Co-funded by the European Union

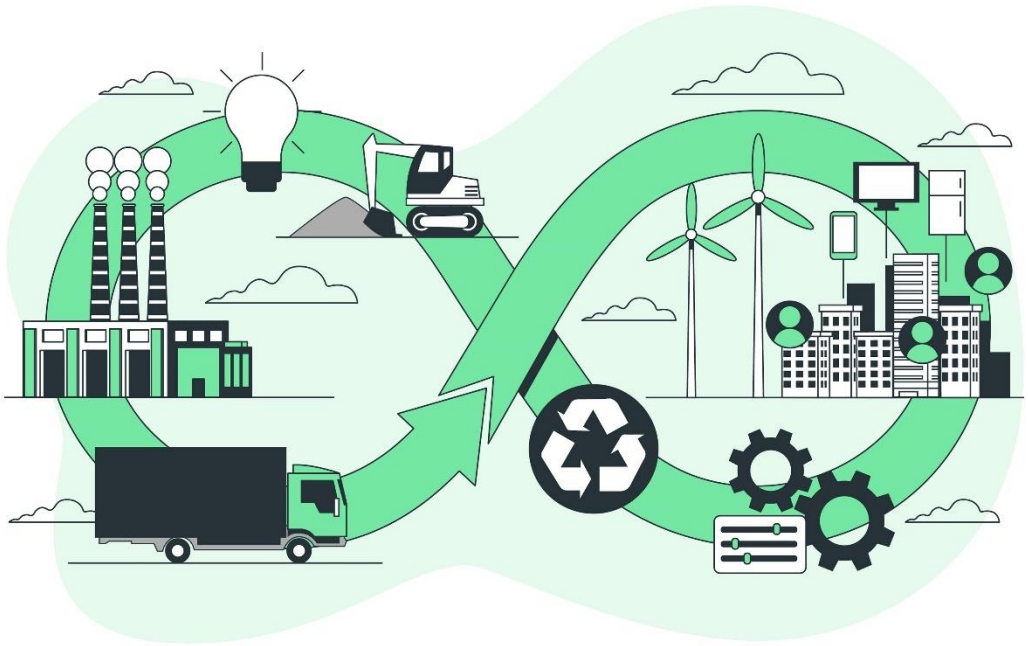
Project number:
2024-1-NO01-KA220-HED-000246621

FReINDs

DIGITAL SYMBIOSIS FRAMEWORK

Research Report on Digital Industrial Symbiosis

Work package n°2



Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

AUTHORS:

Valerij Dermol, International School for Social and Business Studies, Slovenia

Špela Dermol, International School for Social and Business Studies, Slovenia

Thomas Laudal, University of Stavanger, School of Business and Law, Norway

Ali Turkyilmaz, University of Stavanger, School of Business and Law, Norway

Joanna Bać, Senior Project Manager, Danmar Computers, Poland

Valeria Lavano, EXEOLAB, Potenza, Italy

Diasozousa Anna Gryllaki, EXEOLAB, Potenza, Italy

Natālija Cudečka-Puriņa, BA School of Business and Finance, Riga, Latvia

Dzintra Atstāja, BA School of Business and Finance, Riga, Latvia

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

CONTENTS

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

INTRODUCTION TO THE REPORT

This report provides a comprehensive, multi-method examination of the state, potential, and challenges of **digital industrial symbiosis (DIS)**, with a specific focus on the experiences and readiness of small and medium-sized enterprises (SMEs) across Europe. Drawing on complementary data sources—desk research, a cross-country survey, semi-structured interviews, and practical case studies—it offers a rich, evidence-based foundation for strategic decision-making, policy recommendations, and future research.

Part I: Desk Research – Theoretical Framework and Key Concepts

The desk research synthesizes current scientific literature, EU-funded project outputs, and real-world practices in industrial symbiosis (IS) and digital circular economy. It establishes the conceptual foundations of IS, outlining its distinguishing characteristics, benefits, and integration with digital technologies. It also maps emerging digital tools—such as matchmaking platforms, AI-based planning systems, blockchain, and digital twins—and evaluates their role in facilitating resource sharing and symbiotic partnerships. Furthermore, this section identifies enabling conditions and barriers for implementing IS in both large enterprises and SMEs, with an emphasis on governance, policy support, and technological innovation.

Part II: Quantitative Analysis – Survey of Companies Across Five Countries

The second section presents the results of a structured survey conducted among 78 organizations from Slovenia, Italy, Latvia, Poland, and Norway. It explores company awareness, digital readiness, resource use, and interest in IS-related practices. The analysis identifies levels of familiarity with IS/DIS, perceived benefits, barriers, training needs, and institutional factors influencing engagement. Statistical insights reveal that awareness strongly correlates with readiness, and that digital competencies significantly influence willingness to participate in IS initiatives. National differences highlight the influence of context, while SME-specific challenges (limited capacity, lack of guidance) underscore the need for tailored interventions.

Part III: Qualitative Analysis – Thematic Insights from Semi-Structured Interviews

The third part draws on thematic analysis of 16 in-depth interviews with SME representatives, public institutions, and expert stakeholders in Slovenia, Poland, Italy, Latvia, and Norway. This qualitative perspective enriches the statistical findings, offering contextualized insights into lived experiences, strategic intentions, technological frustrations, and local experimentation. Six key themes emerge: (1) barriers and challenges, (2) innovation and strategic transformation, (3) local actions and engagement, (4) user experience and tool design, (5) platforms and ecosystem development, and (6) digital integration and automation. These findings offer critical feedback for improving digital IS tools, governance models, and capacity-building efforts.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Part IV: Case Studies – Examples of Industrial Symbiosis in Practice

This section showcases real-world examples of industrial symbiosis (IS) across sectors and regions. Each case highlights how companies and communities transform waste into value, embed circular economy principles, and leverage innovation and collaboration for sustainability.

Structured by summary, context, solution, impacts, key lessons, and discussion points, these cases illustrate the practical benefits of IS—from reduced emissions to cost savings and new business models. They provide replicable insights for SMEs, policymakers, and innovators seeking to implement circular strategies.

FINAL SECTION: CONCLUSIONS AND IMPLICATIONS FOR PRACTICE

The final part of the report synthesizes findings from the desk research, survey, interviews, and case studies to highlight key patterns, gaps, and actionable insights. It confirms that while awareness of industrial symbiosis (IS) and digital IS (DIS) is growing, it remains uneven—particularly among SMEs. Despite low familiarity, there is clear recognition of the potential benefits, including cost savings, innovation, and sustainability gains.

However, systemic barriers—such as lack of regulation, poor platform interoperability, limited digital skills, and low data quality—continue to hinder progress. All data sources underline the urgent need for targeted training, capacity building, and more supportive policy environments.

The report concludes with tailored recommendations for SMEs, platform developers, policymakers, and training providers. It calls for integrating DIS into strategic planning, improving digital tool usability, investing in public digital infrastructure, and developing practical training materials to bridge the digital and circular knowledge gaps.

In the final section, a list of so-called blocking points is provided, along with action plans for addressing them.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

PART I: DESK RESEARCH – THEORETICAL FRAMEWORK AND KEY CONCEPTS

1 About Industrial Symbiosis

Industrial Symbiosis (IS) is a collaborative approach where industries exchange resources, such as byproducts, energy, and water, to enhance resource efficiency and reduce environmental impacts. Unlike traditional waste management, which primarily focuses on disposal, IS emphasises the reuse and recycling of materials within industrial networks, contributing to a Circular Economy (CE). This approach not only diverts waste from landfills but also creates economic value from waste materials, reduces greenhouse gas emissions, and lowers the use of virgin materials. The concept of IS extends beyond waste management to encompass resource optimisation, energy efficiency, and industrial collaboration, making it a fundamental strategy for achieving sustainability goals in modern industries. As industries increasingly recognise the benefits of IS, there is a growing need to understand its key characteristics, applications, challenges, and the role of digital technologies in its implementation.

1.1 Key Characteristics of Industrial Symbiosis

Industrial symbiosis reduces **waste** by enabling the capture, recovery, and reuse of resources that would otherwise be discarded. This process reduces industrial waste and the need for new material extraction, contributing to a more sustainable production system (Biswas & John, 2022; Patricio et al., 2022).

One of IS's defining characteristics is **resource sharing and efficiency**, where industries exchange physical resources such as byproducts, water, and energy to optimise their usage and minimise waste (Ulusoy et al., 2024; "Industrial Ecology," 2022). This exchange fosters a more sustainable industrial network by ensuring that materials that would otherwise be discarded are repurposed, contributing to environmental conservation.

Economic and environmental benefits play a crucial role in IS, as industries engaging in symbiotic exchanges can significantly reduce energy, transportation, and logistics costs. Furthermore, IS helps industries **comply with environmental regulations** more efficiently while simultaneously reducing pollution and industrial water consumption (Ulusoy et al., 2024; Mirata et al., 2024).

Another fundamental aspect of IS is its **integration with the circular economy**, making it a vital mechanism in transitioning from a linear economy to a CE. IS promotes sustainable production and consumption patterns, ensuring that secondary materials are continually reused rather than disposed of, thereby enhancing industrial sustainability (Nyakudya et al., 2023; Nyakudya et al., 2022).

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Additionally, IS relies on **collaborative networks**, which require industries to work together—often within geographical proximity—to collectively manage waste and resource utilisation. This cooperation fosters mutual benefits and enhances operational stability, particularly in regions with limited access to raw materials ("Industrial Symbiosis: Novel Supply Networks for the Circular Economy," 2022; Nyakudya et al., 2022).

IS encompasses **diverse synergies**, which allow industries to optimise resource use and minimise waste by leveraging different types of collaborations.

- **Inorganic byproduct synergies** involve exchanging materials such as metal scraps, slag, or chemical byproducts that can be repurposed by another industry instead of being discarded.
- **Utility synergies** focus on sharing resources like excess heat, steam, or water between industrial partners, reducing energy consumption and improving overall efficiency.
- **Supply chain or Mutuality synergies** integrate companies within a production network, enabling them to share logistics, transportation, or packaging resources to streamline operations and cut costs. These synergies ensure that industrial byproducts are effectively reused in various applications, fostering sustainability and economic growth while reducing environmental impact ("Industrial Ecology," 2022).
- **Substitution Synergies** involve using one company's residual flows, such as waste or byproducts, as inputs for another company's processes. For example, a neighboring plant can utilise excess heat from one facility, thereby reducing energy consumption and promoting resource efficiency (Boquera & Marcos, 2023).
- **Genesis Synergies**: This type refers to creating new activities or businesses specifically designed to utilise residual flows from existing industries. For instance, establishing a new enterprise to process waste materials into valuable products exemplifies a genesis synergy (Boquera & Marcos, 2023).

1.2 Differences from Traditional Waste Management

IS differs significantly from traditional waste management, which predominantly focuses on disposing of waste rather than reusing it. The focus on **reuse and recycling** is a critical differentiator, as traditional waste management prioritises landfill disposal. IS emphasises material reuse and recycling within industrial networks, thereby reducing the extraction of virgin materials (Patricio et al., 2022; Kumar, 2022).

Another key distinction is **proactive resource management**, where industries in an IS network actively seek opportunities to develop synergies that repurpose waste as a resource instead of simply treating it as a byproduct to be discarded (Mirata et al., 2024; Petrova, 2022).

Moreover, IS contributes to **economic and social value creation**, as it addresses environmental concerns and generates economic value by reducing production

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

costs, fostering the creation of green jobs, and supporting local communities through sustainable industrial practices (Petrova, 2022).

IS is also **integrated with circular economy principles**, ensuring that industries maximise the sustainable use of resources and minimise environmental impacts, unlike traditional waste management, which often lacks a holistic sustainability approach ("Industrial Symbiosis: Novel Supply Networks for the Circular Economy," 2022; Nyakudya et al., 2023).

1.3 Industrial Symbiosis Implementation Strategies, Challenges and Considerations

To successfully implement industrial symbiosis, businesses and policymakers must adopt structured frameworks, leverage advanced digital tools, and address industry-specific challenges.

Various frameworks and models have been developed to support industries in establishing effective symbiotic relationships. **Business value frameworks**, for example, assess the economic and environmental benefits of IS initiatives while accounting for potential trade-offs. These frameworks help industries balance cost savings, revenue generation, and sustainability goals, ensuring that symbiotic exchanges contribute positively to long-term business strategies (Mirata et al., 2024; Belykh, 2023).

On the other hand, models describing the formation and **evolution of symbiotic chains** help industries transition from traditional linear production models to interconnected resource-sharing networks. These models facilitate the identification of industrial clusters that can benefit from IS and outline best practices for fostering collaboration among businesses.

Advanced **digital tools** are crucial in facilitating these symbiotic exchanges by optimising resource allocation and minimising waste. Artificial intelligence (AI) and machine learning algorithms analyse data on waste streams, material concentrations, and market prices to identify profitable material exchanges, ultimately uncovering new economic and ecological opportunities (Makropoulos et al., 2024). Digital matchmaking platforms help industries connect with suitable partners for resource exchanges, reducing transaction costs and improving supply chain efficiency. Additionally, blockchain technology ensures transparency and traceability in IS transactions, mitigating data security and regulatory compliance concerns.

Despite its potential, industrial symbiosis presents several implementation challenges that must be addressed. One major challenge is **integrating IS into existing industrial processes**. Many businesses operate within rigid production systems that require significant modifications to accommodate symbiotic exchanges. This challenge requires investments in adaptable production technologies and process redesigns that enable seamless resource sharing.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Another significant barrier is the **need for improved collaboration and trust** among industries. Many businesses hesitate to share resource data due to concerns about competitive disadvantages. Establishing secure data-sharing frameworks and third-party verification systems can alleviate these concerns and foster greater transparency in IS networks. Additionally, **regulatory inconsistencies** across different regions can complicate the adoption of IS practices, necessitating the development of standardised policies and incentives that encourage participation.

Sector-specific industrial symbiosis applications demonstrate its versatility and potential to drive sustainability across various industries. In the agri-food sector, for example, substantial amounts of organic byproducts are generated during food processing. By integrating these byproducts into eco-industrial systems, industries can enhance material and energy recovery, reducing waste while creating new revenue streams for agricultural businesses (Hamam et al., 2023). In the manufacturing sector, industrial symbiosis enables repurposing production residues, such as metal scraps or plastic waste, into raw materials for other industries, thereby reducing reliance on virgin resources. The energy sector also benefits from IS through heat and energy recovery systems, where waste heat from one industrial facility is utilised to power neighbouring production plants, improving overall energy efficiency.

Addressing these implementation challenges while leveraging digital tools and tailored frameworks will be key to the widespread adoption of industrial symbiosis. Industries can transition toward more sustainable and resource-efficient production models by fostering stronger collaborations, standardising regulatory approaches, and investing in innovative digital solutions.

2 Examples of Industrial Symbiosis

2.1 Good Practices and Lessons Learned

2.1.1 Examples Exhibited in Scientific Literature

In the scientific literature, numerous real-world examples demonstrate the successful implementation of IS across various sectors.

One of the most well-documented examples is **Kalundborg, Denmark**, where multiple industries engage in systematic resource exchanges. The Kalundborg Symbiosis model demonstrates how industrial waste, and surplus materials can be transformed into valuable resources. For example, excess heat from a power plant is utilised by a fish farm to maintain optimal water temperatures, while a wallboard manufacturer repurposes gypsum from a power station. Additionally, treated wastewater from a pharmaceutical company is redirected for reuse in cooling systems, creating a closed-loop industrial ecosystem that minimises waste and enhances resource efficiency (Ulusoy et al., 2024).

A similarly effective model is found in the **Śmiłowo Eco-Industrial Park in Poland**, particularly within the agri-food sector. The park specialises in processing meat

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

production waste into valuable secondary products, such as meat-bone meal biofuel and fertilisers. The facility significantly reduces CO2 emissions by employing innovative processing techniques while generating substantial bioenergy. Annually, the plant processes approximately 300,000 tons of meat waste, producing 110,000 tons of biofuel and generating around 460,000 GJ of bioenergy. This contributes to sustainable waste management and enhances energy self-sufficiency, reducing dependence on non-renewable energy sources (Kowalski et al., 2023).

The **Spanish ceramics industry**, which produces 95% of the nation's ceramics, also adopts IS principles by incorporating waste materials as inputs, aligning with circular economy models to extend the lifecycle of resources (Castellet-Viciano et al., 2022). This sector has successfully integrated recycled glass, ceramic sludge, and construction waste into ceramic tile production, reducing reliance on virgin raw materials and lowering environmental impact (Castellet-Viciano et al., 2022). Furthermore, innovations in waste heat recovery and water recirculation systems have enhanced energy efficiency, minimised emissions and reduced overall production costs. These advancements demonstrate how industrial symbiosis can drive sustainability while maintaining industrial competitiveness.

Another notable example is the **Russian oil and gas sector**, where IS is employed to manage associated petroleum gas (APG). Instead of flaring APG—a practice that contributes to environmental degradation—industries process and utilise APG to create economic value (Mironova et al., 2023). Companies in the sector have developed gas reinjection and gas-to-liquid (GTL) conversion technologies to capture and repurpose APG, thereby reducing emissions and maximising energy efficiency. The captured gas is either reinjected into reservoirs to enhance oil recovery or converted into valuable liquid fuels and petrochemicals. Furthermore, partnerships between oil companies and petrochemical industries have enabled the conversion of APG into feedstock for chemical production, minimising waste and fostering cross-sector collaboration. This approach aligns with circular economy principles by ensuring that byproducts are continuously repurposed, reducing reliance on virgin fossil fuels and lowering the industry's environmental footprint.

In Brazil, an agricultural network implements IS by converting waste into fertilisers, enhancing crop productivity, reducing landfill waste, and supporting local economies (Sahu, 2023). These examples highlight the diverse applications of IS across industries and regions, demonstrating its potential to improve sustainability and economic efficiency.

2.1.2 Examples of IS in SMEs

Industrial symbiosis among small and medium-sized enterprises (SMEs) is a growing area of interest, particularly in regions where resource optimisation and waste reduction are critical. This concept involves the collaboration of different industries to utilise each other's byproducts, thereby minimising waste and enhancing sustainability. Several examples worldwide illustrate how SMEs engage in industrial symbiosis to

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

achieve these goals. Below are some notable instances of industrial symbiosis among SMEs, highlighting their strategies and outcomes.

In **Muzaffarnagar, India**, a cluster of paper and sugar mills and other manufacturing SMEs engage in industrial symbiosis by exchanging byproducts. For instance, waste from sugar mills is used as a raw material in paper mills, reducing waste and improving resource efficiency(Chattopadhyay et al., 2016). The strong community ties among industry owners facilitate these exchanges, demonstrating the importance of social networks in enabling industrial symbiosis (Chattopadhyay et al., 2016).

Rusayl Industrial Estate, Oman. SMEs within the Rusayl Industrial Estate are exploring waste exchange opportunities. The focus is developing a waste management model that supports industrial symbiosis, aiming to conserve resources and reduce pollution while enhancing economic benefits (Al-Harrasi et al., 2017). The feasibility of these exchanges is assessed through economic analysis, ensuring that the symbiotic relationships are financially viable(Al-Harrasi et al., 2017).

Use of Material Flow Cost Accounting (MFCA). The MFCA method is employed to design industrial symbiosis among SMEs by analysing material, energy, and cost flows. This approach helps SMEs effectively evaluate their environmental efficiency and plan symbiotic exchanges (Astuti et al., 2018). MFCA has been used to assess and improve the performance of SME clusters, demonstrating its utility in facilitating industrial symbiosis (Astuti et al., 2018). While MFCA is not yet widely used among SMEs, its potential for cost savings and sustainability improvements makes it an attractive tool. Increased awareness, technological advancements, and policy support are key factors that can drive greater adoption in the SME sector.

While these examples highlight successful industrial symbiosis among SMEs, challenges remain, such as the need for robust regulatory frameworks and economic incentives to encourage participation. Additionally, integrating local resources and markets is crucial for the sustainability of these symbiotic systems (Ristola & Mirata, 2007). Developing industrial symbiosis models and platforms, as seen in these cases, provides valuable insights into overcoming these challenges and fostering sustainable industrial practices.

Industrial symbiosis is a fundamental component of the circular economy. It emphasises the collaborative and strategic use of resources to minimise waste, optimise energy efficiency, and promote long-term sustainability. By fostering inter-industry cooperation, IS transforms traditional production and waste management systems into interconnected, resource-efficient networks.

2.1.3 Examples of IS Identified Throughout Various EU-Funded Projects

Across Europe and beyond, numerous EU-funded initiatives have successfully demonstrated the effectiveness of industrial symbiosis, yielding significant environmental and economic benefits. These projects showcase how industries can

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

repurpose byproducts, share energy resources, and create closed-loop production cycles.

The following paragraphs highlight exemplary practices from Slovenia, Finland, Italy, and the United Kingdom, providing insights into their approaches, outcomes, and broader impacts. These case studies illustrate how targeted policy support, innovative technological integration, and cross-sectoral collaboration can drive the successful implementation of industrial symbiosis.

Donar. Slovenia: Sustainable Furniture Production: Donar exemplifies industrial symbiosis by using recycled polyethylene terephthalate (PET) and polyester (PES) felt, transforming waste into sustainable furniture. Their process reduces primary raw material usage by 15 tons annually while producing award-winning products such as NicoLess and ChatLoop chairs. Collaboration with recycling companies ensures a steady supply of raw materials, emphasising resource efficiency and environmental stewardship (European Circular Economy Stakeholder Platform, 2024).

AquafilSLO, Slovenia: Heat Reuse for Energy Efficiency. AquafilSLO demonstrates industrial symbiosis by repurposing surplus thermal energy from its synthetic fibre production processes. This energy is used to heat facilities like Vodno mesto Atlantis and HELLA Saturnus Slovenija, resulting in CO_2 emission reductions of approximately 3,500 tons annually. Partnerships with local organisations highlight sustainable energy-sharing models' scalability and economic feasibility (AquafilSLO, 2024).

City of Ljubljana, Slovenia: Recycling Invasive Plants. In an innovative approach, Ljubljana repurposes Japanese knotweed, an invasive plant, into recycled paper products. This initiative mitigates environmental impacts and fosters collaborations with local institutions, such as the Pulp and Paper Institute, creating sustainable alternatives to conventional paper (European Circular Economy Stakeholder Platform, 2024).

Kemi-Tornio Industrial Symbiosis Cluster, Finland. The Kemi-Tornio initiative integrates industries such as forestry, mining, and energy to repurpose industrial byproducts into bioenergy and materials like recovered metals. This regional approach creates new markets for secondary raw materials while reducing CO_2 emissions and generating an annual value of €200 million (Interreg Europe Policy Learning Platform, 2024).

LABIO Ltd.: Biowaste-to-Biogas, Finland. LABIO Ltd., Finland's largest biogas producer, converts municipal and industrial biowaste into biogas and compost. Using waste heat from composting processes enhances energy efficiency, while partnerships with public and private entities underscore the project's sustainability and economic viability (Interreg Europe Policy Learning Platform, 2024).

The Finnish Industrial Symbiosis System (FISS) facilitates symbioses by connecting regional actors through workshops and a SYNERGie® database. The initiative has engaged over 700 companies, created 2,500 synergy opportunities, and promoted resource efficiency and new business ventures (Interreg Europe Policy Learning Platform, 2024).

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Recycling Thermal Spray Waste for Ceramics. Italy. In Emilia-Romagna, overspray waste from zirconia coating processes is repurposed into ceramic frits and glazes. This initiative reduces ceramic manufacturers' raw material and energy costs, lowering production costs by up to 40%. Collaborative efforts highlight the transferability of such practices to other regions (Interreg Europe Policy Learning Platform, 2024).

International Synergies Limited (ISL), UK. ISL has pioneered industrial symbiosis globally through its National Industrial Symbiosis Programme (NISP®). Using the SYNERGie® platform, ISL enables resource matching, reduces carbon emissions, and supports net-zero strategies. Their projects have saved 42 million tonnes of CO_2 equivalent in England alone, showcasing the transformative potential of industrial symbiosis on a global scale (International Synergies Limited, 2024).

2.1.4 Examples Given by a Private Company's AI-Supported Value Chain Generator

VCG.AI tool has been instrumental in advancing circular economy initiatives across various regions and industries. Their case studies highlight their Value Chain Generator® practical applications in transforming waste into valuable resources and fostering sustainable business models (See vcg.ai).

Turning Food Bio-waste into Circular Business in North Macedonia. In North Macedonia, the agricultural and food processing sectors generate substantial amounts of organic biomass, much of which remains underutilised. VCG.AI collaborated with the Economic Chamber of Commerce North Macedonia (ECM) to identify key residual streams, such as grape pomace and tomato production waste. Through their analysis, VCG.AI proposed economically viable conversion processes to transform these residuals into high-value products like pectin, polyphenols, and lycopene, which are in demand in the pharmaceutical and cosmetics industries. This initiative promotes sustainable practices and opens new revenue streams for local businesses.

Developing Value Chains for Biorefineries in Six EU Regions. Leading organisations from six European regions partnered with VCG.AI to develop value chains for biorefineries. Utilising the Value Chain Generator®, the collaboration aimed to identify and establish sustainable value chains that convert biomass into valuable products. This project underscores the importance of regional cooperation and the role of digital tools in accelerating the transition to a circular bioeconomy.

Leading Regional Companies Towards Circularity: WFG Heilbronn, Germany. In Heilbronn, Germany, VCG.AI worked with the regional economic development agency, WFG Heilbronn, to guide local companies towards circular economy practices and carbon neutrality. By leveraging the Value Chain Generator®, they identified opportunities for businesses to implement circular strategies, thereby enhancing sustainability and competitiveness in the region.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

2.2 Key Learnings and Recommendations

Effective industrial symbiosis (IS) implementation hinges on robust collaborative frameworks, technological integration, and supportive policies. Partnerships among industries, governments, and academic institutions are essential for optimising resource utilisation and fostering innovation. Digital tools like SYNERGie® and tailored workshops enhance resource matching and monitoring, facilitating scalability and adaptability across diverse industries and regions.

Government incentives and funding play a crucial role in supporting IS initiatives. Projects like LABIO Ltd. and the Finnish Industrial Symbiosis System (FISS) underscore the importance of public-private partnerships in fostering sustainable industrial ecosystems. These collaborations demonstrate how tailored approaches can be successfully adapted to different sectors and regions, maximising their impact.

The highlighted best practices illustrate IS's transformative potential in advancing the circular economy. By reducing waste, conserving resources, and fostering collaboration, these initiatives establish benchmarks for sustainability and industrial innovation. The lessons learned from these case studies provide a roadmap for stakeholders to implement effective IS strategies in their respective contexts.

However, implementing IS successfully requires overcoming financial, technological, regulatory, and social barriers. The adoption of digital technologies can significantly enhance IS by facilitating resource exchange and decision-making. Continued policy support, industrial cooperation, and technological innovation will be critical in realising IS's full potential on a global scale.

In summary, integrating collaborative frameworks, technological tools, and supportive policies is vital for successfully implementing industrial symbiosis. By learning from existing best practices and addressing current challenges, stakeholders can effectively advance towards a more sustainable and resource-efficient industrial future.

3 About Digital Technology in Industrial Symbiosis

Digital technology enhances IS by facilitating the identification and optimisation of symbiotic opportunities (Makropoulos et al., 2024), enabling real-time information exchange (Akrivou et al., n.d.), and providing support for small and medium enterprises (SMEs) through platforms like e-Symbiosis (Cecelja et al., 2015). It also fosters the development of Digital Industrial Symbiosis Ecosystems (DISE) to improve user adoption (Kosmol & Leyh, 2021) and leverages Information and Communication Technology (ICT) to create more resource-efficient production systems (Grant et al., 2010).

While digital technologies significantly enhance industrial symbiosis, data availability and system integration challenges persist. Overcoming these barriers requires continued innovation and collaboration among industries, technology developers,

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

and policymakers. The potential for digital tools to transform industrial symbiosis is vast, but realising this potential necessitates addressing these challenges and fostering a culture of cooperation and openness to new technologies.

Digital technology significantly enhances industrial symbiosis by facilitating resource exchange, optimising waste management, and promoting sustainability across various industries. These advancements are evident in several key applications:

3.1 Enhancing Industrial Symbiosis Through Digital Tools

3.1.1 Matchmaking Tools

Advanced digital platforms are designed to **identify and quantify symbiotic potential between industries**. These tools propose profitable material exchanges by analysing data on waste stream volumes, material compositions, and market values. They employ algorithms to assess economic and environmental benefits, uncovering potential connections between waste producers and resource consumers. For instance, a state-of-the-art digital tool introduced by Makropoulos et al. (2024) pinpoints and quantifies symbiotic possibilities between industries with liquid waste streams, emphasising the most lucrative inter-industry connections.

3.1.2 Online Platforms

Digital platforms facilitate industrial symbiosis by **connecting industries across different regions**. These platforms use intelligent systems to recommend synergies, enhancing the decision-making process. They also address challenges such as data availability and the reluctance to use repurposed materials. Silva et al. (2022) highlight the role of such platforms in promoting sustainability and economic efficiency.

The SymbioSyS tool, presented by Álvarez and Ruiz-Puente (2017), uses ICT-web systems to promote resource sustainability and facilitate networking among companies. It supports synergy detection and provides feasibility studies, enhancing the visualisation and mapping of industrial symbiosis opportunities.

3.1.3 Intelligent Management Systems

Platforms that use existing industrial symbiosis knowledge models and analyse potential networks are crucial for **discovering new synergies and optimising material exchanges**. Chatzidimitriou et al. (2021) discuss intelligent management platforms that support identifying and implementing symbiotic relationships.

3.1.4 Ontology Engineering

The e-Symbiosis project employs ontology engineering to model industrial symbiosis flows and develop matching services. This approach combines expert knowledge with participant data to create **systematic solutions for industrial symbiosis networks**, particularly benefiting small and medium enterprises. Cecelja et al. (2015) detail how this method enhances the discovery and implementation of symbiotic opportunities.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

3.1.5 Industry 4.0 Digital Platforms

Industry 4.0 digital platforms support environmental sustainability through industrial symbiosis by **facilitating value co-creation and resource optimisation**, aligning with sustainable business models. Aquilani et al. (2020) explore how these platforms enable industries to collaborate effectively, enhancing resource efficiency.

3.1.6 Blockchain Technology

Blockchain is explored as an enabling technology of Industry 4.0 to disseminate industrial symbiosis practices. The literature discusses a preliminary two-step approach, highlighting the potential of blockchain to **facilitate secure and transparent transactions in industrial symbiosis networks**.

3.1.7 Digital Twins

A digital twin is a virtual representation of a physical object, system, or process that is continuously updated with real-time data to mirror its real-world counterpart. This dynamic model allows for simulation, analysis, and control, **providing insights into performance and potential issues before they occur**.

Leveraging digital twins supports industrial symbiosis networks by providing a framework for user perspective analysis before developing digital twins-based supply chain collaboration. This approach promotes the design of digital twins from the user perspective, enhancing collaboration and efficiency in industrial symbiosis networks.

Concrete Applications:

- Manufacturing: In production lines, digital twins monitor equipment health, predict failures, and optimise operations, reducing downtime and maintenance costs.
- Urban Planning: Cities develop digital twins of urban environments to simulate traffic flow, energy consumption, and infrastructure development, aiding in efficient planning and resource management.
- Retail: Retailers like Walmart use digital twins to optimise store layouts and enhance customer experiences by simulating different configurations before implementing physical changes.
- Healthcare: Digital twins of medical devices or even human organs can assist in personalised treatment planning, predictive diagnostics, and improved patient outcomes.

3.2 Digital Innovations Driving Industrial Symbiosis: Practical Case Studies

Digital facilitate IS by connecting businesses, optimising waste exchanges, and improving decision-making through data analytics (Álvarez & Ruiz-Puente, 2017; Silva et al., 2022), as well as facilitating the exchange of resources, such as materials, energy, and information, between industries to promote sustainability and economic efficiency. These tools enhance transparency, efficiency, and traceability within industrial ecosystems. Below is an overview of several notable platforms:

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

3.2.1 SymbioSyS Platform

Developed by the University of Cantabria, the SymbioSyS tool aids in detecting industrial symbiosis synergies among companies. It enables the identification and visualisation of potential collaborations based on waste exchanges and resource sharing. The platform supports data collection, resource mapping, and the identification of synergies to promote sustainable circular economy practices. The platform is available at https://symbiosys.unican.es/.

3.2.2 FLOW2

FLOOW2 is an online platform that enables businesses to collaborate by exchanging residual flows and materials. By facilitating the sharing of underutilised assets, companies can acquire materials at lower costs without consuming new raw materials, thereby promoting industrial symbiosis and contributing to a circular economy. The platform is available at https://www.floow2.com/en.html.

3.2.3 InduSym

InduSym supports area management by facilitating circular energy, water, and materials connections between regional companies. By collecting data on residual streams in industrial areas, InduSym identifies opportunities for collaboration and advises and supports area-oriented projects to advance the circular economy. The platform is available at https://www.indusym.nl/.

3.2.4 SHAREBOX

SHAREBOX is an online platform designed to enable next-generation industrial symbiosis. It provides a secure environment for companies to manage shared resources, including materials, energy, and services. The platform offers real-time information and decision-making tools to facilitate the flexible management and optimisation of industry resource sharing. The platform is available at https://sharebox-project.eu/. (see also aspire2050.eu)

3.2.5 e-Symbiosis

The e-Symbiosis platform is a web-based tool that enables users to participate in industrial symbiosis activities to improve resource efficiency and sustainability. It facilitates the exchange of underutilised resources among companies, contributing to the realisation of a circular economy. The platform is available at the e-Symbiosis Platform. (see also researchgate.net). It leverages technology to support industrial symbiosis among SMEs by using ontology engineering to model symbiotic flows. This systematises the development of matching services, enabling SMEs to discover and implement innovative symbiotic solutions (Cecelja et al., 2015). The platform has been validated with real-life data, showcasing its potential to enhance industrial symbiosis networks(Cecelja et al., 2015).

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

3.2.6 Symbiosis Platform (ENEA)

This is the first industrial symbiosis platform in Italy. It connects over 80 SMEs, facilitating nearly 690 potential resource matches. This platform helps SMEs identify opportunities to substitute resources with waste products and share waste management services (Cutaia et al., 2015). The initiative underscores the role of regulatory frameworks and stakeholder participation in successful industrial symbiosis implementation (Cutaia et al., 2015).

Developed by ENEA, the Italian National Agency for New Technologies, Energy and Sustainable Economic Development, the Symbiosis Platform aims to connect supply and demand for resources, activating transfers between companies. It features an expert structure to identify potential industrial symbiosis solutions, a comprehensive information system describing available resources, and a network that connects various stakeholders. The platform's goals include improving waste valorisation, facilitating territorial management of industrial waste, and promoting industrial symbiotic schemes. The platform is available at http://www.industrialsymbiosis.it/piattaforma. (see also interregeurope.eu)

3.2.7 E-Simbioza

E-Simbioza is an initiative aimed at leading the way to a circular economy through industrial symbiosis in Slovenia. It provides insights into the level of understanding and implementation of industrial symbiosis in the region, promoting the exchange of underutilised resources among companies to enhance sustainability. The platform is available at http://esimbioza.fis.unm.si/. (see also researchgate.net)

3.2.8 Value Chain Generator (VCG.AI)

Anteja ECG is an international consulting firm headquartered in Ljubljana, Slovenia, with additional offices in Nairobi, Kenya; Stuttgart, Germany; and Boston, USA. Established in 2005, the company specialises in sustainable development, focusing on designing and implementing innovation strategies and circular business models, among others, optimising value chains and maximising resource efficiency. Anteja has developed several digital solutions to promote sustainability and transparency in value chains.

The Value Chain Generator (VCG.AI) platform uses artificial intelligence and machine learning to connect companies across sectors and countries into circular and resilient value chains. Another solution, phy2app, is a digital transparency and traceability tool that helps East African agribusinesses establish direct trade relationships with regional and global buyers. Additionally, INATrace is an open-source traceability system based on blockchain technology that promotes trust and security between trading partners and enhances supply chain efficiency. The digital tools are available at https://anteja-ecg.com/.

The following table categorises various industrial symbiosis initiatives based on the digital tools and technologies they employ:

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Initiative	Matchmaking Tools	Online Platforms	Intelligent Management Systems	Ontology Engineering	Industry 4.0 Digital Platforms	Blockchain Technology	Digital Twins
SymbioSyS Platform	✓	✓	✓	✓	✗	✗	✗
FLOOW2	✓	✓	✗	✗	✗	✗	✗
InduSym	✓	✓	✓	✗	✗	✗	✗
SHAREBOX	✓	✓	✓	✗	✗	✗	✗
e-Symbiosis	✓	✓	✓	✓	✗	✗	✗
Symbiosis Platform (ENEA)	✓	✓	✓	✗	✗	✗	✗
E-Simbioza	✓	✓	✗	✗	✗	✗	✗
Value Chain Generator (VCG.AI)	✓	✓	✓	✗	✓	✓	✗

3.3 Obstacles to Implementation

While the platforms described in the previous section have played significant roles in industrial symbiosis, some have ceased operations due to governance challenges, funding constraints, and limited user adoption.

Key challenges to implementing digital IS tools include governance and policy issues, collaboration challenges due to lack of trust, economic and market uncertainties affecting IS profitability, technical and logistical barriers related to integrating digital solutions into existing processes, and social and environmental concerns, including regulatory compliance and societal acceptance (Michelini & Mattelin-Pierrard, 2023).

Governance and policy issues present a significant challenge for digital industrial symbiosis, as inconsistent regulations and a lack of clear governmental support can create uncertainty for businesses looking to adopt IS practices. Many industries struggle with navigating complex environmental policies that may vary across regions, making it challenging to establish standardised approaches for resource exchange and waste reuse.

Collaboration challenges, particularly the lack of trust among industrial partners, further hinder IS adoption. Many businesses are reluctant to share proprietary data about waste streams and byproducts, fearing potential risks to their competitive advantage. Establishing transparent communication channels and secure data-sharing frameworks can help mitigate these concerns and foster stronger collaborations among industries.

Economic and market uncertainties play a critical role in IS implementation, as industries may hesitate to invest in new digital tools without clear financial incentives or proven profitability. The fluctuating costs of raw materials and waste management services can impact the viability of IS exchanges, making it essential to develop robust business models that highlight long-term economic benefits.

Technical and logistical barriers are also significant, as integrating digital solutions into existing industrial processes often requires substantial infrastructure upgrades. Many businesses, particularly SMEs, lack the technical expertise or financial resources to

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

implement advanced digital matchmaking and monitoring tools effectively. Addressing these gaps through targeted support programs and training initiatives can accelerate digital IS adoption.

Social and environmental concerns must also be considered, including regulatory compliance and societal acceptance. Some communities may resist IS initiatives due to perceived environmental risks, such as increased pollution or waste repurposing practices that could affect public health. Strengthening stakeholder engagement and ensuring transparent decision-making processes can help build public trust and promote wider acceptance of industrial symbiosis initiatives.

To conclude, industrial symbiosis presents a promising pathway for sustainable industrial development by integrating circular economy principles. However, its successful implementation requires overcoming financial, technological, regulatory, and social barriers. The adoption of digital technologies can significantly enhance IS by facilitating resource exchange and decision-making. Continued policy support, industrial cooperation, and technological innovation will be critical in realising the full potential of IS on a global scale.

3.4 Key Learnings and Recommendations

Integrating digital technologies into industrial symbiosis (IS) has demonstrated significant potential in enhancing resource efficiency and sustainability across various industries. Advanced digital platforms, such as matchmaking tools, analyse data on waste streams and material compositions to identify profitable exchanges between industries. For example, tools Makropoulos et al. (2024) developed a focus on liquid waste streams, pinpointing lucrative inter-industry connections. Online platforms further facilitate IS by connecting industries across regions, utilising intelligent systems to recommend synergies and address challenges like data availability and reluctance to use repurposed materials. The SymbioSyS tool, as presented by Álvarez and Ruiz-Puente (2017), exemplifies this by promoting resource sustainability and networking among companies through ICT-web systems.

Intelligent management systems leverage existing IS knowledge to model and analyse potential networks, which is crucial for discovering new synergies and optimising material exchanges. Chatzidimitriou et al. (2021) discuss platforms that support the identification and implementation of symbiotic relationships. As employed by the e-Symbiosis project, ontology engineering models IS flows and develops matching services, combining expert knowledge with participant data to create systematic solutions, particularly benefiting small and medium enterprises (Cecelja et al., 2015).

Industry 4.0 digital platforms support environmental sustainability through IS by facilitating value co-creation and resource optimisation, aligning with sustainable business models. Aquilani et al. (2020) explore how these platforms enable effective collaboration, enhancing resource efficiency. Blockchain technology is also being explored as an enabling technology of Industry 4.0 to disseminate IS practices, offering secure and transparent transactions within IS networks. Additionally, digital twins—

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

virtual representations of physical systems updated with real-time data—provide insights into performance and potential issues before they occur. Leveraging digital twins supports IS networks by offering a framework for user perspective analysis before developing digital twin-based supply chain collaborations, thereby enhancing efficiency and collaboration.

Practical applications of these digital innovations are evident in various sectors. In manufacturing, digital twins monitor equipment health, predict failures, and optimise operations, reducing downtime and maintenance costs. Urban planning utilises digital twins to simulate traffic flow, energy consumption, and infrastructure development, aiding in efficient resource management. Retailers like Walmart employ digital twins to optimise store layouts and enhance customer experiences by simulating different configurations before implementing physical changes. In healthcare, digital twins of medical devices or even human organs assist in personalised treatment planning, predictive diagnostics, and improved patient outcomes.

Despite these advancements, several challenges hinder the widespread adoption of digital IS tools. Governance and policy issues, including inconsistent regulations and a lack of clear governmental support, create uncertainty for businesses considering IS practices (Michelini & Mattelin-Pierrard, 2023). Collaboration challenges arise from a lack of trust among industrial partners, as businesses may be reluctant to share proprietary data about waste streams and byproducts, fearing potential risks to their competitive advantage. Economic and market uncertainties also play a critical role, as industries may hesitate to invest in new digital tools without clear financial incentives or proven profitability. Technical and logistical barriers are significant, as integrating digital solutions into existing industrial processes often requires substantial infrastructure upgrades. Many businesses, particularly SMEs, lack the technical expertise or financial resources to implement advanced digital matchmaking and monitoring tools effectively. Social and environmental concerns must also be considered, including regulatory compliance and societal acceptance. Some communities may resist IS initiatives due to perceived environmental risks, such as increased pollution or waste repurposing practices that could affect public health.

To overcome these challenges, it is essential to establish standardised regulations, provide financial incentives, and develop robust digital infrastructure. Strengthening stakeholder engagement and ensuring transparent decision-making processes can help build public trust and promote wider acceptance of IS initiatives. Continued policy support, industrial cooperation, and technological innovation will be critical in realising the full potential of IS on a global scale.

4 References

A comprehensive review of industrial symbiosis. (2019). https://doi.org/10.1016/j.jclepro.2019.119113

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

A Review of Industrial Symbiosis in Influencing Green Manufacturing. (2022). https://doi.org/10.1109/icmimt55556.2022.9845273

Akrivou, C., Łękawska-Andrinopoulou, L., Manousiadis, C., Tsimiklis, G., Oikonomopoulou, V., Papadaki, S., Krokida, M., & Amditis, A. (n.d.). Industrial symbiosis marketplace concept for waste valorisation pathways. *E3S Web of Conferences*. https://doi.org/10.1051/e3sconf/202234911005

Albu, A. (2017). *Industrial Symbiosis: An Innovative Tool for Promoting Green Growth* (pp. 1–29). Springer International Publishing. https://doi.org/10.1007/978-3-319-45081-0_1

Al-Harrasi, A., Abu Qasida, A., Al-Qassabi, H., & Shamsuzzoha, A. (2017). *Study of the Possibility to Industrial Symbiosis within Selected Omani SMEs*. *2017*. https://journals.library.ryerson.ca/index.php/ictea/article/view/57

Álvarez, R., & Ruiz-Puente, C. (2017). Development of the Tool SymbioSyS to Support the Transition Towards a Circular Economy Based on Industrial Symbiosis Strategies. *Waste and Biomass Valorization*, *8*(5), 1521–1530. https://doi.org/10.1007/S12649-016-9748-1

AquafilSLO. (2024). *Example of a Good Practice in Slovenia*.

Aquilani, B., Piccarozzi, M., Silvestri, C., & Gatti, C. (2020). *Achieving Environmental Sustainability Through Industry 4.0 Tools: The Case of the "Symbiosis" Digital Platform* (pp. 513–539). IGI Global. https://doi.org/10.4018/978-1-7998-1419-1.CH003

Astuti, R. S. D., & Astuti, A. D. (2018). *Preliminary Design of Industrial Symbiosis of Smes Using Material Flow Cost Accounting (MFCA) Method*. *31*, 04008. https://doi.org/10.1051/E3SCONF/20183104008

Barile, S., Bassano, C., D'Amore, R., Piciocchi, P., Saviano, M., & Vito, P. (2021). Insights of Digital Transformation Processes in Industrial Symbiosis from the Viable Systems Approach (vSa). *Sustainability*, *13*(17), 9696. https://doi.org/10.3390/SU13179696

Bauchat Grant, G., Seager, T. P., Massard, G., & Nies, L. (2010). Information and Communication Technology for Industrial Symbiosis. *Journal of Industrial Ecology*, *14*(5), 740–753. https://doi.org/10.1111/J.1530-9290.2010.00273.X

Boquera, P., & Marcos, Á. (2023). *Industrial Symbiosis Guideline*. AIDIMME. Retrieved from https://iproduce-project.eu/industrial-symbiosis-guideline/

Castellet-Viciano, L., Hernández-Chover, V., Bellver-Domingo, Á., & Hernández-Sancho, F. (2022). Industrial Symbiosis: A Mechanism to Guarantee the Implementation of Circular Economy Practices. *Sustainability*, *14*(23), 15872. https://doi.org/10.3390/su142315872

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Cecelja, F., Raafat, T., Trokanas, N., Innes, S., Smith, M., Yang, A., Zorgios, Y., Korkofygas, A., & Kokossis, A. C. (2015). *e-Symbiosis: technology-enabled support for industrial symbiosis targeting SMEs and innovation*. https://epubs.surrey.ac.uk/804145/

Chatterjee, A., Brehm, C., & Layton, A. (2021). Evaluating benefits of ecologically-inspired nested architectures for industrial symbiosis. *Resources Conservation and Recycling*, *167*, 105423. https://doi.org/10.1016/J.RESCONREC.2021.105423

Chattopadhyay, S., Kumar, N., Fine, C. H., & Olivetti, E. (2016). *Industrial Symbiosis Among Small and Medium Scale Enterprises: Case of Muzaffarnagar, India* (pp. 173–177). Springer, Cham. https://doi.org/10.1007/978-3-319-48768-7_25

Chatzidimitriou, T., Gentimis, T., Michalopoulos, C., Kokossis, A. C., & Dalamagas, T. (2021). *Intelligent Management Platform for Material Exchange Optimization and Industrial Symbiosis* (Vol. 50, pp. 761–766). Elsevier. https://doi.org/10.1016/B978-0-323-88506-5.50119-4

Cui, H., & Liu, C. (2017). *Applying industrial symbiosis to chemical industry: A literature review*. *1864*, 020090. https://doi.org/10.1063/1.4992907

Cutaia, L., Luciano, A., Barberio, G., Sbaffoni, S., Mancuso, E., Scagliarino, C., & La Monica, M. (2015). The experience of the first industrial symbiosis platform in Italy. *Environmental Engineering and Management Journal*, *14*(7), 1521–1533. https://doi.org/10.30638/EEMJ.2015.164

Dolgova, O., & Nikitaeva, A. (2023). Industrial Symbiosis as a Way to Solve Environmental Problems in Regions (on the Example of the Russian Black Sea Area). *BIO Web of Conferences*, *63*, 03007. https://doi.org/10.1051/bioconf/20236303007

Duan, Y. (2005). Symbiosis Model: the Strategic Choice of SMEs. *Journal of Yunnan University of Finance and Economics*.

European Circular Economy Stakeholder Platform. (2024). *CEstakeholderEU - European Circular Economy Stakeholder Platform*.

Evans, S., Benedetti, M., & Holgado Granados, M. (2017). *Library of Industrial Symbiosis case studies and linked exchanges*. https://doi.org/10.17863/CAM.12608

Ferreira, I., Godina, R., & Carvalho, H. (2020). Waste Valorization through Additive Manufacturing in an Industrial Symbiosis Setting. *Sustainability*, *13*(1), 234. https://doi.org/10.3390/SU13010234

Golev, A. (2012). *Application of Industrial Ecology Principles for Enhanced Resource Efficiency in Heavy Industrial Areas*. https://espace.library.uq.edu.au/view/UQ:306125

Haq, H. M. K. U., Välisuo, P., & Niemi, S. (2021). Modelling Sustainable Industrial Symbiosis. *Energies*, *14*(4), 1172. https://doi.org/10.3390/EN14041172

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Hariyani, D., Hariyani, P., Mishra, S., & Sharma, M. K. (2024). Leveraging digital technologies for advancing circular economy practices and enhancing life cycle analysis: A systematic literature review. *Waste Management Bulletin*. https://doi.org/10.1016/j.wmb.2024.06.007

Industrial Ecology. (2022). 167–190. https://doi.org/10.1002/9781119721079.ch6

Industrial Symbiosis: Novel Supply Networks for the Circular Economy (pp. 29–48). (2022). Emerald Publishing Limited eBooks. https://doi.org/10.1108/978-1-83982-544-620221002

International Synergies Limited. (2024). *International Synergies Limited (ISL)*.

Interreg Europe Policy Learning Platform. (2024). *Interreg Europe Policy Learning Platform*.

Isenmann, R. (2009). *Bringing together Environmental Informatics and Industrial Ecology − The role of ICT in industrial symbiosis projects*. 213–216. https://dl.gi.de/handle/20.500.12116/26314

Isenmann, R., & Chernykh, K. (2009). *The role of ICT in industrial symbiosis projects – Environmental ICT applications for eco-industrial development*. 223–234. https://dl.gi.de/handle/20.500.12116/26316

Islam, K., Rahman, Md. F., & Islam, K. N. (2016). Industrial Symbiosis: A Review on Uncovering Approaches, Opportunities, Barriers and Policies. *Social Science Research Network*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2767107

Kosmol, L., & Leyh, C. (2021). *A Conceptual Design for Digital Industrial Symbiosis Ecosystems* (pp. 362–374). Springer, Cham. https://doi.org/10.1007/978-3-030-82405-1_35

Kosmol, L., & Otto, L. (2020). Implementation Barriers of Industrial Symbiosis: A Systematic Review. *Hawaii International Conference on System Sciences*, 1–9. https://doi.org/10.24251/HICSS.2020.741

Kowalski, Z., Kulczycka, J., Makara, A., Mondello, G., & Salomone, R. (2023). Industrial Symbiosis for Sustainable Management of Meat Waste: The Case of Śmiłowo Eco-Industrial Park, Poland. *International Journal of Environmental Research and Public Health*, *20*(6), 5162. https://doi.org/10.3390/ijerph20065162

Kumar, U. (2022). *Industrial Symbiosis: An Exploration of the Potential of Sustainable Waste Management in the UAE*. https://doi.org/10.18502/aqf.0189

Makropoulos, C., Kritikos, N.-A., & Pantazis, C. (2024). Matchmaking for industrial symbiosis: a digital tool for the identification, quantification and optimisation of symbiotic potential in industrial ecosystems. *Frontiers in Chemical Engineering*, 6. https://doi.org/10.3389/fceng.2024.1363888

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Michelini, L., & Mattelin-Pierrard, C. (2023). *Exploring Industrial Symbiosis: an analysis of current critical issues to identify technologies and digital opportunities*. https://doi.org/10.26481/mup.2302.14

Mirata, M., Lindfors, A., & Kambanou, M. L. (2024). A business value framework for industrial symbiosis. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.13545

Mironova, D. Yu., Baranov, I. V., Kapustin, D. S., Kozhukhov, Y. V., & Svinkin, I. A. (2023). Application of industrial symbiosis concept to oil and gas sector on example of associated petroleum gas processing. *Oil and Gas Business*, *21*(3), 220–231. https://doi.org/10.17122/ngdelo-2023-3-220-231

Models of industrial symbiosis formation. (2023). *Upravlenie*, *11*(1), 51–63. https://doi.org/10.26425/2309-3633-2023-11-1-51-63

Neves, A., Godina, R., Azevedo, S. G., & Matias, J. C. O. (2018). *Environmental, Economic, and Social Impact of Industrial Symbiosis: Methods and Indicators Review* (pp. 157–165). Springer, Cham. https://doi.org/10.1007/978-3-030-14973-4_15

Nikitaeva, A. (2023). Digital Technologies and Circular Value Chains for Sustainable Development. *Lecture Notes in Information Systems and Organisation*, 169–179. https://doi.org/10.1007/978-3-031-30351-7_14

Nyakudya, P., Madushele, N., & Madyira, D. M. (2022). *A Review of Industrial Symbiosis in Influencing Green Manufacturing*. 80–84. https://doi.org/10.1109/ICMIMT55556.2022.9845273

Nyakudya, P., Madushele, N., & Madyira, D. M. (2023). *Industrial Symbiosis: A Panacea to Industrial Waste Management Challenges in Harare*. 238–243. https://doi.org/10.1109/icmimt59138.2023.10201222

Patricio, J., Kalmykova, Y., Rosado, L., Cohen, J., Westin, A., & Gil, J. (2022). Method for identifying industrial symbiosis opportunities. *Resources Conservation and Recycling*, *185*, 106437. https://doi.org/10.1016/j.resconrec.2022.106437

Perillo, G. (2024). Digital and Circular Economy Models. *Journal of Civil Engineering and Environmental Sciences*, *10*(2), 061–062. https://doi.org/10.17352/2455-488x.000085

Petrova, V. (2022). <i>Industrial symbiosis in raw material sector as an overarching solution in circular economy, 3(3), 61–65. https://doi.org/10.58903/c16182120

Rahman, Md. F., Islam, K., & Islam, K. N. (2016). *Industrial Symbiosis: A Review on Uncovering Approaches, Opportunities, Barriers and Policies*. *2*(1), 011–019. https://doi.org/10.17352/2455-488X.000009

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Ristola, P., & Mirata, M. (2007). Industrial symbiosis for more sustainable, localised industrial systems. *Progress in Industrial Ecology, An International Journal*, *4*, 184–205. https://doi.org/10.1504/PIE.2007.015186

Sahu, R. K. (2023). Industrial Symbiosis: Expanding Waste Reuse in a Brazilian Network of Agricultural Companies. *Sustainability and Climate Change*, *16*(1), 36–47. https://doi.org/10.1089/scc.2022.0099

Silva, M., Carvalho, T., Gehrke Castagna, A., do Rocio Strauhs, F., & Piekarski, C. M. (2022). The role of online platforms to enable the process of industrial symbiosis: An analysis of tools available in the market. *Cleaner Production Letters*, *3*, 100021. https://doi.org/10.1016/j.clpl.2022.100021

The concept of industrial symbiosis: experience of application in various countries and prospects for implementation in Russia on the example of the Pskov region. (2022). *Naučnyj Žurnal NIU ITMO*. https://doi.org/10.17586/2310-1172-2022-16-2-129-141

Ulusoy, K., Doğan-Sağlamtimur, N., Çiner, F., Sternik, A., & Sekula, P. (2024). Industrial Symbiosis Practices: A Case Study of Türkiye and Denmark. *Environmental Research & Technology*. https://doi.org/10.35208/ert.1271679

Vladimirova, D., & Miller, K. (2020). *Enablers and barriers for industrial symbiosis : Lessons learnt from twenty-five case studies* (pp. 305–314). Routledge. https://doi.org/10.4324/9780429346347-33

Weenen, H. (1999). *Design for sustainable development : practical examples of SMEs*. European Foundation for the Improvement of Living and Working Conditions, Office for Official Publications of European Communities. https://ci.nii.ac.jp/ncid/BA40777083

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

PART II: QUANTITATIVE ANALYSIS – SURVEY OF COMPANIES ACCROSS 5 COUNTRIES

1 Introduction

Industrial Symbiosis (IS) is widely recognized as a key strategy in transitioning toward a circular economy. It involves the collaborative exchange of resources, energy, information, and logistics between organizations with the goal of reducing waste, improving resource efficiency, and generating mutual economic and environmental benefits (Chertow, 2007; Paquin & Howard-Grenville, 2013). By creating networks of interconnected companies that reuse each other's by-products and underutilized resources, IS facilitates a shift from linear production models toward more sustainable and regenerative systems.

In recent years, the integration of digital technologies—such as online platforms, artificial intelligence (AI), Internet of Things (IoT), and blockchain—has emerged as a powerful enabler of IS. These technologies support the identification of potential symbiotic partners, the real-time tracking of material flows, enhanced data transparency, and the automation of contractual and compliance processes (Yazan et al., 2021; Makropoulos et al., 2024). For example, digital platforms can match companies with complementary waste and resource profiles, while blockchain can ensure traceability and trust in exchanges, especially in complex supply chains.

This report presents the results of a quantitative survey conducted among companies in five European countries (Italy, Latvia, Norway, Poland, and Slovenia), aimed at assessing their awareness, readiness, and interest in IS and digital tools that support its implementation. The analysis is contextualized through the lens of theoretical insights from the Digital Industrial Symbiosis: Literature Review (2025), which synthesizes recent advancements in IS research, digital transformation, and sustainability transitions. It builds upon a growing body of literature that calls for cross-sectoral collaboration, digital innovation, and supportive policy environments to unlock the full potential of IS in Europe and beyond (Bocken et al., 2022; Patricio et al., 2022; Michelini & Mattelin-Pierrard, 2023).

2 Objectives of the Analysis

The main objectives of the analysis were to assess companies' awareness and readiness for IS, their interest in digital tools, and to identify perceived benefits, challenges and barriers. The report further evaluates the influence of digital skills, practical experience, institutional factors and collaboration intensity on company behavior regarding IS.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

3 Methodology

This qualitative research is based on a survey questionnaire developed within the project framework. The data was collected online using the 1KA online surveying tool between December 17, 2024, and March 19, 2025. The analysis is based on a structured questionnaire distributed to companies in Italy, Latvia, Norway, Poland, and Slovenia. It included questions about company characteristics, awareness and readiness for IS, use of digital tools, practical experiences, collaboration practices, and barriers to implementation. Data were processed using descriptive statistics, Spearman correlation, Kruskal-Wallis's test, and chi-square test.

The sample consists of 78 valid responses, representing a diverse range of industry sectors. Traditional industries are well represented, with 19% of respondents from manufacturing, 21% from the agri-food sector, and 22% from technology. Notably, 38% selected "Other," indicating a broad mix of sectors including business consulting, public administration, financial services, research and development, biotechnology, waste management, construction, and education. This suggests that industrial symbiosis involves not only core production sectors but also a wide range of supporting and knowledge-based industries.

From the perspective of organizational size, the sample is predominantly composed of smaller entities. Micro-enterprises (1–9 employees) make up the largest group, accounting for 44% of respondents, followed by small enterprises (10–49 employees) at 28%. Medium-sized organizations (50–249 employees) represent 18%, while large organizations (250+ employees) are the least represented, at 10%. This indicates that the sample is largely oriented toward micro and small organizations.

From the perspective of organizational headquarters location, the sample includes organizations from five main countries, with the majority based in Slovenia (29% when including the one "Other" response listed as Austria but referring to a Slovenian organization). This is followed by Italy (22%), Latvia (21%), and Poland (21%), while Norway accounts for 8% of the sample. Overall, the organizations are evenly distributed across these countries, with a slight predominance of Slovenian-based entities.

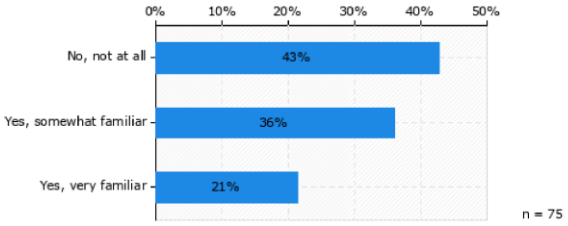
4 Results and Interpretation

4.1 Awareness and Familiarity with Industrial Symbiosis (IS)

43% of respondents reported having no awareness of the concept of industrial symbiosis (IS), while 36% were somewhat familiar and only 21% reported being very familiar. On average, awareness scored 1.8 out of 3 (SD = 0.8), indicating limited familiarity across the sample.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Figure 1: Knowledge about the concept of industrial symbiosis



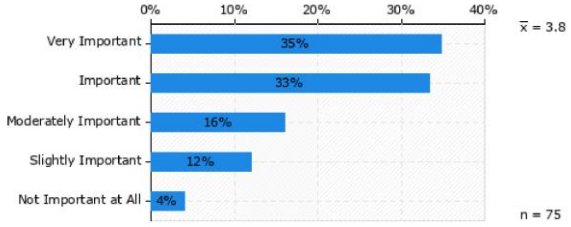
When asked about digital industrial symbiosis—where ICT is used to identify resource-sharing opportunities, only 20% of respondents were familiar with examples related to their own organization, while 36% reported no familiarity with any examples at all. The average score was 2.0 out of 5 (SD = 1.0), suggesting that digital industrial symbiosis is still a relatively new or unknown concept to many.

Figure 2: Familiarity with examples of digital industrial symbiosis

4.2 Perceived Importance of Sustainability

Sustainability and resource efficiency are seen as crucial to competitiveness and profitability by most surveyed organizations. A combined 68% rated these factors as "important" or "very important", with an average rating of 3.8 out of 5 (SD = 1.2). This reflects strong general support for sustainable business practices.

Figure 3: Importance of sustainability and resource efficiency



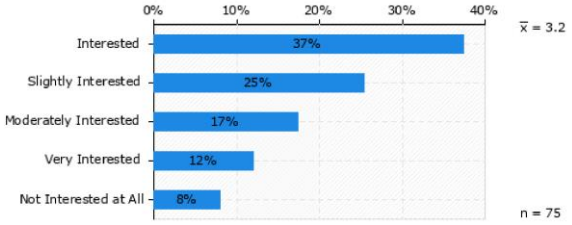
4.3 Interest in Learning and Participation

Despite varying levels of familiarity, there is considerable interest in learning more about industrial symbiosis. Nearly half of the respondents (49%) said they were

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

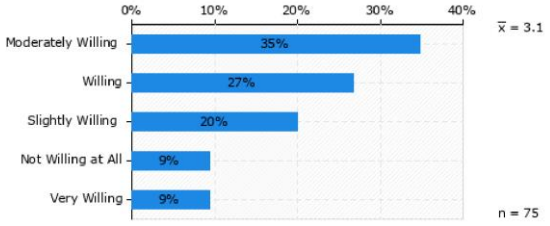
interested or very interested in how sharing resources could benefit their business (avg. 3.2/5).

Figure 4: Interest in learning more about sharing resources



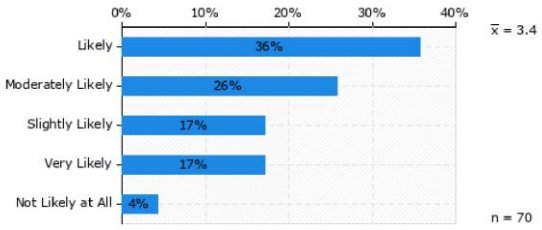
Similarly, 62% expressed moderate to high willingness to participate in digital IS initiatives, with an average score of 3.1 (SD = 1.1).

Figure 5: Willingness to participate in initiatives for digital industrial symbiosis



When asked about the likelihood of considering resource-sharing if it would reduce costs or create value, 53% responded positively (likely or very likely), with an average of 3.4 out of 5 (SD = 1.1).

Figure 6: Likelihood of Considering Resource Sharing or Reuse

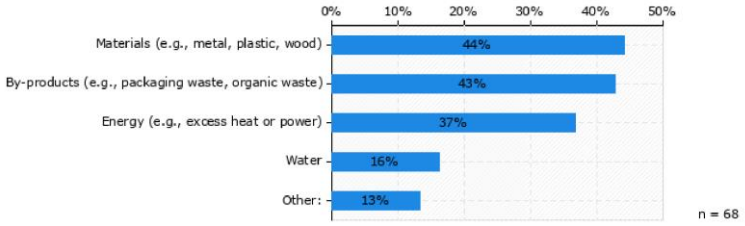


4.4 Resources and Waste Materials

The most common types of waste or leftover resources organizations deal with include materials such as metal, plastic, or wood (44%), by-products like packaging or organic waste (43%), and energy (37%). Fewer organizations reported water (16%) or other resources (13%) as significant waste outputs.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Figure 7: Resources or materials currently produced



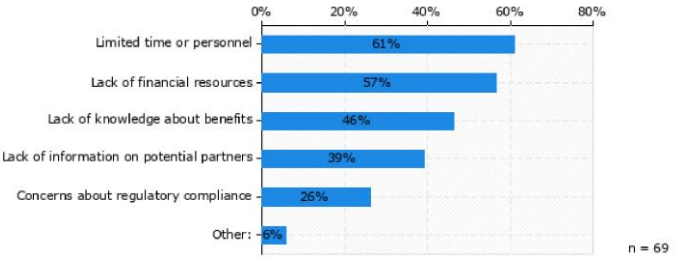
4.5 Barriers to Participation in IS Initiatives

The main barriers identified were:

- Limited time or personnel (61%)
- Lack of financial resources (57%)
- Lack of knowledge about benefits (46%)
- Lack of information on potential partners (39%)
- Concerns about regulatory compliance (26%)

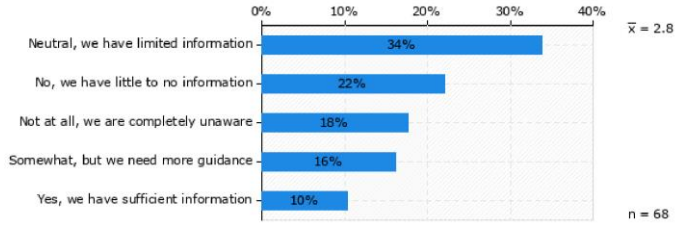
This indicates that both resource constraints and information gaps play a significant role in preventing engagement.

Figure 8: Obstacles for participating in IS and CE initiatives



4.6 Knowledge and Guidance Needs

Figure 9: Enough information to make decisions about sustainable practices

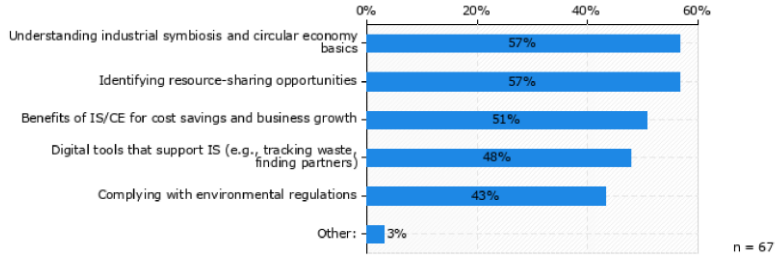


Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Only 10% of respondents felt they had sufficient information to make decisions about IS or circular economy (CE) practices, while 74% indicated they had limited or no information (avg. 2.8/5).

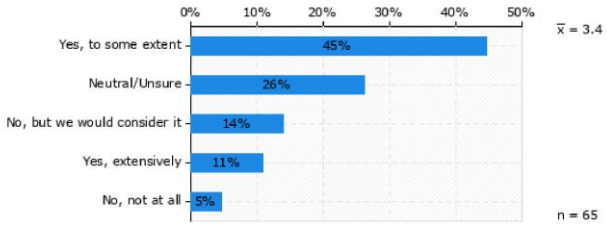
Training interest was high in the following areas:
- IS/CE basics (57%)
- Identifying sharing opportunities (57%)
- Cost-saving and growth benefits (51%)
- Environmental regulation compliance (43%)
- Digital tools for IS (48%)

Figure 10: Benefits from training or guidance on IS or CE



When asked whether clear and simplified guidelines on sustainability and resource sharing would increase their organization's likelihood of participation, the majority of respondents (56%) answered positively. Specifically, 45% indicated they would be more likely to participate "to some extent," while 11% said "yes, extensively." A further 26% were neutral or unsure, and 18% expressed some level of hesitation, with only 5% stating outright that clear guidelines would not influence their participation. These results suggest that accessible and practical guidance could play a key role in encouraging broader engagement.

Figure 11: Likeliness to participate in IS initiatives in case of simplified guidelines on sustainability and resource sharing

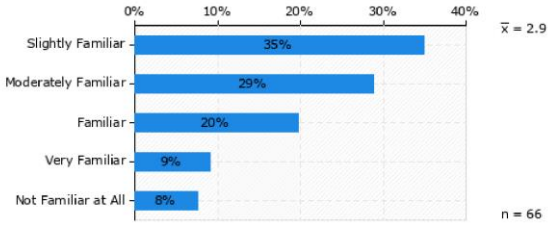


4.7 Legal Awareness and Challenges

Familiarity with legal requirements for sustainability was moderate (avg. 2.9/5). Only 29% rated themselves as familiar or very familiar.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

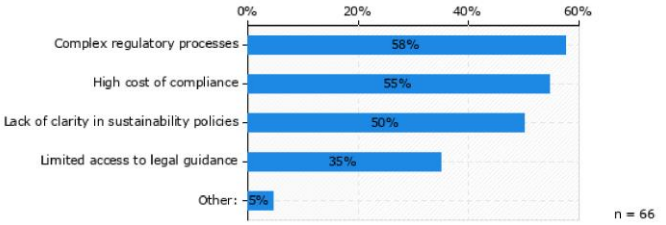
Figure 12: Familiarity with legal requirements for waste reduction, resource sharing, or sustainability



Common challenges included:

- Complex regulatory processes (58%)
- High compliance costs (55%)
- Lack of clarity in sustainability policies (50%)
- Limited access to legal guidance (35%)

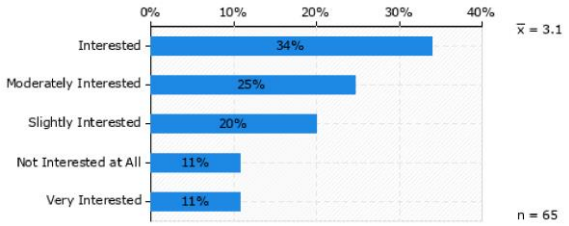
Figure 13: Challenges in adopting sustainable practices



4.8 Digital Tools and Their Adoption

Interest in digital tools for waste management and reduction was moderate (avg. 3.1/5), with 45% indicating they were interested or very interested.

Figure 14: Interest in Digital Tools



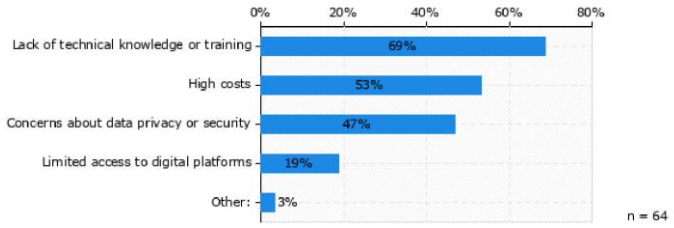
However, adoption is hindered by:

- Lack of technical knowledge or training (69%)
- High costs (53%)
- Data privacy concerns (47%)
- Limited access to platforms (19%)

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

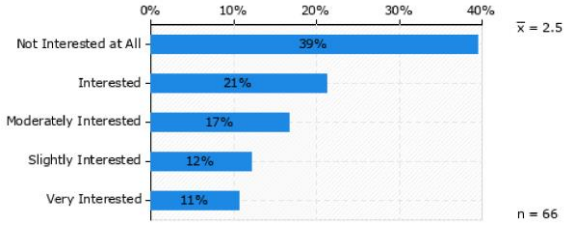
– Training and Information Needs

Figure 15: Challenges in Adopting Digital Tools



Respondents expressed clear interest in receiving training or guidance on industrial symbiosis and circular economy topics. However, when asked directly about interest in training on digital IS and market potential, responses were more divided: 39% were not interested at all, while 32% showed moderate to high interest (avg. 2.5/5).

Figure 16: Interest in receiving more information or training on digital industrial symbiosis and its market potential



4.9 Drivers and Determinants of Organizational Readiness for IS

The analysis revealed a strong positive correlation between awareness and readiness to engage in IS ($r = 0.546$, $p < 0.001$), suggesting that informed companies are more likely to collaborate. Kruskal-Wallis test indicated significant differences in awareness between countries ($H = 14.72$, $p = 0.0053$). Differences in readiness were marginally significant ($\chi^2 = 15.31$, $p = 0.053$). Norway showed the highest scores in awareness (3.06), readiness (3.92), and digital interest (4.50), while Latvia scored the lowest.

Interest in digital tools (Q24) was not significantly related to company size ($p = 0.24$) or sector ($p = 0.83$), but significant differences were observed between countries ($H = 18.45$, $p = 0.001$). Companies already applying IS practices (Q12) or collaborating with others (Q13) showed higher readiness (e.g., $r = 0.23$ for material exchanges).

Digital proficiency (Q16) and use of IT tools (Q17) were also positively related to readiness (correlations up to $r = 0.34$), indicating that digital competencies are essential for IS implementation. Interestingly, barriers such as high costs (Q25a), lack of technical knowledge (Q25b), and data security concerns (Q25d) were not negatively correlated with readiness. In fact, they showed positive correlations, suggesting that

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

more experienced companies are more aware of such challenges. Recognized benefits (Q22) had the strongest correlation with readiness (r = 0.37).

Figure 17: Comparison Between FRIeNDs Partner Countries

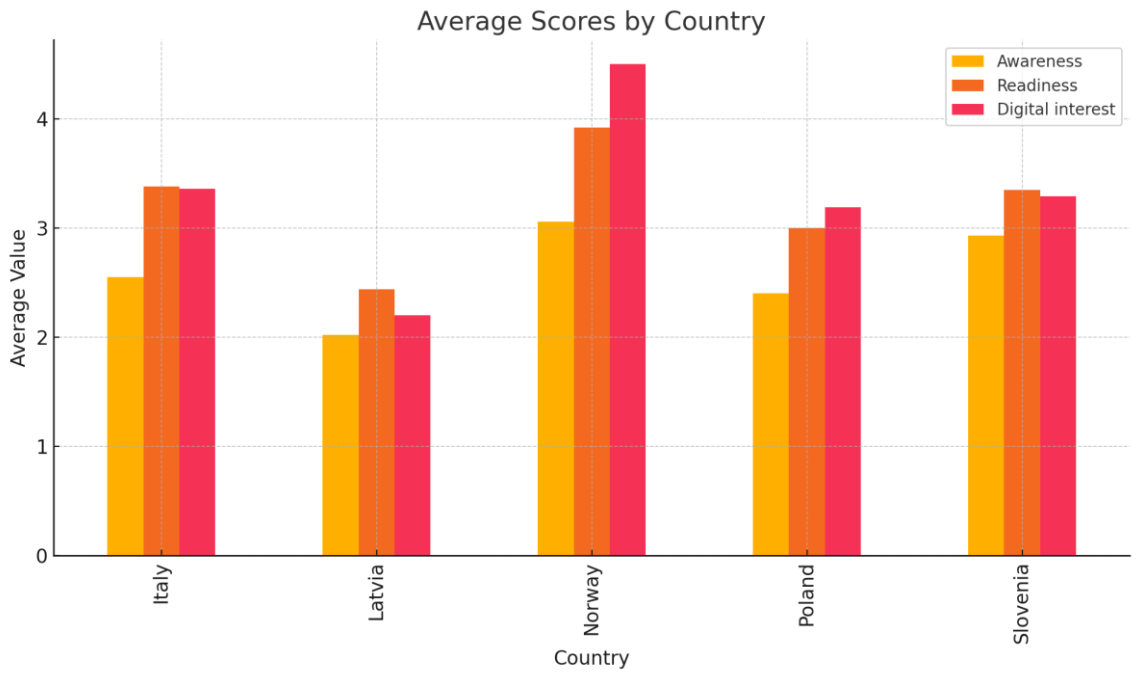


Figure 17 shows average scores for awareness, readiness, and interest in digital tools by country.

5 Discussion, Limitations and Further Research

The findings of this study confirm several theoretical propositions regarding industrial symbiosis (IS). The strong positive relationship between awareness and readiness to engage in IS ($r = 0.546$, $p < 0.001$) aligns with prior research that emphasizes the critical role of knowledge and familiarity in reducing uncertainty and fostering inter-organizational collaboration (Ulusoy et al., 2024; Patricio et al., 2022). Informed companies appear significantly more open to cooperation and resource-sharing practices, underscoring the importance of awareness-raising measures and targeted outreach.

The significant correlation between digital competence and readiness reinforces claims that digitalization, and particularly Industry 4.0 technologies, act as key enablers of IS (Makropoulos et al., 2024). Notably, the use of digital tools (e.g. platforms for partner matching and resource tracking) and digital proficiency (e.g., awareness of legal and sustainability practices) were positively associated with companies' readiness to participate in IS, suggesting that digital maturity is a necessary condition for operationalizing IS strategies.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Cross-country differences in awareness, readiness, and digital interest further highlight the importance of national and institutional context. For example, Norwegian organizations scored highest on all three indicators, while Latvian organizations scored the lowest. These findings are consistent with research emphasizing the influence of institutional support structures, national policies, and cultural readiness in shaping IS adoption (Michelini & Mattelin-Pierrard, 2023). Tailored national or regional interventions may therefore be needed to foster IS in countries where awareness and readiness lag behind.

Interestingly, perceived barriers such as high costs, lack of technical knowledge, and data privacy concerns—often cited as deterrents—were not negatively associated with readiness. On the contrary, these barriers showed weak but positive correlations with readiness, suggesting that organizations with more experience in IS or digital sustainability practices are more aware of the complexities involved. This implies that higher levels of engagement come with increased recognition of real-world challenges, and such awareness does not necessarily reduce the willingness to participate.

The strongest correlation with readiness was found in the recognition of tangible benefits from IS and circular economy practices ($r = 0.37$). This finding reinforces the idea that when organizations see a clear business case—through cost savings, efficiency gains, or competitive advantage—they are more likely to commit to IS initiatives.

While these results provide valuable insights, the study also has several limitations. First, the sample size (N=78) is relatively modest, and the number of respondents per country may not sufficiently capture national-level variation. Second, the reliance on self-reported data introduces the possibility of bias, including overreporting of sustainability practices or readiness. Third, the cross-sectional nature of the study limits the ability to make causal inferences about the relationships between awareness, readiness, and digital engagement.

To address these limitations, future research could adopt longitudinal designs that track changes in IS engagement over time and examine causal pathways. Expanding the geographic scope to include a more diverse set of countries would also enhance the generalizability of the findings. Additionally, integrating qualitative methods—such as interviews or case studies—could uncover deeper insights into organizational motivations, contextual barriers, and best practices for implementing IS in different settings.

Finally, there is a clear need for further evaluation of digital tools used to support IS. Comparative studies of different platforms and ICT solutions could help determine what works best in different sectors or organizational contexts. Moreover, future research should explore the role of policy incentives, regulatory frameworks, and support services in accelerating IS uptake and mainstreaming circular business models.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

6 References

Bocken, N. M. P., Ritala, P., Albareda, L., & Verburg, R. (2022). Business model innovation for the circular economy: Growing opportunities for IS through digitalisation. *Journal of Cleaner Production, 367*, 132901. https://doi.org/10.1016/j.jclepro.2022.132901

Chertow, M. R. (2007). "Uncovering" industrial symbiosis. *Journal of Industrial Ecology, 11*(1), 11–30. https://doi.org/10.1162/jiec.2007.1150

Makropoulos, C., Cecelja, F., & Yang, A. (2024). Digital transformation of industrial symbiosis: Tools and implementation pathways. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.13567 *(DOI placeholder if not yet available)*

Michelini, G., & Mattelin-Pierrard, M. (2023). Institutional support for industrial symbiosis in Europe. *Sustainability, 15*(6), 2152. https://doi.org/10.3390/su15062152

Paquin, R. L., & Howard-Grenville, J. (2013). Blind dates and arranged marriages: Longitudinal processes of network orchestration. *Organization Studies, 34*(11), 1623–1653. https://doi.org/10.1177/0170840613495330

Patricio, J., Ferreira, M. S., & Costa, I. (2022). The benefits and barriers of industrial symbiosis: A systematic literature review. *Journal of Cleaner Production, 368*, 132725. https://doi.org/10.1016/j.jclepro.2022.132725

Ulusoy, A., Demirel, E., & Ciftci, M. (2024). Drivers of circular economy and IS adoption among SMEs. *Resources, Conservation & Recycling, 198*, 106123. https://doi.org/10.1016/j.resconrec.2023.106123

Yazan, D. M., Romano, V. A., & Albino, V. (2021). The role of digital technologies in supporting industrial symbiosis: A systematic review. *Resources, Conservation & Recycling, 164*, 105190. https://doi.org/10.1016/j.resconrec.2020.105190

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

PART III: QUALITATIVE ANALYSIS – THEMATIC INSIGHTS FROM THE INTERVIEWS

1 Introduction

This part of the report presents an in-depth thematic analysis of 16 semi-structured interviews conducted with SMEs, public institutions, and sector experts involved in digital industrial symbiosis (DIS) and circular economy practices. The interviews were carried out between October 2024 and February 2025 as part of Erasmus+ project activities exploring the potential for scaling DIS across Europe.

The interviewees represent a diverse cross-section of stakeholders from Slovenia, Poland, Italy, and Norway, covering both early-stage adopters and advanced actors in the field. The Norwegian interview sample, in particular, includes organizations from the construction and urban development sectors, reflecting a strong national focus on reuse innovation and digital transition in the built environment. Meanwhile, responses from Central and Southern European countries capture a range of perspectives from SMEs, sustainability consultants, platform developers, and circular initiative leaders.

Drawing on this qualitative data, supported by theoretical insights from the desk research done by the FReIND project (February 2025); the report explores opportunities, barriers, and capacity-building needs related to the implementation of DIS in real-world contexts. Special attention is given to the integration of digital tools such as platforms, tracking systems, and AI in circular collaboration processes — with a particular focus on construction, reuse logistics, and inter-organizational coordination.

The objective is to provide practical and policy-relevant findings that can support the broader adoption of industrial symbiosis principles aligned with digital innovation, environmental sustainability, and systemic transformation. Through its multi-country scope and cross-sectoral insights, this report contributes to a deeper understanding of how DIS is emerging in practice — and what is required to support its effective, inclusive, and scalable implementation.

2 Research Questions

RQ1. What is the current level of awareness and understanding of digital industrial symbiosis (DIS) among SMEs and institutions?

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

RQ2. What benefits and opportunities do participants associate with implementing digital industrial symbiosis solutions?

RQ3. What barriers or challenges hinder the adoption of digital industrial symbiosis practices in SMEs?

RQ4. What types of training or support do participants need to engage effectively with DIS solutions?

RQ5. How do participants view the role of digital platforms in facilitating circular collaboration and resource sharing?

RQ6. What policy recommendations or systemic changes do participants suggest promoting DIS at local or regional level?

3 Methodology

The analysis was conducted on qualitative responses from 10 SME and institutional representatives across Europe – 1 interview from Slovenia, 2 interviews from Italy, 4 interviews from Poland, and 3 interviews from Latvia, complemented by six expert interviews from the Norwegian construction sector. A mixed approach was used, combining manual coding and automated topic modelling (TF-IDF + NMF)[1] to derive themes and dominant codes. Quotes were extracted and translated into English. Findings are contextualized with recent theoretical literature on industrial symbiosis and digital technologies (Desk Research Report, February 2025).

4 Results of Thematic Analysis

Six overarching themes were derived from the data. Each theme is described below, including top English keywords (codes) and selected interview excerpts.

4.1 Theme 1: Barriers and Practical Challenges

This theme encapsulates the structural, technical, and organizational barriers that limit the adoption and scaling of digital industrial symbiosis (DIS) across sectors. A recurring concern among interviewees is the **absence of sarong regulatory frameworks** that would mandate or incentivize the reuse of materials, especially in the construction sector. Without legal obligations, many companies see little reason to invest in circular solutions or data-sharing platforms.

[1] TF-IDF + NMF is a method used to automatically identify important topics in text data, such as interview transcripts. TF-IDF finds words that are frequent in a particular interview but rare across others — highlighting unique and meaningful terms. NMF (Non-negative Matrix Factorization) then groups these words into themes or topics based on how often they appear together. Together, this method helps reveal patterns in what people are talking about — supporting and enriching manual coding in qualitative research.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Additionally, participants frequently noted the **fragmentation of existing infrastructures**—both physical and digital. Many reuse systems are still localized, lack connectivity, or operate manually, which inhibits their integration into broader DIS ecosystems. The lack of **interoperability between tools** (e.g., reuse platforms and building planning software like BIM) leads to inefficiencies and duplicated efforts.

Data quality and traceability also emerge as critical concerns. Some actors reported that available material inventories are incomplete, poorly classified, or quickly outdated, making reuse planning unreliable. This directly affects trust and decision-making processes for companies attempting to engage in digital symbiosis.

Cost-related barriers are particularly challenging for SMEs, who often lack the financial flexibility to invest in unproven or complex solutions. The upfront cost of digital tools, combined with uncertainty about return on investment, discourages experimentation.

Logistical complexity is another major theme, particularly in construction and manufacturing. Transporting, storing, and coordinating the reuse of materials requires new workflows and often new partnerships, which are difficult to implement without systemic support.

Theme 1 reflects how **interconnected technical, economic, and institutional limitations** act as inhibitors of digital industrial symbiosis. Addressing these barriers requires a multi-layered response involving policy reform, technological standardization, capacity building, and shared digital infrastructures.

Top Keywords (Codes):

- barriers, reuse, lack of regulation, mapping, data quality, costs, integration, logistics, planning, reliability

Illustrative Quotes:

- "The reuse mandate doesn't exist yet. Without it, many actors are unwilling to participate." — Asplan Viak (Norway)
- "Data quality in existing platforms is very inconsistent, which affects planning." — Resirqel (Norway)
- "We would reuse more materials if there were standards and stable systems in place." — Survey respondent (SME)
- "Logistics is a huge barrier. Coordinating reuse across multiple sites is time-consuming without the right digital support." — Sirkulær Ressurssentral (Norway)

4.2 Theme 2: Innovation and Strategic Thinking

This theme highlights the **forward-looking, creative, and transformational potential** of digital industrial symbiosis (DIS). Many participants see DIS not just as a technical solution, but as a **strategic enabler** of long-term sustainability goals, circular business models, and organizational transformation. Interviewees emphasized the value of **rethinking resource flows**, not merely optimizing them — pointing to opportunities for

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

creating entirely new services, products, or cooperation models based on waste streams and shared data.

Central to this vision is the use of **digital simulation tools** and **predictive analytics**, which allow companies to forecast resource needs, model environmental impacts, and plan reuse scenarios more effectively. These technologies help move from reactive to **proactive decision-making**, supporting more resilient and adaptive operations.

Participants also linked DIS to **collaborative innovation**, where the digital sharing of information between firms, cities, and institutions can unlock previously hidden synergies. In this context, creativity is not limited to product design but extends to **systems-level thinking**, where companies co-develop solutions to shared problems — such as surplus handling, space optimization, or logistics coordination.

Several interviewees discussed how DIS aligns with their **long-term transformation strategies**, especially in the transition toward net-zero, climate-neutral, or low-carbon business models. The emphasis on **value creation from residuals** reflects a shift from compliance-based thinking to opportunity-driven innovation.

Ultimately, this theme positions DIS as a **catalyst for strategic reorientation**, allowing organizations to embed circular thinking into core planning and innovation processes — particularly when digital tools are made accessible, interoperable, and responsive to user needs.

Top Keywords (Codes):

- innovation, ideas, potential, simulation, collaboration, creativity, value creation, rethinking, transformation, long-term

Illustrative Quotes:

- "Digital tools allow simulation and prediction. This saves time and supports better decisions." — Slovenian SME
- "We are exploring ways to rethink how we use residuals to create new services." — Circular SME (survey)
- "We see DIS as a strategic opportunity — not just for compliance, but for innovation and competitiveness." — FutureBuilt (Norway)
- "It's not just about reusing what's left over. It's about seeing waste as a resource for innovation." — Survey respondent (Poland)
- "We use planning data and digital twins to test reuse scenarios and improve efficiency before construction even starts." — Asplan Viak (Norway)

4.3 Theme 3: Involvement and Local Action

This theme highlights the **active engagement of organizations in applying digital industrial symbiosis (DIS) principles through real-world initiatives**, especially at the local and regional levels. Unlike themes focused on strategic vision or future potential, this

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

theme emphasizes what participants are already doing — including **pilot projects, circular procurement, partnerships, and tool adoption**.

Many interviewees report being part of **reuse-focused experiments or collaborative pilots**, often supported by public institutions, regional development programs, or EU projects. These efforts demonstrate that even small-scale actions — such as digitizing warehouse inventory, mapping material flows, or integrating reuse platforms into urban planning — can serve as powerful learning environments and confidence builders.

Participants frequently link their **involvement in DIS to sustainability and climate goals**, noting that engaging in reuse is part of broader organizational missions around environmental responsibility. Several cases show how **local action is often the entry point** into more complex digital systems. For example, a construction SME that begins by reusing leftover materials on-site may eventually adopt inventory software, join a circular marketplace, or participate in collaborative reuse networks.

This theme also reveals that **local governments, research institutions, and NGOs play a catalytic role** in promoting DIS by facilitating pilot funding, matchmaking events, and access to tools. Such intermediaries often provide the enabling context for experimentation, especially where commercial viability is not yet proven.

Moreover, the theme underscores that **involvement is driven by more than compliance** — there is a growing sense of ethical responsibility and innovation mindset motivating action. Still, participants emphasize that scaling these local efforts requires stable support, long-term policy alignment, and digital capacity-building tailored to grassroots realities.

Top Keywords (Codes):

- reuse, participation, pilots, local, projects, sustainability, action, support, adoption, efforts

Illustrative Quotes:

- "We're already involved in a pilot using reused materials. It's part of our sustainability goals." — Construction SME (survey)
- "We have developed a reuse warehouse and now want to digitize it for better coordination." — Sirkulær Ressurssentral (Norway)
- "DIS is not just an idea for us. We work with the city to reuse timber and integrate it into our building stock." — Circular innovation lab (Norway)
- "We started small, but being part of a local reuse project helped us understand the value of data and tracking." — Survey respondent (Italy)
- "Collaboration with public actors is essential. They provide the infrastructure and coordination needed for these efforts to scale." — NHO Association (Norway)

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

4.4 Theme 4: Practical Experiences and Case Feedback

This theme captures the hands-on, user-centered perspective of organizations that have engaged directly with digital industrial symbiosis (DIS) tools and practices. Participants reflect on what works, what doesn't, and what's needed to improve real-world adoption. Rather than discussing high-level strategies, these insights come from actual experience using digital platforms, tracking systems, and material reuse workflows.

A key issue raised across interviews is **usability**. Many tools are seen as technically complex, requiring advanced digital skills or prior experience with data systems. This creates barriers for small or less tech-savvy organizations, particularly SMEs, who may not have dedicated IT staff or training resources. As a result, **many respondents call for simpler, more intuitive platforms**, with clear interfaces and workflows tailored to non-experts.

Training and onboarding emerge as essential components for effective DIS implementation. Participants express a strong need for **visual, step-by-step instructions**, as well as access to **case-based learning**, where real examples show how similar organizations have adopted tools, solved logistical problems, or created reuse workflows. Some respondents also emphasize the importance of **sector-specific training**, especially for construction, where materials, regulations, and timelines vary widely.

Cost remains a consistent concern — not only the **financial cost of implementing digital tools**, but also the **hidden costs** related to time, change management, staff training, and system integration. Some interviewees expressed disappointment with pilot tools that were too rigid, poorly documented, or failed to deliver measurable benefits.

This theme also includes feedback on **workflow integration** — the need for DIS tools to fit smoothly into existing planning and operations. Standalone apps or platforms that don't connect to procurement systems, logistics planning, or material inventories are often perceived as more of a burden than a solution.

Overall, the theme underlines the importance of **designing DIS tools from the user's point of view**, ensuring they offer real value in daily practice — not just in theory. The voices in this theme remind us that **successful digital transformation is as much about people and processes as it is about technology**.

Top Keywords (Codes):

- usability, tools, training, costs, step-by-step, learning, real examples, workflow, user experience, barriers

Illustrative Quotes:

- "We need basic training materials. Step-by-step, ideally visual." — SME (survey)

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

- "Tool usability needs to improve. Right now it requires too much technical knowledge." — Norwegian respondent
- "We tried a reuse dashboard, but it didn't link to our procurement system, so we dropped it." — Construction firm (survey)
- "Costs are not just about licenses — it's the time to train our people and align with our internal workflow." — Reuse coordinator (Norway)
- "The most helpful thing was seeing what another SME did. Practical examples make all the difference." — Italian SME respondent

4.5 Theme 5: Platforms and Ecosystem Design

This theme focuses on the **central role of digital platforms as enablers of industrial symbiosis**, emphasizing the importance of system-level thinking, integration, and accessibility. Participants consistently described platforms as **the backbone of circular collaboration**, enabling the visibility, coordination, and tracking of reusable materials across different actors and locations.

A key insight is that platforms are valued not only for **connecting supply and demand** (matchmaking) but also for supporting **trust and transparency** in reuse transactions. Interviewees stressed that platforms must include features for **material documentation, origin traceability, and quality control**, especially in sectors like construction where compliance and safety are paramount.

Respondents advocate for platforms that go beyond basic databases—those that integrate AI-supported recommendations, dashboards for decision-making, and lifecycle analysis tools. This reflects a shift from passive repositories to interactive, intelligent ecosystems capable of facilitating real-time collaboration and optimization.

Interoperability emerged as a critical need. Many participants noted that platforms must be able to **connect with other systems**, particularly planning and building information systems (e.g., BIM), procurement tools, and public data registries. Without such integration, even well-designed platforms risk being underused or duplicative.

Another recurring idea is the call for **public or semi-public platform models**, supported by government, industry clusters, or consortia. These platforms are seen as essential infrastructure for the circular economy — much like roads or energy grids — and should be governed in ways that ensure **open access, data standardization, and long-term maintenance**.

Participants also stressed the importance of designing ecosystems, not just tools. This includes addressing the **legal, financial, and operational environment** that surrounds the platform — ensuring that incentives, regulations, and user support structures are aligned with the platform's objectives.

Overall, this theme underscores the idea that **platforms are more than technical solutions** — they are **institutional and relational infrastructures** that can enable or inhibit the success of digital industrial symbiosis.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Top Keywords (Codes):

- platform, ecosystem, tracking, matchmaking, integration, collaboration, monitoring, transparency, reuse systems, access

Illustrative Quotes:

- "Platforms should be public and linked to planning systems like BIM." — FutureBuilt (Norway)
- "We use platforms with tracking tools and AI to optimize reuse logistics." — Sirken (Norway)
- "The ecosystem matters. A platform is just a tool unless the whole system supports it." — NHO Association (Norway)
- "We need one entry point, not five different reuse platforms that don't talk to each other." — Survey respondent (Poland)
- "Access to reliable reuse data is critical. Without trust in the data, no one will use the platform." — Digital platform developer (survey)

4.6 Theme 6: Full Digital Integration and Automation

This theme represents the **most technologically advanced vision** of digital industrial symbiosis (DIS) expressed by participants. It centers around the **use of cutting-edge digital technologies** — such as artificial intelligence (AI), sensors, digital twins, and real-time dashboards — to **automate and optimize material flows, logistics, and reuse processes** at scale.

Respondents engaging with this theme describe DIS not as a manual or semi-digital process, but as a **fully integrated, data-driven system**. In this system, materials can be tracked continuously from deconstruction to reapplication, decisions are supported by intelligent algorithms, and **human input is focused on strategic oversight rather than operational detail**.

Several organizations are already developing or piloting **AI-supported platforms** that can match supply and demand, predict reuse potential, suggest routing logistics, and flag opportunities for circular intervention. These tools are praised for increasing **efficiency, responsiveness, and decision quality**, particularly in high-volume or fast-paced environments like construction or manufacturing.

Sensors and IoT technologies are also becoming part of the DIS ecosystem. Some participants mentioned efforts to equip materials or components with **QR codes or RFID tags**, enabling them to be identified, logged, and tracked automatically through dismantling, transport, and reuse. When connected to cloud systems or dashboards, this infrastructure allows for **real-time monitoring of inventory, availability, and flows**.

The most visionary examples refer to the use of **digital twins** — virtual replicas of buildings or materials that are dynamically updated. These systems allow simulation of reuse scenarios, integration with planning data, and impact forecasting, thereby moving DIS into the realm of **predictive, scenario-based decision-making**.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Scalability is a recurring theme. Participants note that without automation and digital integration, DIS remains labor-intensive and difficult to scale. The ambition is to move from fragmented pilots to **automated, systemic reuse infrastructures** that are embedded in regional or national circular strategies.

However, this theme also surfaces concerns around **data governance, standardization, and technical access**. While the technology exists, many organizations still lack the capacity or budget to implement these tools. Thus, full digital integration is seen as a goal to work toward — one that requires joint investment, policy alignment, and open standards.

Top Keywords (Codes):
- automation, AI, sensors, digital twin, dashboards, real-time, scalability, data sharing, optimisation, integration

Illustrative Quotes:
- "We are developing a dashboard to connect inventory and logistics digitally." — Sirkulær Ressurssentral (Norway)
- "AI tools help us identify opportunities for reuse that we would otherwise miss." — Sirken (Norway)
- "In future, we hope to link sensors with our platform so we can track material flow in real time." — Reuse platform developer (survey)
- "Digital twins allow us to test reuse scenarios before anything is built — it changes everything." — Asplan Viak (Norway)
- "Automation is the only way to scale reuse without huge increases in staff or time." — Circular construction expert (Norway)

5 Answers to Research Questions

5.1 RQ1: What is the current level of awareness and understanding of digital industrial symbiosis (DIS) among SMEs and institutions?

The analysis reveals that awareness and understanding of digital industrial symbiosis (DIS) is growing but remains uneven and fragmented across organizational types and regions. Among the 16 interviewed entities, a clear distinction emerged between institutions that are actively piloting DIS tools and those that are still unfamiliar with the concept.

Several participants — particularly those from large consultancies and specialized reuse platforms — **demonstrate a deep understanding of the DIS concept and its practical implementation**. For instance, a representative from Asplan Viak (Norway) noted, "We are using platforms and simulations to manage reuse in construction — but many SMEs don't see how digital tools can help them." This highlights a digital divide not only in tool usage, but also in conceptual grasp of what DIS entails.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

On the other end of the spectrum, several SMEs expressed that while they engage in reuse or circular practices, they are **not familiar with the term IS or its digital components (DIS)**. As one respondent from Poland explained, "I didn't know the term, but we are already trying to reuse leftovers with other companies — we just don't call it that." This suggests that relevant activities are happening, but often outside the DIS vocabulary or without digital coordination.

Another SME from Slovenia reflected this **partial understanding**, stating, "The idea is very useful, but our understanding is still limited — especially the digital side." This comment illustrates a broader pattern: DIS is often perceived as an abstract or technical concept, and many smaller organizations lack the exposure or capacity to explore its strategic benefits.

Furthermore, **awareness is shaped by perceived relevance and institutional pressure**. One SME noted, "We're just starting to explore circularity. DIS sounds interesting, but we need more concrete guidance." Similarly, a representative from NHO Association (Norway) emphasized that, "If the government required it, more people would pay attention. Right now, it's still voluntary, and many don't see the urgency."

Across the interviews, **there is a clear openness and interest in the idea of digital symbiosis**, especially among those already working on sustainability targets or public procurement projects. However, the transition from basic awareness to informed engagement is still at an early stage for many. Barriers include conceptual ambiguity, lack of exposure to functional tools, and a limited understanding of the role of data integration and platforms in facilitating material exchanges.

5.2 RQ2: What benefits and opportunities do participants associate with implementing digital industrial symbiosis solutions?

Across the interviews, participants identified a broad range of tangible and strategic benefits associated with the implementation of digital industrial symbiosis (DIS). These benefits span cost efficiency, sustainability, operational optimization, and innovation. While the emphasis varies by organization type and level of digital maturity, the overall tone is one of optimism about the long-term value of adopting DIS solutions.

One of the most frequently mentioned benefits is **cost reduction** — both through waste minimization and more efficient resource utilization. As a representative from a Polish SME explained, "We save money by reusing leftover materials from previous projects. With better planning tools, we could go even further." Similarly, respondents highlight how material tracking and forecasting tools can reduce over-ordering and waste during procurement and construction phases.

Several interviewees stressed the importance of **transparency and predictability** in DIS processes. For example, a stakeholder from Sirken (Norway) described how "AI tools help us identify opportunities for reuse that we would otherwise miss." The ability to digitally map materials and forecast reuse potential supports data-informed decision-

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

making, which not only improves efficiency but also builds trust between stakeholders in shared value chains.

Logistics optimization is another key area of opportunity. One participant noted, "Digital planning allows us to align reuse logistics with production schedules, which saves both time and emissions." This aligns with the broader view that DIS tools can enable leaner, more sustainable operations, especially when paired with geolocation and real-time data feeds.

From a strategic perspective, participants associate DIS with **new business models and service innovation**. A survey respondent from a circular SME stated, "We are exploring ways to rethink how we use residuals to create new services." Others see potential in digital marketplaces, reuse networks, and circular design consultancy, where value is created not from selling materials, but from orchestrating and optimizing flows.

Moreover, DIS is linked to simulation capabilities that support **proactive planning and scenario testing**. As one Slovenian SME put it, "Digital tools allow simulation and prediction. This saves time and supports better decisions." These tools are particularly valuable in complex construction projects, where circular options must be weighed against budget and time constraints.

The interviews also reflect a growing **alignment between DIS and organizational transformation goals**. For some, DIS is more than a tool — it's part of their identity. "We see DIS as a strategic opportunity — not just for compliance, but for innovation and competitiveness," explained a representative from FutureBuilt (Norway).

In summary, participants associate DIS with a unique convergence of environmental, economic, and technological value. It enables organizations to meet sustainability objectives, reduce costs, unlock creative reuse possibilities, and strengthen cross-sector collaboration. While some benefits are already being realized, many see even greater potential as tools mature and ecosystems evolve.

5.3 RQ3: What barriers or challenges hinder the adoption of digital industrial symbiosis practices in SMEs?

While digital industrial symbiosis (DIS) holds significant promise, its adoption remains limited — especially among small and medium-sized enterprises (SMEs). Interviews revealed a range of interrelated challenges, spanning regulatory gaps, financial constraints, technical complexity, and systemic fragmentation.

One of the most consistently cited obstacles is the **lack of regulation or legal mandates for reuse and digital coordination**. Without enforceable policies or circular procurement rules, many SMEs remain reluctant to invest in reuse-oriented tools or workflows. As one respondent from Asplan Viak (Norway) noted, "The reuse mandate doesn't exist yet. Without it, many actors are unwilling to participate." This sentiment reflects a wider concern that voluntary adoption lacks momentum in the absence of policy drivers.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Financial limitations represent another major barrier — both in terms of upfront costs and perceived return on investment. A Norwegian SME explained, "We want to try new digital solutions, but it's hard to justify the cost when savings aren't guaranteed." For many smaller companies, the risk of adopting unfamiliar and complex technologies without clear economic returns is too high.

The **complexity and usability of current tools** also emerged as a recurring concern. Several participants shared that available platforms are not user-friendly and require technical expertise that SMEs often lack. As one survey respondent put it, "Tool usability needs to improve. Right now, it requires too much technical knowledge." The absence of simplified onboarding, intuitive design, and SME-friendly documentation discourages wider use.

Another critical barrier is the **lack of standardized data formats and classification systems**, which makes it difficult to share, compare, or match reuse opportunities across platforms. A participant from Resirqel (Norway) stated, "Data quality in existing platforms is very inconsistent, which affects planning." This lack of trust in digital inventories — whether due to outdated entries, missing material specifications, or format mismatches — limits the effectiveness of DIS tools.

In addition, many reuse workflows are still manual and siloed, leading to **high coordination costs.** A reuse coordinator from Norway shared, "Logistics is a huge barrier. Coordinating reuse across multiple sites is time-consuming without the right digital support." These operational frictions make it difficult to scale reuse efforts, especially when materials need to be transported, stored, or modified before reapplication.

Finally, several respondents highlighted **fragmentation across systems and actors**, noting that disconnected tools and competing reuse initiatives often confuse rather than support users. As one Polish respondent put it, "We need one entry point, not five different reuse platforms that don't talk to each other."

In conclusion, while interest in DIS is growing, systemic barriers continue to hinder widespread adoption — particularly among SMEs. Overcoming these challenges will require a mix of policy alignment, financial incentives, platform standardization, and user-centred tool development, all grounded in the specific needs and constraints of smaller actors.

5.4 RQ4: What types of training or support do participants need to engage effectively with DIS solutions?

One of the clearest and most consistent findings from the interviews is that effective training and support are essential prerequisites for engaging SMEs and institutions in digital industrial symbiosis (DIS). Participants across the board expressed a strong desire for practical, accessible, and context-specific training, tailored to their existing capacities and everyday workflows.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

A recurring request is for **basic, visual, and step-by-step training resources**. These would help users — particularly those in smaller organizations — understand not only how to use digital tools, but why they matter. As one SME respondent noted, "We need basic training materials. Step-by-step, ideally visual." This preference reflects the fact that many users engaging with DIS are not IT professionals, but technical staff or managers with limited digital literacy.

Beyond usability, participants also seek **training that focuses on business cases and real-world examples**, not just technical manuals. Several respondents said they would be more willing to adopt digital solutions if they could see how others have done it successfully. One participant from Italy emphasized, "The most helpful thing was seeing what another SME did. Practical examples make all the difference." This points to the importance of peer learning, case-based demonstrations, and storytelling in training formats.

Another important theme is the **need for sector-specific guidance**, particularly in construction and manufacturing, where material types, regulations, and workflows vary. A respondent from Norway shared, "Training should be adapted to our industry. Right now, it's too generic and doesn't reflect how things work on the ground." This highlights the importance of contextualizing DIS education within real operational environments.

Participants also call for **training on the broader system, not just tool interfaces**. This includes learning how to interpret data, connect reuse planning with building information modelling (BIM), navigate legal and regulatory frameworks, and coordinate with multiple actors in a symbiosis network. As one survey participant put it, "We need to understand the whole system — not just the tool, but also the rules, the partners, and the processes."

Finally, interviewees emphasized the role of **public institutions, trade associations, and research organizations as enablers of knowledge transfer**. Ongoing support — through helplines, info hubs, toolkits, or regional workshops — is seen as vital for building capacity, especially in areas where digital or circular expertise is still emerging.

In summary, participants are not asking for more tools — they are asking for better ways to understand and apply those tools in meaningful, manageable ways. Effective DIS training must be simple yet strategic, accessible yet ambitious, and always grounded in the realities of users and sectors on the front lines of circular transformation.

5.5 RQ5: How do participants view the role of digital platforms in facilitating circular collaboration and resource sharing?

Participants across all sectors and countries consistently emphasized that digital platforms are central to enabling effective digital industrial symbiosis (DIS). Far from being seen as optional tools, platforms are described as the foundation for visibility, coordination, and collaboration in circular systems.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Respondents highlighted several core functions of digital platforms: **reuse tracking**, **material matchmaking**, and **impact monitoring**. These capabilities are seen as essential for turning circular ambitions into operational reality. As one representative from Sirken (Norway) explained, "We use platforms with tracking tools and AI to optimize reuse logistics." By automating the identification of available materials and matching them with potential users, such platforms reduce transaction costs and enable faster, smarter decision-making.

Participants also emphasized that platforms must not operate in isolation. There is a strong **call for integration with existing planning and management systems**, particularly in construction. For example, a respondent from FutureBuilt (Norway) stated, "Platforms should be public and linked to planning systems like BIM." This integration is seen as critical to embedding reuse thinking into core workflows such as project design, procurement, and permitting.

A recurring concern among participants was the **fragmentation of current reuse platforms**. Many noted that the growing number of tools — often developed for specific projects or regions — leads to confusion and inefficiency. A Polish SME shared, "We need one entry point, not five different reuse platforms that don't talk to each other." This highlights the need for interoperability and coordination between systems, ideally guided by shared standards or public governance.

Trust and transparency also emerged as key themes. Participants stressed that for platforms to function as ecosystems, they must offer reliable data, clear documentation, and open access. One developer noted, "Access to reliable reuse data is critical. Without trust in the data, no one will use the platform." Others suggested that public or semi-public platforms, supported by governments or industry alliances, are more likely to gain traction across user groups.

Another important insight is that **platforms should support ecosystem-building, not just transactions**. A respondent from NHO Association (Norway) commented, "The ecosystem matters. A platform is just a tool unless the whole system supports it." This reflects the view that platforms must be embedded within legal frameworks, incentive structures, user networks, and institutional support systems to deliver real circular impact.

In conclusion, participants view platforms not only as enablers of digital reuse, but also as structural infrastructures for industrial collaboration. To succeed, platforms must be integrated, interoperable, trustworthy, and designed with user needs and ecosystem dynamics in mind.

5.6 RQ6: What policy recommendations or systemic changes do participants suggest promoting DIS at local or regional level?

Participants provided a wide range of concrete, actionable policy recommendations aimed at removing structural barriers and accelerating the uptake of digital industrial symbiosis (DIS). Their suggestions span regulatory mandates, economic incentives,

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

digital infrastructure, and governance reforms, reflecting a deep awareness that systemic change is needed to enable DIS beyond isolated pilot projects.

A central recommendation is the **introduction of legal reuse requirements or quotas**, particularly in sectors like construction where reuse potential is high but underutilized. Several participants emphasized that **voluntary approaches are insufficient**. As one interviewee from Asplan Viak (Norway) noted, "The reuse mandate doesn't exist yet. Without it, many actors are unwilling to participate." Establishing minimum reuse percentages in building codes or public tenders was seen as a powerful lever to drive adoption.

Participants also called for the **development of national or regional logistics systems** that could support the operational side of DIS. These would include shared transport, storage, and reverse supply chain coordination, especially for bulky or perishable materials. A representative from Sirkulær Ressurssentral suggested, "We need national systems that can coordinate logistics and ensure materials don't go to waste just because no one can pick them up." These systems would help bridge the gap between material availability and reuse feasibility.

Another high-priority area is the **standardization of digital reuse documentation**, including **taxonomies for materials**, **metadata requirements**, and **integration protocols for platforms**. The lack of consistent classification was seen as a major barrier to scaling DIS. As one platform developer explained, "We can't scale reuse if every actor uses a different name or format for the same material." Participants urged policymakers to establish open data standards, co-created with industry and municipalities.

Financial incentives were another recurring recommendation. Respondents called for grants, subsidies, and tax breaks to support circular business models and digital investments. These incentives would lower the initial risk for SMEs and encourage broader participation. One SME respondent stated, "If we had funding for tool adoption and training, we'd move forward much faster."

Tax policy emerged as a surprising but critical topic. Several respondents pointed out that current tax frameworks penalize reuse — for example, by taxing reused materials as if they were new or by applying full VAT to secondary components. As one interviewee explained, "We need tax reform to make reuse economically viable — it can't cost more to reuse than to buy new."

Finally, participants emphasized the role of **public procurement and government leadership**. Mandating circular and digital requirements in public projects would send a strong market signal. A representative from NHO Association (Norway) noted, "Public clients should lead by example. If municipalities demand reuse and DIS, the rest of the market will follow."

In summary, participants called for a multi-layered policy approach to support DIS — combining regulatory clarity, economic incentives, digital infrastructure investment, and strategic procurement reform. These systemic changes would not only reduce

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

current barriers but also create stable market conditions for circular innovation to thrive.

6 Discussion

The findings from this thematic analysis provide strong empirical support for and expansion of the theoretical concepts outlined in the Desk Research Report (February 2025). They underscore that the transition from linear to circular production models is not purely a technological challenge, but fundamentally a socio-organizational transformation. Digital industrial symbiosis (DIS) emerges as a key facilitator in this shift — offering tools, platforms, and coordination mechanisms that make circular collaboration measurable, manageable, and scalable.

A recurring theme across the interviews is that DIS platforms serve as "boundary objects", as described in the literature, bridging gaps between diverse actors such as municipalities, SMEs, industry networks, and digital service providers. These platforms mediate trust, transparency, and operational alignment, allowing stakeholders to visualize resource flows, coordinate reuse efforts, and monitor environmental and economic impacts. However, interviews also confirm that such platforms cannot succeed in isolation — they depend on shared taxonomies, legal clarity, and institutional support, echoing Baas and Boons' (2004) notion that successful industrial symbiosis is as much about social norms and governance structures as it is about physical exchanges.

Another insight reinforced by the data is the phased nature of DIS maturity, as proposed in the Desk Research Report. Some actors remain in early experimental stages — engaging in informal, ad hoc reuse practices without digital coordination — while others are entering a platform-mediated ecosystem phase, where real-time tracking, AI matchmaking, and BIM integration define their operations. This staged development suggests that DIS implementation pathways must be flexible, adaptive, and responsive to sectoral and regional contexts.

Importantly, the interviews surface persistent gaps between potential and practice. Despite growing enthusiasm, many SMEs still lack the digital literacy, financial resources, or regulatory incentives to fully engage in DIS. This reflects a dual-layered asymmetry: one between the technological potential of DIS and actual institutional capacity, and another between early adopters and lagging sectors or regions. These gaps are not just technical but structurally embedded in current policy, economic, and training systems.

One of the most striking findings is the absence of consistent valuation mechanisms for reused materials, a challenge also emphasized in the Desk Research Report. Without clear standards for how reused materials are priced, assessed, and certified — particularly in relation to new materials — the economic case for reuse remains fragile. This discourages investment and makes circular practices vulnerable to fluctuations in market conditions.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Furthermore, the empirical data expand on the idea of platforms as infrastructure, a point briefly discussed in the theoretical literature. Participants suggest that DIS platforms should be viewed and governed not as private tools but as public or semi-public digital infrastructures, similar to roads, energy grids, or environmental monitoring systems. This reconceptualization would have major implications for platform design, funding models, access rules, and governance frameworks.

Finally, the interviews introduce a nuanced understanding of agency and motivation in DIS adoption. While some organizations are driven by compliance or financial logic, others are motivated by ethical, environmental, or reputational considerations. This confirms that DIS engagement is multi-motivated and culturally embedded, requiring communication strategies that speak to more than just economic value.

In sum, this discussion illustrates that while digital industrial symbiosis holds tremendous transformative potential, realizing that potential depends on integrated strategies across technical, regulatory, institutional, and cultural dimensions. The insights here offer a strong empirical foundation for shaping such strategies.

7 Conclusions, Limitations, and Future Research

Digital industrial symbiosis offers substantial benefits in terms of efficiency, innovation, and environmental performance. However, its adoption remains uneven. Systemic barriers such as regulatory uncertainty, limited interoperability, and digital literacy must be addressed. To fully realize DIS potential, coordinated efforts between public authorities, private firms, and technology providers are required.

This study is based on a non-random sample of 16 interviews and may not fully capture all regional or sectoral variations. Language diversity and manual coding may also introduce interpretation bias. Despite these limitations, the findings offer a strong empirical basis for future action.

Future research should focus on testing DIS platforms in real-world pilot settings, evaluating economic impacts of reuse mandates, and exploring human-centered design approaches for digital tools. Additionally, longitudinal studies are needed to assess long-term shifts in industrial collaboration patterns enabled by DIS.

8 References

Baas, L. W., & Boons, F. A. (2004). The introduction and diffusion of industrial symbiosis: an explorative study. Ecological Economics, 49(1), 1–13.

Chertow, M. R. (2007). Uncovering industrial symbiosis. Journal of Industrial Ecology, 11(1), 11–30.

Paquin, R. L., & Howard-Grenville, J. (2012). The evolution of facilitated industrial symbiosis. Journal of Industrial Ecology, 16(1), 83–93.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Digital Industrial Symbiosis: Literature Review. (2025). Desk Research Report. Prepared for Erasmus+ Project (Version: 16.2.2025).

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

PART IV: CASE STUDIES – EXAMPLES OF INDUSTRIAL SYMBIOSIS IN PRACTICE

1 From Fishing Nets to Fashion – How AquafilSLO Implements Circular Economy

Summary:

AquafilSLO, part of the Aquafil Group, specializes in the collection and pre-processing of nylon waste, which is regenerated into high-quality ECONYL® yarn. Through innovative technology and strategic global partnerships, the company has created a model circular economy solution that transforms waste into valuable products.

Context and Challenge:

Nylon waste, including fishing nets and carpets, contributes significantly to global pollution. AquafilSLO aimed to reduce this impact by turning waste into a resource, closing the loop in the synthetic fiber industry.

Solution – AquafilSLO's Approach:

Collection of Waste:
- AquafilSLO's plant in Ajdovščina, Slovenia, collects nylon waste from around the world.

Sources include:
- Abandoned fishing nets from NGOs and coastal communities (e.g., Healthy Seas),
- Carpet waste from manufacturers (e.g., Interface),
- Industrial scraps from production processes.

Pre-processing:
- Waste is mechanically cleaned and sorted in Slovenia to prepare it for chemical regeneration.

Regeneration:
- Waste is sent to Aquafil facilities in Italy where it is transformed into ECONYL® – 100% regenerated nylon used in fashion, sportswear, and interiors.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Results and Impacts:

Aspect	Impact
Environmental	Up to 90% CO_2 emission reduction compared to virgin nylon
Economic	Value creation from waste, global brand partnerships
Social	Collaboration with local communities and NGOs

Key Learning Points:

- Technological innovation and collaboration are key to circular systems.
- Waste becomes a valuable input when approached strategically.
- Circular business models can drive both sustainability and profitability.

Discussion Questions:

1. What are the critical success factors of AquafilSLO's model?
2. How does external collaboration enhance sustainability?
3. Could this model be replicated in other industries?

Resources:

- AquafilSLO: https://www.aquafil.com/locations/aquafilslo-ajdovscina/
- Healthy Seas: https://www.healthyseas.org/
- SYMBI Interreg Project: https://projects2014-2020.interregeurope.eu/fileadmin/user_upload/tx_tevprojects/library/file_1583136065.pdf

2 From Bottles to Chairs – Donar's Sustainable Design Strategy

Summary:

Slovenian furniture manufacturer Donar transforms recycled PET and polyester felt into award-winning furniture. By collaborating with recycling companies, Donar integrates industrial symbiosis into its production model and diverts over 15 tons of raw materials annually.

Context and Challenge:

The furniture industry relies heavily on virgin resources like wood and plastics. Donar saw an opportunity to redesign the supply chain using locally available recycled materials and focusing on circular product design.

Solution – Donar's Circular Practice:

Material Use:

- Uses recycled PET bottles and PES felt as primary raw materials.
- Reduces need for virgin materials by 15 tons per year.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Product Innovation:

Notable products include:
- NicoLess – a minimalist glue-free chair.
- ChatLoop – a conference chair made entirely from recyclable materials.

Industrial Symbiosis:
- Collaborates with local recycling firms to ensure consistent material supply.
- Strengthens local circular value chains.

Results and Impacts:

Aspect	Impact
Environmental	Reduced raw material use and plastic waste reuse
Economic	Cost savings and unique market positioning
Social	Awareness raising through design and local collaboration

Key Learning Points:
- Industrial symbiosis creates economic and environmental value.
- Design for circularity goes beyond materials – it includes product lifecycle.
- Sustainability can be integrated with aesthetics and innovation.

Discussion Questions:
1. How does industrial symbiosis contribute to production stability?
2. Could this approach be adapted to other sectors?
3. What role does design play in promoting circular economy?

Resources:
- Donar: https://www.donar.si
- NicoLess: https://donar.si/nicoless/
- ChatLoop: https://donar.si/chatloop/

3 From Invasive Weeds to Notebooks – Ljubljana's Circular Innovation

Summary:

The City of Ljubljana repurposes Japanese knotweed, an invasive plant, into paper products through an innovative partnership with local institutions. This initiative addresses environmental challenges while producing sustainable alternatives to traditional paper.

Context and Challenge:

Japanese knotweed is one of Europe's most aggressive invasive plants, damaging infrastructure and biodiversity. Ljubljana aimed to manage this waste while promoting sustainable material use.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Solution – Circular Processing of Knotweed:

Harvesting and Processing:
- Knotweed is harvested during city maintenance operations.
- The plant is dried, shredded, and prepared for pulp production.

Partnerships:
- The Pulp and Paper Institute developed a method to turn knotweed fibers into usable paper pulp.
- Collaborations with local producers result in finished products.

Products:
- Recycled paper is used for notebooks, invitations, promotional materials, etc.

Results and Impacts:

Aspect	Impact
Environmental	Invasive species control and biomass reuse
Economic	New product lines and support for local green businesses
Social	Public education and municipal innovation

Key Learning Points:
- Local challenges can inspire circular innovations.
- Public institutions can lead sustainable change through partnerships.
- Natural waste streams can be transformed into high-value products.

Discussion Questions:
1. How can this model be applied to other biological waste streams?
2. What is the role of cities in promoting the circular economy?
3. Can invasive species become valuable resources?

Resources:
- European Circular Economy Stakeholder Platform (2024)
- Pulp and Paper Institute: https://www.icp-lj.si
- City of Ljubljana: https://www.ljubljana.si

4 Transforming Waste into Energy: Balticovo's Circular Approach to Poultry Manure Management in Latvia

Summary:

Balticovo, Latvia's leading egg producer and one of the largest in Northern Europe, has implemented innovative circular economy practices by converting poultry manure into renewable energy. Through advanced technologies and strategic collaborations, the company has developed a model of internal industrial symbiosis

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

that reduces environmental impact, boosts operational efficiency, and supports national energy independence. This case study explores Balticovo's circular strategy, challenges faced, solutions developed, and the outcomes achieved.

Context and Challenge:

With over 3 million laying hens and the production of approximately 700 million eggs annually, Balticovo generates over 70,000 tonnes of poultry manure each year. Managing such waste posed major challenges:

- Waste Management: Handling and disposing of large quantities of manure in an environmentally responsible way.
- Environmental Impact: Mitigating greenhouse gas emissions and nutrient leaching associated with untreated manure.
- Energy Demand: Seeking cleaner, renewable alternatives to fossil fuels to meet operational energy needs.

These challenges prompted Balticovo to pursue a circular solution that would convert waste into value.

Solution – Balticovo's Approach:

Biogas and Biomethane Production:

- Balticovo established a pioneering process to convert poultry manure into biogas and then refine it into biomethane. The system involves:
- Egg Energy Plant: Where raw manure is fermented to generate biogas.
- Bovo Gas Facility (Iecava): Where the biogas is upgraded into biomethane – a renewable alternative to natural gas.

Technological Innovation:

- Manure from laying hens has a high calcium content, which typically impedes biogas production. Balticovo, collaborating with experts, overcame this limitation by designing a tailored fermentation system capable of handling poultry manure efficiently.

Industrial Symbiosis:

- The manure, previously a byproduct, now fuels renewable energy production, creating a closed-loop system between Balticovo's farms and the biogas facility.

Results and Impacts:

Aspect	Impact
Environmental	Significant reduction in CO_2 and methane emissions. Reduced environmental risk from nutrient run-off. Substitution of fossil fuels with renewable energy.
Energy Independence	Contributes to Latvia's renewable energy goals. Enables Balticovo to use self-generated, green energy in operations.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Operational Efficiency	Reduced waste disposal costs. Lower energy costs over the long term.
Reputation & Market	Positioned Balticovo as a sustainability leader in the agri-food sector. Boosted brand image with environmentally conscious consumers.

Key Learning Points:

- Waste Can Become a Resource – Balticovo's model shows that even challenging waste streams can be valuable inputs in a circular economy.
- Innovation Overcomes Barriers – Technical challenges, such as manure composition, can be solved through targeted R&D and partnerships.
- Industrial Symbiosis Drives Efficiency – Aligning production outputs (waste) with renewable energy systems creates economic and environmental synergy.
- Sustainability Enhances Market Position – Circular practices not only reduce environmental footprint but also boost brand value.

Discussion Questions:

1. What are the potential risks and benefits of relying on manure-based biogas for large-scale operations?
2. How can this model be adapted for smaller farms or other types of agricultural waste?
3. What role do governments and subsidies play in making such systems viable?
4. How can industrial symbiosis expand beyond energy to include water, heat, or nutrient recovery?

Resources:

- Balticovo Website: https://balticovo.lv/lv
- Balticovo's Biomethane Project (media coverage): https://balticovo.lv/lv/jaunumi/balticovo-atklaj-latvija-pirmo-biometana-uzpildes-staciju
- EU Bioeconomy Report (for context): https://ec.europa.eu

5 Turning Textile Waste and Recycled Paper into Eco-Friendly Building Materials

Summary:

Balticfloc, a Latvian manufacturer, transforms recycled paper and textile waste into high-performance thermal and acoustic insulation materials. Balticfloc provides environmentally friendly alternatives for the construction and automotive sectors by repurposing secondary raw materials that would otherwise be discarded. This case study explores the company's circular economy approach, its innovations in material processing, the challenges faced, and the resulting economic and environmental impacts.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Context and Challenge:

The global construction industry contributes significantly to resource consumption and waste. Traditional insulation materials often rely on energy-intensive processes and virgin materials. Balticfloc aimed to:

- Reduce dependence on non-renewable resources.
- Prevent textile and paper waste from ending up in landfills.
- Provide cost-effective and sustainable insulation solutions.
- Comply with rising demand for eco-certified materials across EU markets.

Solution – Balticfloc's Approach:

Recycled Material Use:

- Balticfloc sources its raw materials from post-consumer textile and paper waste streams. Cellulose insulation is produced from the newspaper, while textile panels use repurposed fibres.

Eco-Friendly Manufacturing:

- Production avoids chemical additives and uses low-energy mechanical processes to transform raw materials into safe, high-quality insulation and fibre products.

Product Applications:

- Balticfloc's products are used in sustainable construction for thermal and acoustic insulation, as well as in automotive soundproofing and geotextile projects.

Results and Impacts:

Aspect	Impact
Environmental	Significant reduction in landfill waste by reusing paper and textiles. Lower carbon footprint compared to conventional insulation materials.
Innovation	Demonstrated technical feasibility of turning secondary raw materials into high-performance construction inputs.
Market Reach	Supplies environmentally certified products across the Baltic and EU construction markets.
Resource Efficiency	Closed-loop manufacturing process utilizing non-virgin, biodegradable inputs.
Brand & Compliance	Enhanced green credentials and alignment with EU circular economy targets.

Key Learning Points:

- Waste as a Resource – Balticfloc proves that post-consumer materials can deliver industrial-grade performance.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

- Green Materials Meet Market Demand – Eco-conscious construction firms actively seek low-impact insulation solutions.
- Simple, Scalable Production – Low-tech, low-energy processes can support high-value circular innovations.
- Alignment with EU Policies – Compliance with EU green standards strengthens market opportunities and access to funding.

Discussion Questions:

1. How can policy makers support businesses converting textile waste into construction products?
2. What are the limitations of cellulose and textile insulation compared to mineral wool or foam alternatives?
3. How can smaller businesses enter the circular construction product market?
4. In what ways can architects and builders be encouraged to choose recycled material solutions?

Resources:

- Balticfloc Website: https://www.balticfloc.lv/
- Cellulose Insulation Information: https://www.balticfloc.lv/produkts/celulozes-siltumizolacija/

6 Creating Value from Residues: Agrofirma Tērvete's Closed-Loop Biogas and Farming System

Summary:

Agrofirma Tērvete, one of Latvia's most diversified agricultural companies, demonstrates successful industrial symbiosis by integrating livestock farming, crop cultivation, and biogas energy production. By closing nutrient and energy loops, the company transforms manure and agricultural residues into renewable energy and organic fertilisers, fostering a circular model that benefits both the environment and operational efficiency. This case study explores Agrofirma Tērvete's symbiotic systems, their implementation, and their broader impacts.

Context and Challenge:

Agrofirma Tērvete operates in multiple sectors, including dairy farming, crop production, and beverage manufacturing. Its extensive agricultural activity generates significant volumes of manure and biomass residues, posing both logistical and environmental challenges:

- Waste Utilization: Finding sustainable methods to manage and valorise manure and crop residues.
- Renewable Energy Needs: Reducing dependence on fossil fuels and improving energy self-sufficiency.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

– Nutrient Recycling: Enhancing soil fertility without synthetic fertilisers.
- Environmental Compliance: Aligning operations with EU green regulations and climate goals.

Solution – Agrofirma Tērvete's Approach:

Biogas Production:
– Agrofirma Tērvete collects manure and biomass from its dairy operations and fields to feed into a biogas plant. This anaerobic digestion process produces biogas for electricity and heat.

Energy Integration:
– The energy generated from biogas is used to power the farm's operations and district heating systems, decreasing reliance on fossil energy sources.

Digestate Use:
– The byproduct of the biogas process—digestate—is applied back to fields as an organic fertilizer, closing the nutrient loop and improving soil health.

Systemic Circularity:
– This industrial symbiosis model not only reduces emissions and input costs but also boosts resource efficiency and local sustainability.

Results and Impacts:

Aspect	Impact
Environmental	Lower greenhouse gas emissions through biogas utilisation. Significant reduction in synthetic fertiliser use. Improved soil structure and biodiversity.
Energy Security	Self-sufficiency in electricity and thermal energy for farm operations. Contributes to local district heating.
Operational Efficiency	Reduced input and waste management costs. Increased productivity through closed-loop resource use.
Regulatory Compliance	Meets EU environmental standards and benefits from renewable energy incentives.
Community Engagement	Supports local energy systems and serves as a model of sustainable rural development.

Key Learning Points:
– Circular Agriculture Enhances Resilience – Integrated biogas systems can stabilise farm economics and reduce environmental pressure.
– Nutrient Loops Improve Soil and Reduce Chemicals – Organic digestate substitutes synthetic fertilisers and closes material cycles.
– Symbiotic Systems Are Scalable – The Tērvete model can be adapted to farms of different sizes with appropriate investment.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

– Energy-Resource Synergy Drives Innovation – Connecting energy, waste, and food systems delivers high-impact sustainability outcomes.

Discussion Questions:

1. What barriers exist for more farms to adopt biogas-based circular systems?
2. How can public policy and funding accelerate agricultural industrial symbiosis models?
3. What role do local communities play in supporting shared resource systems?
4. How can agricultural businesses better communicate the benefits of circular operations to stakeholders?

Resources:

– Agrofirma Tērvete Website: https://tervete.lv/
– Symbiosis Profile (Sinergia): https://sinergia.lv/esosa-simbioze/agrofirma-tervete/

7 Turning Waste into Growth: Getliņi EKO's Circular Model for Greenhouse Cultivation

Summary:

Getliņi EKO, the largest municipal solid waste landfill in the Baltic region, has become a flagship example of internal industrial symbiosis by using landfill gas to power modern greenhouse operations. This innovative circular economy model reduces environmental impacts associated with waste management and supports year-round vegetable cultivation using renewable energy.

Context and Challenge:

As a growing landfill site managing thousands of tonnes of municipal waste annually, Getliņi EKO faced the dual challenge of reducing greenhouse gas emissions and generating value from waste byproducts. Key challenges included:

– Landfill Emissions: Managing methane emissions, a potent greenhouse gas released during waste decomposition.
– Energy Recovery: Converting landfill gas into a viable renewable energy source.
– Food Sustainability: Addressing Latvia's demand for locally-grown, year-round produce while minimising energy input.

Solution – Getliņi EKO's Approach:

Landfill Gas Collection and Energy Production:

– Getliņi EKO captures methane-rich gas from its landfill site and uses it in cogeneration units to produce heat and electricity. This energy is then redirected to power advanced greenhouses adjacent to the landfill.

Energy-Efficient Greenhouse Farming:

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

- The greenhouses grow tomatoes and cucumbers all year round, made possible by controlled environments powered by the energy recovered from landfill gas. This represents a closed-loop system where waste decomposition supports food production.

Circular Integration:

- Getliņi's model connects waste management, energy generation, and agriculture into one synergistic system—demonstrating practical circular economy principles at scale.

Results and Impacts:

Aspect	Impact
Environmental	Significant reduction of methane emissions through capture and reuse. The utilization of renewable energy reduces fossil fuel dependency.
Energy Recovery	Continuous energy generation from landfill gas enables self-sufficient heating and electricity for greenhouses.
Food Security	Local, sustainable vegetable production reduces reliance on imports. Year-round harvesting supports regional food supply.
Operational Synergy	Integration of waste management and agriculture enhances efficiency and sustainability.
Public Perception	Getliņi is recognized as a leader in circular practices, strengthening its public and institutional credibility.

Key Learning Points:

- Waste-to-Energy is a Viable Agricultural Input – Renewable energy from landfill gas can power intensive farming operations.
- Integrated Systems Maximize Value – Combining waste management, energy, and food systems demonstrates high circularity potential.
- Green Innovation Strengthens Brand – Implementing visible, sustainable practices enhances public and policy support.
- Circular Economy Reduces Emissions and Costs – Efficient resource use benefits both the environment and operational budgets.

Discussion Questions:

1. How can other landfills replicate Getliņi's waste-to-greenhouse model?
2. What are the limitations of landfill gas as a renewable energy source?
3. How does local food production contribute to national sustainability goals?
4. Can similar energy integration models be applied to urban farming or vertical agriculture?

Resources:

- Getliņi EKO Website: https://www.getlini.lv/

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

– Greenhouse Information: https://www.getlini.lv/par-mums/siltumnicas/

8 Turning Wastewater into Wealth: The Circular Model of the Tuscan Tanning District

Summary:

In Santa Croce sull'Arno (Tuscany), over 250 tanning companies collaborate in a regional circular economy system that transforms wastewater and tanning waste into valuable resources. Through shared purification infrastructure, digital monitoring, and valorisation of sludge, the district demonstrates a high-performing model of industrial symbiosis.

Context and Challenge:

The Tuscan leather district faced high environmental pressure due to intensive water and chemical use. Traditional disposal methods were unsustainable, and EU regulations demanded circular transitions.

Solution – The Symbiosis Approach:

Water Reuse:
– The Aquarno consortium treats wastewater and reuses 95% of it in tanning processes.

Sludge Valorisation:
– Sludge from treatment is transformed into fertilizers and materials for construction.

Digital Monitoring:
– SCADA systems monitor flows, environmental parameters, and quality in real time.

Blockchain Pilot:
– Digital traceability of sustainable leather through blockchain pilots managed by the Leather Tech Pole.

Results and Impacts:

Aspect	Impact
Environmental	Massive water savings; waste reduction and decreased pollution.
Economic	Shared infrastructure lowers operational costs for SMEs.
Innovation	New biomaterials and digital systems developed in the Polo Tecnologico Conciario.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Reputation	Recognition as a European model for green leather supply chains.

Key Learning Points:
- Collective infrastructure reduces individual environmental burdens.
- Digital systems ensure compliance and optimize resource use.
- Sustainable leather increases value in global markets.
- Policy incentives facilitate circular transitions in traditional industries.

Discussion Questions:
1. How can legacy industries transition to circularity without losing competitiveness?
2. What role do consortia and innovation hubs play in industrial symbiosis?
3. How to scale blockchain traceability across fragmented sectors like fashion?

Resources:
- ENEA – Atlante della Simbiosi Industriale: https://www.enea.it/it
- Consorzio Aquarno: https://www.aquarno.it/
- Polo Tecnologico Conciario: https://www.polotecnologico.it/

9 Reinventing Waste as Resource: The Symbiosis Hub of Manfredonia

Summary:

In Manfredonia (Puglia), an emerging industrial symbiosis ecosystem is transforming the local economy through a circular use of water, energy and organic residues. The initiative involves agro-industrial firms, a bio-refinery, and local utilities that exchange by-products and utilities to optimize resource use, cut emissions, and foster innovation. This case study explores how cross-sector collaboration led to the creation of a circular cluster that revitalizes a traditionally fragile industrial area.

Context and Challenge:

Manfredonia is home to a mixed industrial area historically affected by environmental and economic fragilities. The main challenges include:
- High resource consumption (water, gas, electricity) by agro-food and chemical industries.
- Costly waste disposal and lack of recycling infrastructure.
- Disconnection between stakeholders limiting knowledge exchange and cooperation.
- Need to align with regional circular economy plans and the EU Green Deal.

Solution – The Symbiosis Approach:

Waste heat and water recovery:

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

– A former ENI petrochemical site is repurposed to host a bio-refinery and food processing plant. Waste heat and purified water from the refining process are reused in adjacent agro-food factories, such as those processing pasta and tomatoes.

Organic by-product exchange:
– Tomato skins, wheat husks and other biomass from food production are sent to the bio-refinery to generate bioethanol and biogas. Digestate from this process is turned into biofertilizers for local farms.

Shared energy system:
– Installation of solar PV and smart meters connects various companies in a shared local energy community (LEC). Predictive tools powered by AI help monitor demand peaks and automate load balancing.

Digital coordination:
– A symbiosis digital dashboard maps resources and suggests new synergies in real time. Blockchain is used for traceability of resource flows.

Results and Impacts:

Aspect	Impact
Environmental	CO_2 emissions cut by 25%; less landfill use; closed nutrient cycles
Economic	18% energy cost savings; new circular businesses emerged
Social	Creation of 25 new green jobs; youth training on IS and green skills
Regulatory Compliance	Full alignment with Italy's Circular Economy Strategy (2022)
Technological	Testing of blockchain-enabled resource matching and AI in circular flows

Key Learning Points:
– Local Collaboration Unlocks Hidden Value – Building trust among firms is the first step toward exchanging resources.
– Digital Platforms Enhance Visibility – Mapping tools enable real-time identification of potential symbiotic links.
– Policy Backing is Crucial – Regional incentives and EU funds facilitated infrastructural investments.
– Flexibility is Key to Scalability – The model is being adapted for use in other areas of Apulia and Campania.

Discussion Questions:
1. How can digital tools accelerate industrial symbiosis in rural or peripheral regions?

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

2. What governance models best support cross-sector industrial clusters?
3. How to replicate the Manfredonia model in regions with low industrial density?

Resources:
- ENEA – Atlante della Simbiosi Industriale: https://www.enea.it/it
- Progetto BIONET – Cluster Tecnologico Nazionale Chimica Verde
- Regione Puglia – Piano per l'Economia Circolare 2022

10 Paper Without Waste: Circular Loops in the Lucca Paper District

Summary:

The Lucca paper district, one of Europe's largest, implemented an industrial symbiosis strategy among pulp mills, recycling plants, and energy companies. By exchanging heat, waste, and secondary materials, the district has become a circular benchmark for the paper industry.

Context and Challenge:

Paper production generates large volumes of sludge and energy demand. In Lucca, traditional disposal and energy costs prompted firms to develop shared systems for circularity.

Solution – The Symbiosis Approach:

Sludge recovery:
- Over 90% of paper sludge is processed into solid recovered fuel (CSS) or compost.

Energy sharing:
- Heat and power produced from waste incineration are shared among paper mills.

Digital coordination:
- Lucense developed a resource mapping system and digital monitoring platform.

Circular training:
- Cartesio Network trains employees and entrepreneurs on symbiosis strategies.

Results and Impacts:

Aspect	Impact
Environmental	Major landfill reduction and lower carbon footprint.
Economic	Reduced energy costs and valorisation of by-products.
Social	Workforce upskilling and new jobs in environmental services.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Replicability	Model applied to other paper districts in Italy and Europe.

Key Learning Points:
- Sector-wide cooperation maximizes material efficiency.
- Digital monitoring strengthens industrial resilience.
- Knowledge-sharing networks amplify innovation.
- Circularity attracts new investments and improves reputation.

Discussion Questions:
1. How can traditional manufacturing benefit from industrial symbiosis?
2. What are the barriers to inter-company energy sharing?
3. How to integrate circular practices in value chain management?

Resources:
- Rete Cartesio: https://www.retecartesio.it/
- Lucense: https://www.lucense.it/
- Regione Toscana – Economia Circolare: https://www.regione.toscana.it/

11 Rooted in Nature: How Sylveco Cultivates Circular Economy in Polish Skincare

Summary:

Sylveco, a Polish natural cosmetics brand, has embedded circular economy principles into its business model – from sourcing to packaging to consumer education. This case explores how Sylveco minimized waste, empowered local economies, and built customer trust, offering a powerful example of how circularity can be a core growth strategy in a competitive market.

Context and Challenge:

Founded in 2006, Sylveco entered a market increasingly concerned about environmental issues, ingredient transparency, and ethical sourcing. The challenge? To compete with global cosmetic giants while staying true to ecological values – and without compromising quality, affordability, or growth. At the time, many "natural" brands were greenwashing. Sylveco saw an opportunity: Be truly sustainable. Not just in product, but in process.

They faced key questions:
- How to sustainably source ingredients in Poland?
- How to minimize plastic use while remaining shelf-stable and safe?
- How to scale without becoming extractive?

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Solution – Sylveco's Approach:

Sylveco took a circular economy approach, focusing on locality, longevity, and loop-closing:

Sourcing:
- Ingredients like birch bark, calendula, and chamomile are locally grown, reducing transport emissions.
- Partnerships with Polish farmers created traceable, low-impact supply chains.

Production:
- Water-efficient manufacturing and low-waste production lines.
- Use of biodegradable or reusable materials whenever possible.

Packaging:
- Focus on recyclable materials and simplified labeling to encourage proper sorting.
- Shift toward glass and biodegradable tubes in premium lines.
- Collaboration with zero-waste stores for refills and package returns.

Consumer Engagement:
- Transparent labeling and ingredient education.
- Community workshops on DIY natural skincare and sustainable living.
- Loyalty programs rewarding eco-friendly actions.

Results and Impacts:

Aspect	Impact
Environmental	Drastic reduction in packaging waste per product unit. Lower carbon footprint thanks to local sourcing and short supply chains.
Market Success	Expanded into several sub-brands (e.g. Biolaven, Vianek, Aloesove) while maintaining core values. Loyal eco-conscious customer base. Presence in over 1000 retail locations in Poland and across Europe.
Social	Job creation in rural areas through partnerships with small-scale farmers. Active role in raising environmental awareness in Poland.

Key Learning Points:

- Circular economy isn't just for waste management – it can be a growth engine.
- Local sourcing creates both environmental and social value.
- Transparency builds deep brand loyalty.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

- Eco-design must be user-friendly to scale.
- Small companies can lead big change.

Discussion Questions:

1. What were the trade-offs Sylveco faced between sustainability and scalability?
2. How can packaging innovation further support a circular economy in cosmetics?
3. What other customer incentives could encourage circular behaviour?
4. How might Sylveco's model evolve with stricter EU regulations or global expansion?

Resources:

- Sylveco Official Website – https://sylveco.pl/o-firmie/
- Interview with Sylveco marketing director – https://wirtualnekosmetyki.pl/-wywiady/sylveco:-wymagania-i-oczekiwania-konsumentow-kreuja-trendy,-na-ktore-rynek-reaguje---teraz-najwazniejsze-sa-kwestie-ekologii
- Interviews with Sylveco – https://www.trustedcosmetics.pl/kosmetyki-naturalne-do-pielegnacji-skory-problematycznej-rozmowa-z-firma-sylveco/

12 Transforming Waste into Resources – Derewenda's Circular Economy Approach

Summary:

Derewenda, a Polish company specialising in the processing of electrical and electronic waste, has embedded circular economy principles into its business model. By utilising advanced recycling technologies, the company maximises resource recovery, minimises environmental impact and contributes to sustainable development. This case study explores Derewenda's strategies, challenges, solutions and the resulting impacts on the environment and society.

Context and Challenge:

Derewenda initially focused on professional waste management services. By 2003, the company expanded its offerings to include comprehensive waste management solutions, particularly in the recycling and disposal of electrical and electronic equipment. With the rapid advancement of technology and increased consumption of electronic devices, Poland faced a growing challenge in managing electronic waste. The improper disposal of e-waste posed significant environmental risks, including soil and water contamination and the loss of valuable materials.

Derewenda recognised the need for an efficient system to handle e-waste responsibly, aiming to:

- Implement technologies to maximise material recovery from e-waste.
- Align operations with national and EU environmental regulations.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

– Educate businesses and individuals on the importance of proper e-waste disposal.

Solution – Derewenda's Approach:

Advanced Recycling Technologies:

– The company invested in state-of-the-art processing facilities equipped with modern technologies to efficiently handle various types of e-waste. These facilities enable the separation and recovery of valuable materials such as metals, plastics, and glass, which can be reintroduced into the production cycle, reducing the need for virgin resources.

Comprehensive Waste Management Services:

– Derewenda offers a full spectrum of services, including the collection, transportation, processing, and disposal of e-waste. This holistic approach ensures that waste is managed responsibly at every stage, minimising environmental impact.

Collaboration with Producers and Collectors:

– The company partners with equipment producers and waste collectors to facilitate the proper handling of e-waste. By working together, they ensure compliance with legal obligations related to waste collection and recycling, streamlining the process for all stakeholders.

Regulatory Compliance and Reporting

– Derewenda assists clients in fulfilling their reporting obligations under environmental laws. This includes preparing detailed reports on the quantities of equipment introduced to the market, collected e-waste, and achieved recycling and recovery rates, ensuring transparency and accountability.

Results and Impacts:

Aspect	Impact
Environmental Impact	Efficient recycling processes have led to significant recovery of materials, reducing the demand for virgin resources. Proper e-waste management has minimised the release of hazardous substances into the environment, protecting soil and water quality.
Operational Success	Derewenda has diversified its services to cater to a broad range of clients, including businesses and individual consumer. By assisting clients with regulatory reporting, the company has strengthened its reputation as a reliable partner in environmental sector.

Key Learning Points:

– Educational initiatives have raised public awareness about the importance of proper e-waste disposal and recycling.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

- The company's growth has contributed to employment opportunities in the waste management and recycling sector.
- Advanced processing technologies are crucial for maximising material recovery and minimising waste.
- Offering end-to-end solutions facilitates proper handling of e-waste at every stage.
- Partnering with producers and collectors streamlines processes and ensures adherence to regulations.
- Assisting clients with compliance fosters strong relationships and enhances the company's credibility.

Discussion Questions:

1. How can Derewenda further enhance its recycling technologies to increase material recovery rates?
2. What strategies can be implemented to encourage more businesses and individuals to utilise Derewenda's e-waste management services?
3. How can the company expand its educational initiatives to promote greater public awareness of e-waste issues?
4. What additional services could Derewenda offer to strengthen its position in the circular economy?

Resources:

- Derewenda Website https://derewenda.pl/

13 Closing the Loop: How Dobis Pioneers Circular Economy in Paper Packaging

Summary:

Dobis is a Polish manufacturer specialising in paper bags and food packaging, has embedded circular economy principles into its operations. Through strategic collaborations and a commitment to sustainability. Dobis has reduced material consumption, incorporated recycled fibres and enhanced production efficiency. This case study examines the approach of Dobis approach to circularity, the challenges faced, solutions implemented and the resulting impacts.

Context and Challenge:

The company was established with a vision to become Europe's leading producer of paper-based food packaging, Dobis operates in an industry increasingly scrutinised for its environmental footprint. The growing demand for sustainable packaging solutions presented both an opportunity and a challenge:

- Material Efficiency: Reducing the weight of packaging without compromising strength and quality.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

- Sustainable Sourcing: Incorporating recycled materials while ensuring product safety and performance.
- Production Optimisation: Enhancing manufacturing processes to minimise waste and resource consumption.

Addressing these challenges required coming up with innovative solutions that aligned with circular economy principles.

Solution – Dobis's Approach:

Collaborative Innovation:
- Partnering with Mondi, a global leader in sustainable packaging, Dobis optimised its paper grades to reduce grammage while maintaining strength and print quality. This led to the development of lighter paper shopping bags containing recycled fibres.

Incorporation of Recycled Materials (Using Mondi's Eco/Vantage range):
- Eco/Vantage Light Fashion: 100% recycled fibres, ideal for fashion and gift bags.
- Eco/Vantage Kraft Pro: 20% recycled content with food safety approval, suitable for fast food and grocery applications.
- Eco/Vantage Kraft Classic: 50% recycled content, balancing strength and printability for food and fashion packaging.

Process Optimisation (Using lighter papers and water-based inks):
- Reduced Material Consumption: Lower paper weight decreased the use of raw materials.
- Enhanced Print Quality: Clearer results with less ink.
- Minimised Adhesive Use: Optimised paper quality led to reduced glue consumption during bag assembly.

Results and Impacts:

Aspect	Impact
Environmental	Significant reduction in paper and ink usage contributed to conservation of natural resources. Incorporating recycled fibres and optimising production processes minimised waste generation. Efficient manufacturing and reduced material transport decreased greenhouse gas emissions.
Market Success	Inclusion of diverse eco-friendly packaging solutions, meeting the evolving demands of the fashion, fast-food and retail sector. Positioned as a leader in sustainable packaging, strengthening relationships with environmentally conscious clients.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Operational Efficiency	Reduced material and ink consumption led to lower production costs. Streamlined processes resulted in higher, yet eco-friendly, manufacturing efficiency.

Key Learning Points:

- Strategic Partnerships Amplify Impact – Collaborating with industry leaders can drive innovation and accelerate the adoption of sustainable practise.
- Integrating Recycled Materials is Feasible and Beneficial – Incorporating recycled content without compromising product quality is achievable and enhances environmental sustainability.
- Process Optimization Brings Multiple Benefits – Enhancing production processes can lead to environmental benefits, cost savings, and improved product performance.
- Circular Economy Practices Enhance Competitiveness – Sustainable innovations can differentiate a company in the market and attract eco-conscious clients.

Discussion Questions:

1. How can companies in the packaging industry further reduce their environmental footprint beyond material selection?
2. What role do consumer preferences play in driving companies toward sustainable packaging solutions?
3. How can small and medium-sized enterprises (SMEs) leverage partnerships to implement circular economy practices effectively?
4. What challenges might arise when integrating recycled materials into existing production lines, and how can they be addressed?

Resources:

- Dobis Website: https://dobis.com.pl/en/
- Article on Dobis and Mondi collaboration: https://www.pressreleasefinder.com/Mondi_/MNDPR314/pl/

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

FINAL CONCLUSIONS

1 Synthesis of Findings

1.1 Awareness and Understanding of Industrial Symbiosis (IS) and Digital IS (DIS)

- **Desk research** shows that IS is a well-theorized concept with practical benefits across sectors, especially when integrated with digital tools like AI, IoT, and blockchain.
- **Survey results** show limited awareness: 43% of respondents were unfamiliar with IS, and only 21% were very familiar. For DIS, only 20% had seen relevant examples.
- **Interviewees** confirmed uneven understanding, with SMEs particularly lacking familiarity. Yet, many unknowingly engage in symbiotic practices without naming them as such.

1.2 Benefits and Opportunities

- **Quantitative data** points to strong perceived benefits: cost savings, resource efficiency, competitive advantage, and improved environmental compliance.
- **Interview data** supports this: participants value DIS for strategic transformation, innovation, and scenario simulation via digital twins and reuse planning tools.
- **Desk research** provides evidence from EU projects (e.g. Kalundborg, Donar, AquafilSLO) showing economic, environmental, and systemic benefits of IS.

1.3 Barriers and Challenges

- **Across all data sources**, consistent barriers emerge:
  - Lack of regulation or incentives for reuse
  - Cost and resource constraints (especially for SMEs)
  - Fragmented platforms and poor interoperability
  - Low data quality and trust
  - Limited digital and legal literacy, etc.
- These reflect both **technical** and **institutional** gaps, often impeding the transition from pilot initiatives to systemic implementation. More about the Blocking Points can be found in section 3 of this chapter.

1.4 Digital Platforms and Tools

- **Desk research** emphasizes the role of matchmaking tools, blockchain, and real-time dashboards in scaling IS.
- **Interviewees** stressed usability issues, integration problems, and the need for sector-specific platforms.
- **Survey data** supports this: interest in digital tools exists (45%), but adoption is low due to lack of skills (69%) and cost (53%).

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

1.5 Capacity Building and Training Needs

- All data points to urgent training needs:
  - Basics of IS/CE
  - Tool use and integration
  - Environmental and legal compliance
  - Use-case-based learning
- Survey: 57% interested in IS/CE basics and cost-saving benefits; interviewees call for visual, step-by-step resources and localized support.

1.6 Policy and Ecosystem Support

- Participants want **stronger policy frameworks**, incentives, and public investment in platforms.

- There's a call for **interoperable, public-interest platforms**, with ecosystem-wide alignment of actors (government, SMEs, academia, intermediaries).

2 Conclusions and Implications for Practice

2.1 Conclusions

1. **Digital industrial symbiosis (DIS) is emerging but fragmented.** Awareness and engagement vary by sector, country, and size of the organization. Many SMEs participate informally, lacking terminology, tools, and strategic direction.
2. **DIS is not just a technical fix but a strategic opportunity.** It supports cost efficiency, circular innovation, and organizational transformation — when embedded in long-term planning and supported by intelligent digital tools.
3. **Implementation is hindered by systemic, technical, and cultural barriers.** Lack of interoperability, limited skills, insufficient incentives, and complex regulations prevent scaling. The digital divide is a critical equity issue for SMEs.
4. **Digital platforms must evolve from pilot tools to public infrastructure.** Success depends on shared data standards, trust mechanisms, and governance models that support transparency, traceability, and collaboration.
5. **Training and guidance are essential.** Practical, accessible, and context-specific support (especially for SMEs) is key to moving from awareness to action.

2.2 Implications for Practice

2.2.1 For SMEs and Companies

- **Embed DIS in strategic planning**, not just compliance.
- Start small: map internal resource flows, engage with local reuse initiatives, and build digital familiarity.
- Collaborate with public and academic partners to reduce learning costs.

2.2.2 For Platform Developers

- Prioritize **usability**, **integration**, and **interoperability**.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

- Offer onboarding support, training modules, and case libraries tailored to SME workflows.
- Integrate AI, tracking, and planning functionalities to support real-time decisions.

2.2.3 *For Policymakers and Public Authorities*

- Create **regulatory incentives** for reuse (e.g. mandates in public procurement, tax breaks for symbiotic exchanges).
- Invest in **public-interest platforms** and shared infrastructure for DIS.
- Promote **awareness and capacity building** campaigns through chambers of commerce, regional development agencies, and VET institutions.

2.2.4 *For Training Providers and Support Institutions*

- Develop **modular training programmes** on IS/CE, digital tools, legal frameworks, and cost-benefit analysis.
- Use real-world examples and local success stories to build relevance.
- Target both **technical staff and decision-makers** in SMEs and public institutions.

3 Blocking Points and Action Plan for the Implementation of Digital Industrial Symbiosis (DIS)

3.1 Blocking Points

As part of the final research findings, this section outlines the key blocking points that hinder the widespread implementation of Industrial Symbiosis (IS) and Digital Industrial Symbiosis (DIS) across organizations, especially small and medium-sized enterprises (SMEs). Based on the qualitative interview data and the quantitative survey responses collected from five European countries, a total of 24 unique blocking points were identified. For each of these barriers, a corresponding action plan has been formulated, along with an indication of the responsible actor(s) for executing the proposed measures.

The blocking points may be divided into six groups:

Regulatory & Policy Barriers

- **Lack of legal mandates for reuse or symbiosis** – No enforcement means few takes action voluntarily. (Qualitative)
- **Complex and unclear regulatory procedures** – Difficult to navigate compliance. (Quantitative)
- **High compliance costs** – Legal processes are financially burdensome. (Quantitative)
- **Lack of tax incentives / unfavorable taxation** – Reused materials are taxed as new, discouraging reuse. (Qualitative)

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

- **Low awareness of legal requirements** – Only 29% of survey respondents understood relevant policies. (Quantitative)

Economic & Financial Barriers
- **High initial costs of digital tools/platforms** – Especially for SMEs. (Both)
- **Uncertain return on investment (ROI)** – Difficult to justify investments without clear outcomes. (Qualitative)
- **Limited public funding or subsidies** – Few support mechanisms to offset risk. (Qualitative)
- **Reuse materials often less competitive than new ones** – Due to valuation and availability issues. (Qualitative)

Awareness & Knowledge Gaps
- **Low awareness of IS/DIS concepts** – 43% of survey respondents had no knowledge of IS. (Both)
- **Unfamiliarity with digital IS tools or use cases** – Only 20% knew examples from their context. (Quantitative)
- **Lack of clear, simplified guidelines** – On how to implement IS/DIS. (Quantitative)
- **Confusion due to conceptual ambiguity** – SMEs often do not recognize their reuse efforts as IS/DIS. (Qualitative)

Digital & Technical Barriers
- **Lack of digital skills or IT staff** – 69% of survey respondents lacked technical knowledge. (Quantitative)
- **Low usability of existing tools** – Often too complex or not tailored to SMEs. (Qualitative)
- **Poor interoperability** – Tools and platforms do not integrate with planning (e.g., BIM), procurement, etc. (Qualitative)
- **Data privacy and cybersecurity concerns** – Identified by 47% of respondents. (Quantitative)
- **Fragmentation of tools/platforms** – Too many disconnected solutions causing confusion. (Qualitative)
- **Poor or unreliable material data quality** – Outdated, unclassified, or missing data. (Qualitative)

Organizational & Operational Barriers
- **Lack of time and personnel** – The most cited survey barrier (61%). (Quantitative)
- **Manual, fragmented reuse processes** – High coordination burden across actors. (Qualitative)
- **Incompatibility with existing workflows** – Tools that don't fit procurement or planning cycles are abandoned. (Qualitative)
- **Short-term mindset in organizations** – Lack of strategic commitment to long-term circular models. (Qualitative)

Collaboration & Ecosystem Barriers
- **Lack of knowledge about potential partners** – 39% of survey respondents indicated this as a barrier. (Quantitative)

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

3.2 Action plan

No.	Blocking Point	Recommended Action	Responsible Party
1	Lack of legal mandates for reuse or symbiosis	Advocate for policy reform introducing reuse quotas and mandatory reporting.	Policy Makers / Environmental Ministries
2	Complex and unclear regulatory procedures	Develop simplified, sector-specific regulatory guides and flowcharts.	Regulatory Agencies / Sectoral Ministries
3	High compliance costs	Introduce financial subsidies or fee waivers for SMEs implementing IS.	Government Finance Departments / SMEs Support Funds
4	Lack of tax incentives / unfavorable taxation	Lobby for tax reforms that reduce VAT on reused materials.	Tax Authorities / Circular Economy Policy Units
5	Low awareness of legal requirements	Create awareness campaigns and legal literacy training targeting SMEs.	Chambers of Commerce / Legal Education Bodies
6	High initial costs of digital tools/platforms	Offer grant schemes or public co-funding for tool adoption.	EU/National Grant Agencies / Innovation Ministries
7	Uncertain return on investment (ROI)	Develop and share ROI case studies and simulation tools.	Chambers of Commerce / Industry Associations
8	Limited public funding or subsidies	Increase availability of targeted public funding streams for IS projects.	Regional Development Agencies / EU Structural Funds
9	Reuse materials often less competitive than new ones	Establish certification and quality assurance standards for reused materials.	Standards Bodies / Certification Authorities
10	Low awareness of IS/DIS concepts	Launch regional and sectoral awareness-raising campaigns.	Business Support Organizations / Sustainability NGOs
11	Unfamiliarity with digital IS tools or use cases	Develop and disseminate practical toolkits and video walkthroughs.	Technology Providers / Circular Economy Platforms
12	Lack of clear, simplified guidelines	Create easy-to-follow implementation guides tailored to SMEs.	SME Support Organizations / Circular Hubs
13	Confusion due to conceptual ambiguity	Use consistent terminology and real-world examples in all materials.	Education Providers / Project Dissemination Teams
14	Lack of digital skills or IT staff	Provide basic digital skills training and digital literacy bootcamps.	Vocational Training Institutes / Digital Skills Providers
15	Low usability of existing tools	Involve SMEs in co-design of user-friendly IS platforms.	Tech Developers / UX Designers
16	Poor interoperability	Set standards for platform integration and encourage API development.	ICT Standardization Bodies / Platform Developers
17	Data privacy and cybersecurity concerns	Provide GDPR-compliant frameworks and data protection toolkits.	Data Protection Officers / IT Security Consultants
18	Fragmentation of tools/platforms	Support national or EU-wide federated reuse platform initiatives.	European Commission / National Digital Authorities

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

19	Poor or unreliable material data quality	Introduce standard templates for material logging and verification.	Platform Developers / Industry Consortia
20	Lack of time and personnel	Promote time efficient IS workflows and co-develop shared services.	Productivity Consultants / SME Networks
21	Manual, fragmented reuse processes	Digitize and automate reuse workflows via mobile-friendly apps.	Software Developers / Process Engineers
22	Incompatibility with existing workflows	Ensure new tools integrate with ERP/procurement systems.	Enterprise Software Vendors / Tool Developers
23	Short-term mindset in organizations	Offer strategic foresight workshops and long-term visioning tools.	Strategic Consultants / Leadership Coaches
24	Lack of knowledge about potential partners	Create matchmaking platforms and local symbiosis hubs.	Cluster Organizations / Innovation Intermediaries

The success of DIS implementation depends not only on technological solutions but on a comprehensive understanding of the structural, operational, and cognitive barriers that organizations face. The action plan provided in this annex presents targeted, actionable recommendations that align with the actual needs and constraints identified during fieldwork. The involvement of multiple stakeholders—ranging from policy makers and educators to technology providers and SME support networks—is essential for overcoming these barriers and enabling an inclusive transition toward a circular economy through digital industrial symbiosis.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Co-funded by
the European Union

FReINDs

Project number:
2024-1-NO01-KA220-HED-000246621

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.