

Industrial symbiosis fosters an ecosystem where industries exchange physical resources such as byproducts, water, and energy, optimising their usage and minimising waste (Ulusoy et al., 2024). Participating industries experience cost reductions in energy, transportation, and compliance with environmental regulations while simultaneously reducing greenhouse gas emissions and industrial water consumption (Mirata et al., 2024). By facilitating a shift from a linear economy to a circular economy model, industrial symbiosis ensures that materials are continuously reused instead of being discarded (Nyakudya et al., 2023). Its implementation relies on strong inter-industry collaborations, often within geographic proximity, to manage waste and maximise resource utilisation (Industrial Ecology, 2022). Various forms of synergies exist, including inorganic byproduct exchanges; utility sharing of heat, water, and steam; supply chain integration; and the creation of new business models utilising residual flows (Boquera & Marcos, 2023).

Digital Technologies in Industrial Symbiosis

Integrating digital tools has significantly enhanced industrial symbiosis by optimising resource exchanges, improving decision-making, and fostering cross-industry collaboration. Artificial intelligence and machine learning analyse waste streams, identify potential symbiotic exchanges, and assess economic feasibility (Makropoulos et al., 2024). Digital matchmaking platforms serve as online tools that facilitate industry partnerships by identifying and recommending resource exchanges (Silva et al., 2022). Blockchain technology ensures transparency and traceability in industrial symbiosis transactions, mitigating security concerns and regulatory compliance challenges (Michelini & Mattelin-Pierrard, 2023). Digital twins, virtual models of industrial processes, allow companies to simulate resource-sharing scenarios and optimise sustainability outcomes (Aquilani et al., 2020).

Challenges in Implementing Industrial Symbiosis

Despite its benefits, industrial symbiosis faces several barriers to widespread adoption. Many industries operate within rigid production frameworks that are not easily adaptable to symbiotic exchanges (Mirata et al., 2024). Collaboration and trust issues arise as businesses may hesitate to share data due to concerns about competition and intellectual property (Michelini & Mattelin-Pierrard, 2023). Regulatory inconsistencies across regions hinder the standardisation of industrial symbiosis practices (Petrova, 2022). Furthermore, financial constraints related to fluctuating raw material costs and market demand for secondary resources can impact the feasibility of industrial symbiosis initiatives (Ulusoy et al., 2024).

Future Prospects and Emerging Trends in Industrial Symbiosis

As digitalisation advances, future industrial symbiosis trends are expected to incorporate more sophisticated AI-driven platforms for synergy identification and predictive modelling. Digital twins will likely become more prevalent in industrial networks, allowing for real-time monitoring and optimisation of resource exchanges (Akrivou et al., n.d.). Expanding industrial symbiosis frameworks into new industries, such as technology and healthcare, will further reinforce the importance of circular economy principles in global sustainability efforts (Hariyani et al., 2024).

ANALYSIS OF INDUSTRIAL SYMBIOSIS INITIATIVES

Methodology

The analysis of industrial symbiosis initiatives is based on investigating and evaluating the available literature describing good practices and various EU-funded projects. This research focuses on identifying key industrial symbiosis applications, their effectiveness, and the role of digital tools in supporting these initiatives. The selection of case studies is guided by their relevance, geographic diversity, and the extent to which they integrate industrial symbiosis principles.

Existing Industrial Symbiosis Initiatives

Numerous industrial symbiosis initiatives have been implemented worldwide, demonstrating different approaches to resource exchange. The Kalundborg industrial ecosystem in Denmark is a well-established model where industries collaborate to share byproducts, energy, and water. Excess heat from a power plant is used in fish farming operations, a wallboard manufacturer repurposes gypsum from power station emissions, and pharmaceutical wastewater treatment is redirected for industrial cooling systems (Ulusoy et al., 2024). Another example is the Śmiłowo Eco-Industrial Park in Poland, which specialises in processing meat production waste into biofuel and fertilisers, significantly reducing waste and increasing energy self-sufficiency (Kowalski et al., 2023).

In Slovenia, Donar exemplifies industrial symbiosis by using recycled polyethene terephthalate (PET) and polyester (PES) to produce sustainable furniture, reducing raw material consumption by 15 tons annually. AquafilSLO repurposes surplus thermal energy from fibre production to provide heating for local facilities, reducing 3,500 tons of CO□ emissions annually. The City of Ljubljana has implemented a project that recycles invasive Japanese knotweed into sustainable paper products, demonstrating how municipalities can integrate industrial symbiosis into urban sustainability strategies (European Circular Economy Stakeholder Platform, 2024).

The Finnish Kemi-Tornio Industrial Symbiosis Cluster integrates forestry, mining, and energy industries to repurpose byproducts into bioenergy and recover valuable metals, contributing to an annual economic benefit of €200 million. LABIO Ltd., Finland's largest biogas producer, converts municipal and industrial biowaste into biogas and compost, increasing energy efficiency through heat recovery. Italy's Emilia-Romagna region has successfully repurposed overspray waste from zirconia coating processes into ceramic frits and glazes, reducing material costs by up to 40% (Interreg Europe Policy Learning Platform, 2024).

In the United Kingdom, International Synergies Limited (ISL) has developed the National Industrial Symbiosis Programme (NISP®), which uses the SYNERGie® platform to facilitate resource exchanges. This program has reduced carbon emissions by 42 million tonnes in England alone (International Synergies Limited, 2024).

Digital Support for Industrial Symbiosis

The adoption of digital tools has been instrumental in scaling industrial symbiosis efforts. Platforms such as the SymbioSyS tool aid in detecting synergies among industries by mapping waste exchanges and resource-sharing opportunities (Álvarez & Ruiz-Puente, 2017). FLOOW2 enables businesses to share underutilised assets, while SHAREBOX provides real-time data on resource availability for optimised exchanges. The Value Chain Generator (VCG.AI) applies AI-driven analytics to optimise circular value chains across industries, offering predictive insights into waste valorisation opportunities (Anteja ECG, 2024). Blockchain technology is increasingly being integrated into industrial symbiosis networks to ensure transaction transparency and improve resource traceability (Michelini & Mattelin-Pierrard, 2023).

ANALYSIS OF INDUSTRIAL SYMBIOSIS INITIATIVES

The analysis of industrial symbiosis initiatives indicates that industrial symbiosis has been successfully implemented in various industries and locations. The case studies demonstrate that industrial symbiosis can significantly reduce waste, lower production costs, and enhance environmental sustainability. However, a comparative analysis of the cases also reveals disparities in the degree of implementation and digital support available to facilitate industrial symbiosis.

One key observation is that large-scale industrial clusters, such as Kalundborg in Denmark and Kemi-Tornio in Finland, have well-established industrial symbiosis networks with integrated digital tools supporting resource exchanges. These initiatives show that when industries work collaboratively and benefit from government incentives, industrial symbiosis can result in long-term economic and environmental benefits. Conversely, smaller industrial symbiosis initiatives, particularly those involving SMEs, often struggle with implementation due to limited financial resources, technological barriers, and insufficient regulatory frameworks.

The digital tools analysed in this research provide crucial support for industrial symbiosis by enabling matchmaking between industries, improving transparency, and optimising resource exchanges. Platforms such as SymbioSyS, FLOOW2, and SHAREBOX are particularly valuable for industrial actors seeking efficient, data-driven methods to engage in symbiotic exchanges. However, despite the availability of these digital tools, adoption remains a challenge. Many companies hesitate to share data due to concerns about intellectual property, competitive advantage, and regulatory compliance.

Several gaps exist in implementing industrial symbiosis, particularly in regions with weak policy support or industries lacking awareness of resource exchange's benefits. One of the significant challenges is that many industries operate in silos, making it difficult to identify and establish symbiotic relationships. Additionally, while digital platforms are valuable for resource matching, they often require substantial initial investment and technical expertise, which can be a barrier for SMEs.

Looking ahead, the prospects for industrial symbiosis depend on greater integration of policy incentives, financial support, and technological advancements. Governments and industry leaders must collaborate to create standardised regulations that encourage businesses to participate in industrial symbiosis. Furthermore, emerging technologies such as blockchain, artificial intelligence, and digital twins hold significant potential to overcome some of the barriers identified in this study. Digital innovations can enhance efficiency, promote data security, and facilitate scalable industrial symbiosis models that benefit both large corporations and SMEs. Strengthening collaboration between industries, policymakers, and technology providers will be essential in maximising the benefits of industrial symbiosis and ensuring its long-term sustainability.

CONCLUSION

Industrial symbiosis represents a transformative approach to sustainable industrial development by fostering resource efficiency, reducing waste, and promoting economic and environmental benefits. The findings from this research highlight that industrial symbiosis has been successfully implemented across various industries and regions, with significant contributions from digital tools in facilitating these processes. Large-scale industrial clusters, such as Kalundborg and Kemi-Tornio, have demonstrated the effectiveness of structured collaboration, government support, and digital integration in ensuring the long-term viability of industrial symbiosis. Similarly, smaller initiatives, such as Donar and AquafilSLO, illustrate how targeted industrial symbiosis applications can contribute to sustainability on a smaller scale.

Despite these positive outcomes, several challenges remain, including financial constraints, regulatory inconsistencies, and technological adoption barriers, particularly for SMEs. Many companies still operate in isolation, limiting the potential for cross-industry synergies. Additionally, the reluctance to share resource data due to competitive concerns continues to hinder the broader adoption of industrial symbiosis. While digital tools such as SymbioSyS, FLOOW2, and SHAREBOX have significantly enhanced resource-matching and collaboration, their accessibility and usability require further improvements, particularly for smaller enterprises that may lack the necessary technical infrastructure.

This research has certain limitations that should be acknowledged. The study primarily relies on analysing documented case studies and available literature, which may not capture the full range of ongoing industrial symbiosis initiatives worldwide. Additionally, the assessment of digital tool adoption and effectiveness is based on secondary sources, meaning that insights from direct industry stakeholders and practitioners could provide a more nuanced understanding of practical challenges and opportunities.

Future research should explore empirical, industry-specific studies to examine real-time adoption challenges and the effectiveness of digital solutions in supporting industrial symbiosis. Further investigation is needed into policy interventions and financial mechanisms that encourage industrial participation in symbiosis networks. Additionally, research on the role of artificial intelligence, machine learning, and blockchain in optimising industrial symbiosis exchanges can provide valuable insights into

emerging technological solutions. By addressing these areas, future studies can contribute to more robust strategies for scaling industrial symbiosis and achieving greater sustainability across industries and regions.

Industrial symbiosis is a critical strategy for achieving sustainability by optimising resource use, reducing waste, and fostering economic efficiency. While challenges exist, digital technologies and strong collaborative networks can significantly enhance the adoption of industrial symbiosis. Future developments should focus on strengthening regulatory frameworks, expanding digital solutions, and fostering international cooperation to maximise the benefits of industrial symbiosis on a global scale.

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