The position of European countries regarding opportunities for Industrial Symbiosis: A comparative analysis employing multi-criteria decision-making tools

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Abstract: The Circular Economy is recognized as a significant model of sustainable development that enables waste reduction, more efficient use of resources and climate neutrality. Considering that the estimates indicate that the planet Earth's resources and biodiversity are expiring, the European Union invests constant efforts to foster the transition towards regenerative business models and create opportunities for consumption within the planetary boundaries. Production industries are identified as particularly significant resource consumers. Therefore, special attention is directed to the feasibility of collaborative business models and the application of digital technologies to address resource depletion and negative environmental impacts. The concept of the Circular Economy has become crucial in global efforts to reduce the ecological footprint and transition to a green economy, especially through the concept of Industrial Symbiosis. Through Industrial Symbiosis, *companies from different sectors combine their waste and by-products, considering them as raw materials, thus optimizing energy consumption, decreasing primary resource consumption and reducing harmful gas emissions. Although the EU's efforts are evident and clear targets have been established through the European Green Deal, it is essential to monitor and analyze regional results for European countries to effectively develop their potential, define strategies, and implement plans that transform material consumption and environmental impact modalities. Therefore, understanding the material and value chains and processes is crucial to reaching the potential and establishing adequate frameworks to facilitate the implementation of Industrial Symbiosis. In this sense, this study aims to analyze the potential of Industrial Symbiosis in EU countries. Multi-criteria decision-making tools have been used for this purpose. The data used in the analysis were obtained from the Eurostat database. The results highlight a significant divide between EU member states in terms of opportunities and eagerness to implement Industrial Symbiosis. The results indicate the need to focus attention on targeted policies to strengthen institutions and companies to analyze the applicability of collaborative business models and integrate Industrial Symbiosis at local, regional, and global levels.*

Keywords: Industrial Symbiosis; European countries; comparative analysis; multi-criteria decision-making

1 Introduction

Fifteen years after the European Commission released the First Circular Economy Action Plan, EU countries have been integrating environmental concerns into their policies and planning [1]. Special attention is paid to waste management through EU documents and recommendations. However, many countries have only recently integrated Industrial Symbiosis (IS) into their waste management plans. IS is a business model in which traditionally separate industries collaborate to optimise the use of materials and energy. Thus, the networks of cross-sector industries and companies have been created in order to achieve joint economic, ecological and technical benefits. This Circular Economy business model primarily aims to reduce waste by extending value chains for waste and by-products. The driving force is undoubtedly the economic benefit derived from extending the material cycle by sending waste to another industry and reducing waste disposal costs with an economic gain. Networks built through IS go beyond traditional supply chains in the sense of chains within one industry, sector or country and along those chains. Companies, industries and sectors are reassessing the quantities, types and streams of waste and by-products to assess whether there are opportunities for applying a new business IS model. The application of IS can significantly contribute to reducing the consumption of raw materials, increasing energy utilisation and minimising waste disposal [2].

The promotion of IS in the EU aligns with broader sustainability objectives such as climate change mitigation, improved resource efficiency,and the transition towards a low-carbon economy. As countries seek innovative approaches to address environmental challenges, IS provides a practical and effective way to achieve multiple sustainability goals simultaneously. By establishing stronger connections between industries, IS fosters collaboration that can unlock new business opportunities, reduce reliance on virgin materials and improve waste valorisation. Moreover, IS is increasingly recognised as a key enabler for achieving the objectives set out in the European Green Deal, promoting circular value chains and decoupling economic growth from resource consumption.

Two literature gaps related to IS have been identified. First, it is generally accepted that IS business models must be highly adapted to the specific needs of the environment, therefore, a vast amount of literature deals with case studies related to specific products or companies (micro level), eco-parks (meso level) or regions, counties (macro level) [3-5]. However, comparative studies would help evaluate the potential of specific countries to implement IS within and across borders.

Second, a set of comparable indicators must be established to measure and monitor the potential and progress in IS implementation. Considering the scope and diversity of IS systems, a unique set of indicators, especially those related to entire countries, has not yet been found in the literature. Developing these indicators is essential for policymakers, industry stakeholders, and researchers to track IS progress, assess environmental and economic outcomes, and identify best practices that can be replicated across different regions. By creating consistent evaluation criteria, countries can better measure their progress in achieving IS goals and identify areas requiring further support or innovation.

The paper aims to analyze the potential of Industrial Symbiosis in EU countries. For this type of research, the need for uniformly collected and mutually comparable indicators is additionally expressed. Databases managed by certain international organizations can be a fruitful source for such research. In this sense, the data in this research were obtained from the Eurostat database and used to compare EU member states.

The methodology used in the paper is a hybrid CRITIC-TOPSIS, where CRITIC (CRiteria Importance Through Inter-criteria Correlation) was used to determine the objective weights of the criteria, while TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) was used to determine the order of EU countries based on their IS potential.

The importance of such a study is reflected in the analysis of the potential of neighbouring countries that have diversified production to establish IS networks, especially due to the fact that the EU market is viewed as a single one. The results of this study can be crucial for discovering the factors that can contribute to or hinder the successful implementation of IS in certain countries. The analysis of the results looks back at the comprehensive challenges that may arise, such as geographical and logistical challenges, specific industries and material needs, as well as levels of industry development.

2 Literature review

2.1 Identifying the methods for analyzing IS potentials

In the literature, one cannot find a large number of works that deal with Industrial Symbiosis (IS) using methods for comparison in an international context. Works connecting IS and MCDM (Multi-Criteria Decision-Making) deal with the assessment and selection of the optimal scenario in specific industries [6], eco-industrial parks [7], facilitating frameworks for specific countries [8,9].

Sonel et al. (2022) use MCDM to analyze and compare the factors that affect adopting IS using ANP (Analytic Network Process) by creating a network of groups of factors and sub-factors to evaluate environmental, economic, institutional and legal factors. The results indicate the greatest importance of the environmental factor, and the most significant sub-factor within it is environmental awareness [10]. Chrysikopoulos et al. (2024) analyzed critical factors for the success of IS implementation and, using the DEMATEL (Decision Making and Trial Evaluation Laboratory) method, determined that leadership and technology most significantly influence IS and are the driving forces behind all other factors [11].

In one of the more recent works, which is close to IS due to waste management, Sharma et al. (2025) assessed the potential for improving the sustainability of waste management practices. The authors used the IF-TOPSIS approach to deal with the issue of waste collection and segregation strategies as a way to foster a circular economy and achieve material savings [12].

A bit more research in terms of comparative research is found in works dealing with the Circular Economy [13]. Özkaya (2024) performed a comparative analysis of EU countries focusing on the Circular Economy, considering Sustainable Development Goals. He employed several hybrid methods, the CRITIC-Based MAUT (Multi-Attribute Utility Theory) and COPRAS (COmplex PRoportional ASsessment) [14]. Kaya et al. (2023) analyzed the circular economy in terms of social factors in EU countries. The conclusions of this paper indicate the clustering of EU countries and propose a reliable decision support system for the evaluation of EU countries. This complex analysis was performed using the integrated CRITIC and MEREC (MEthod based on the Removal Effects of Criteria) methods to determine the weights of the criteria, while the MARCOS (Measurement of Alternatives and Ranking according to the Compromise Solution) method was used for clustering [15]. Candan et al. (2024) assessed the social circular economy performance of EU countries using the perspective of sustainable development by evaluating the positions with the fuzzy VIKOR method [16].

2.2 Identifying the evaluation criteria for IS potentials

This research uses quantitative indicators, which allow comparisons of EU countries. Quantitative indicators that can illuminate the potential of IS can be found in the Eurostat database. One indicator of IS potential is the resource base, that is, the amount of waste of individual materials that could be available for IS. Quantitative measures can also express the amount of waste that is already recycled or used as raw material in other industrial processes, thus assessing the level reached by individual countries in this segment. Effective use of resources implies quantitative monitoring of the need for raw materials in order to see the consumption of primary and increase the use of secondary raw materials. Therefore, the material footprint is related to the pressure that the final consumption of the state causes on the environment [17].

It is also possible to estimate the economic value of recycled materials that can be used in new processes. In this way, it is possible to identify economically profitable opportunities for IS. Trade in materials that can be recycled and whose life cycle is extended in this way fosters economic growth while at the same time affecting the reduction of the environmental burden.

The quantification of greenhouse gas emissions indicators is crucial for the assessment of emission reduction and the evaluation of the effectiveness of policies and goals aimed at emission reduction.

Planetary boundaries represent limits that must not be crossed in order to preserve the stability of the Earth's ecosystem [18]. Their measurement is linked to the consumption footprint and measures the environmental impact of EU members. For each category, planetary boundaries represent the ratio of the absolute value divided by the planetary boundary per capita [19]. According to this, the set of indicators used to assess the potential of IS is presented in Table 1.

Label	Indicator	Measure
C1	Circular material use rate	Percentage
C2	Trade in recyclable raw materials -Imports intra-EU27	Thousand euro
C3	Trade in recyclable raw materials -Imports extra-EU27	Thousand euro
C4	Trade in recyclable raw materials -Exports extra-EU27	Thousand euro
C5	Waste generation per capita	Kilograms per capita
C6	Material footprint	Tonnes per capita
C7	Greenhouse gases emissions from production activities	Kilograms per capita
C8	Consumption footprint -Acidification	Planetary Boundary
C9	Consumption footprint -Climate change	Planetary Boundary
C10	Consumption footprint -Resource use, fossil	Planetary Boundary
C11	Consumption footprint - Resource use, minerals and metals	Planetary Boundary
C12	Consumption footprint -Water use	Planetary Boundary

Table 1

IS indicators (Eurostat)

3 Methodology

Given the large number of IS indicators and the fact that some of them have opposing effects, a simple assessment of IS potential is not possible. The selected indicators are used to monitor IS potential in different segments, and at the same time, a unique ranking list that provides insight into the positions of individual EU states must be obtained.

In order to effectively assess the potential of each country, a hybrid evaluation method combining CRITIC and TOPSIS was developed. In decision-making problems that contain many criteria and possible solutions, managers often struggle to determine the relative importance of specific criteria, and even if they can, the results are biased by their subjectivity and can lead to distorted results. However, there are ways to address the limitations of the subjective assessment of weighting coefficients. The CRITIC methodology was proposed by Diakoulaki et al. (1995) for the objective determination of the criteria weight, which is based on the study of the decision matrix and the expression of the conflict and the intensity of the contrast contained in it [20].

For the selection and ranking of alternatives, Hwang and Yoon developed TOPSIS [21]. This method is intensively used in research and has experienced many extensions and hybrid models. Mainly because it also includes criteria weights, it represents a basis for combining various objective and subjective methods for determining the importance of criteria in decision models [22,23]. In research on the Circular Economy and waste management, TOPSIS was used to assess barriers to implementing waste management strategies [12] and analyze barriers in the Circular Economy [24].

The hybrid CRITIC-TOPSIS methodology can also be found in the literature in various segments. It was used, among other things, in the research of material selection [22], stakeholder assessment [25], financial performance assessment [26], and software reliability [27]. A methods flow chart was created to present the process of obtaining results and clarifying the methodology, presented in Figure 1. Detailed methodology with mathematical procedures used for the calculation can be found in the works of [20, 21,28,29].

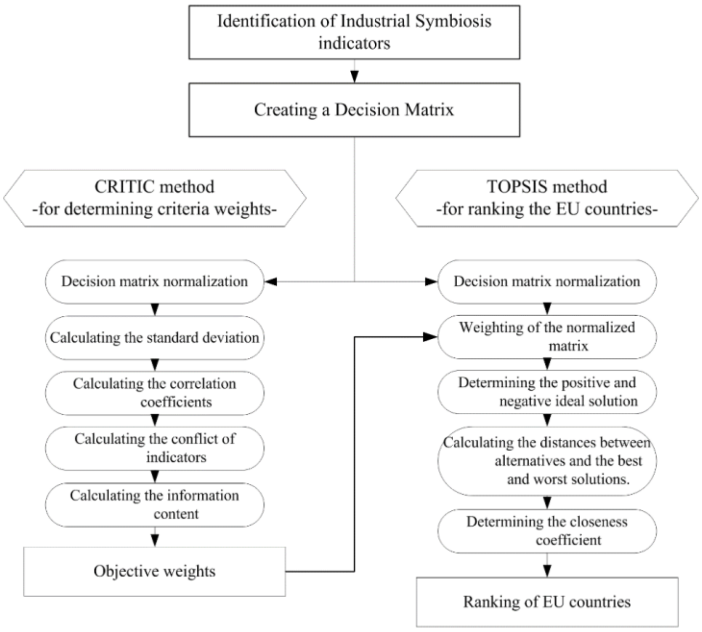

Figure 1
Metods flow chart [29]

4 Results

The initial decision matrix comprised 12 criteria outlined in Table 1 and 27 alternatives consisting of EU member states. Utilising the CRITIC method, indicator weights were determined using an objective approach based on the information contained in the collected data. The data was gathered by employing a representative year in which the data set is complete, as some indicators are collected annually while others are gathered biennially. The results indicate that the biggest contribution to the ranking is the indicator of Circular material use rate. The TOPSIS approach was used to rank EU countries based on 12 proposed criteria, and the obtained results are presented in Table 2.

Rank	**Country**	**Rank**	**Country**	**Rank**	**Country**
1	Germany	10	Greece	19	Lithuania
2	Belgium	11	Denmark	20	Slovenia
3	Netherlands	12	Slovakia	21	Austria
4	Italy	13	Croatia	22	Sweden
5	Spain	14	Czechia	23	Estonia
6	France	15	Latvia	24	Romania
7	Malta	16	Hungary	25	Luxembourg
8	Poland	17	Ireland	26	Bulgaria
9	Portugal	18	Cyprus	27	Finland

Table 2

Rank of EU countries (own research)

Based on their distance from the ideal solution, the results indicate that Germany has been assessed as having the highest IS potential, followed by Belgium and the Netherlands.

Discussion and conclusion

Industrial Symbiosis (IS) is a business model focused on retaining the added value of products as long as possible and eliminating waste simultaneously. This is achieved by monitoring and analyzing business processes within but also beyond production processes. Many institutions and policies support IS through support for the Circular Economy. The IS business model is entirely in line with the Sustainable Development Goals (SDGs), especially SDG 12. SDG 12 aims to improve resource management by reducing waste, increasing recycling and promoting sustainable production practices. Planning operations following IS needs enables the identification of key areas in which it is possible to minimize waste generation, improve resource efficiency and implement sustainable business practices, which leads to numerous positive effects.

Nevertheless, the transformation of companies towards IS is complex and faces numerous challenges [24]. This work is based on the assumption that some EU countries are better prepared and have greater potential for IS implementation. The results indicate that the German economy has the greatest potential for IS implementation based on the analyzed criteria. Namely, when evaluating the current level of IS implementation, Denmark, as the cradle of this type of company integration, is still ahead of its counterparts. The Danish government, seeing the benefits that come from IS, has strongly supported initiatives in the circular economy [30]. Also, the Netherlands is stated as one of the leading countries in this segment, particularly highlighting geographical positions and importance in global logistics as an advantage in IS implementation [31].

However, when it comes to potential, Germany has the greatest potential due to the fact that it has a developed industrial base and is one of the leading industries of the EU. Large industrial systems produce large amounts of waste and by-products that can be used in other industries. Also, developed infrastructure allows for easy trade and transport of these materials. The Netherlands is also at the top of the list, primarily because of its good geographical position and developed transport infrastructure, which contributes to the efficient distribution of resources [31,32].

The position of the last ranked country in this research, Finland, can not be overlooked. Although Finland is recognised as a leader in many environmental aspects, several shortcomings can be identified in the specific context indicators related to its contribution to IS. First of all, the Finnish industry has developed specific branches, such as paper and forestry, and technologies that do not create a wide range of by-products that have not already been recycled, so their capacities for synergy are limited. Secondly, in ranking results, countries with a favourable geographical appeal occupy a high rank, and for Finland, geographical and logistical challenges can be considered as a big drawback for IS.

Overall, the study's results indicate that there are differences between EU countries in terms of their potential for IS implementation. When looking at the results, one cannot see the traditional divisions of east and west or north and south, but rather the connection with the strength and extent of the industrial development of a country, as well as with the estimated institutional support. Therefore, further progress in IS implementation is closely tied to the economic level and the level of development of industrial sectors, as well as infrastructure. Incentives toward IS can additionally help improve economic conditions, create new jobs and improve the general environmental and social situation. The institutional and European support for waste reduction and resource efficiency that helps companies in IS endeavours should not be left out. In future research, it is necessary to examine the conditions in which IS is most fruitfully developed and to adapt the IS model for implementation in the lagging areas.

The most significant limitation of this research lies in the lack of consistent data for European countries that are not EU members. This gap is particularly important, given that certain conclusions suggest that in more advanced countries, particularly in industries, greater attention is devoted to IS. However, this does not imply that less is produced in less developed countries, as their potential for IS may be more pronounced.

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