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Evaluating and Advancing Industrial Symbiosis Solutions Through Stakeholder-Driven Multicriteria Decision Analysis: Insights from The SYMBA Project

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ABSTRACT

Industrial symbiosis is a key enabler of the circular economy, fostering cross-sector collaboration for the reuse of energy, materials, and resources. However, the implementation and scaling of industrial symbiosis solutions are often constrained by differences in maturity, stakeholder readiness, and contextual suitability. This paper presents a stakeholder-driven Multicriteria Decision Analysis methodology developed within the Horizon Europe-funded SYMBA project (101135562) to evaluate and prioritise industrial symbiosis solutions in bio-based industrial ecosystems across Europe. The framework assesses over 150 industrial symbiosis solutions using five readiness dimensions and weighting factors co-created through iterative engagement with internal and external stakeholders. The methodology enables the classification of solutions by maturity and provides targeted implementation guidance, offering a transparent and replicable decision-support tool to advance industrial symbiosis.

KEYWORDS

Industrial symbiosis; Multicriteria decision analysis; Sustainability indicators; Stakeholder engagement; Bio-based economy; Decision support; Readiness levels.

INTRODUCTION

Industrial symbiosis (IS) has emerged as a cornerstone of the circular economy, enabling industries to improve resource efficiency by transforming waste streams, energy, water, and by-products into valuable inputs for other processes [1] By fostering collaboration across sectors and value chains, IS contributes to reduced environmental impacts, enhanced economic performance, and increased resilience of industrial systems [2].

In recent years, IS has gained increasing attention in European policy frameworks, including the EU Circular Economy Action Plan [3] and the updated EU Bioeconomy Strategy [4]. These initiatives emphasise the need to strengthen local value chains, reduce dependency on primary resources, and promote sustainable industrial practices. Despite this growing recognition, the practical implementation of IS solutions remains uneven across regions and

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sectors. While numerous initiatives and tools exist, many IS projects struggle to progress beyond pilot stages or to achieve long-term replication and scaling.

A key barrier to wider adoption lies in the lack of harmonised and transparent approaches to evaluate and prioritise IS solutions [5]. Existing assessments often focus on isolated dimensions, such as technical feasibility, environmental performance, or economic viability, without capturing the multidimensional nature of IS [2]. Recent studies have highlighted the proliferation of assessment methods across the IS lifecycle, as well as the limited integration between technical, organisational, and contextual factors [6]. Moreover, decision-making processes frequently overlook organisational capacity, legal and ethical considerations, or societal acceptance, all of which can critically influence implementation success [7]. At the same time, indicator-based approaches tend to emphasise environmental or resource efficiency metrics, often overlooking governance structures, regulatory constraints, and societal dimensions, which are critical for implementation [2]. As a result, evaluation frameworks frequently fall short in supporting comprehensive and actionable decision-making, particularly in early-stage or heterogeneous IS initiatives. These limitations are consistent with gaps identified in recent reviews of IS assessment methods, which highlight the lack of integrated and implementation-oriented evaluation frameworks [6]

To address these challenges, there is a growing need for indicator-based decision-support frameworks that integrate multiple dimensions of readiness and incorporate stakeholder perspectives. Multicriteria Decision Analysis (MCDA) has proven particularly suitable in sustainability contexts, as it enables the systematic integration of qualitative and quantitative criteria while explicitly accounting for trade-offs and stakeholder preferences [8]. When combined with participatory processes, MCDA can enhance transparency, legitimacy, and practical relevance in complex decision-making environments.

Within this context, the Horizon Europe-funded SYMBA project aims to advance IS in Europe's bio-based industrial ecosystems by developing innovative methods to assess, prioritise, and support IS solutions. A central contribution of SYMBA is the development of a stakeholder-driven MCDA framework that evaluates IS solutions across multiple readiness dimensions and translates assessment results into actionable guidance.

This paper advances a structured and participatory approach to the evaluation of IS solutions. The main contribution lies in the development and application of a stakeholder-driven MCDA framework that integrates multiple readiness dimensions into a unified evaluation model. Specifically, the framework: (i) operationalises readiness levels as a comprehensive indicator system capturing both technical and contextual aspects of IS implementation; (ii) incorporates a participatory weighting process that combines expert judgement with external stakeholder perspectives; and (iii) links evaluation outcomes to a maturity-based interpretation that supports actionable decision-making. By combining these elements, the proposed approach extends existing MCDA applications in sustainability by explicitly addressing the integration of stakeholder preferences, multidimensional readiness, and implementation-oriented guidance.

Building on this contribution, the objective of this paper is to present and demonstrate a stakeholder-driven MCDA framework developed within the SYMBA project to support the evaluation and prioritisation of IS solutions.

METHODOLOGICAL FRAMEWORK

Evaluating IS solutions involves balancing multiple, often interrelated dimensions, including technical performance, environmental benefits, organisational capacity, regulatory compliance, and social acceptance. Traditional single-criterion or purely quantitative approaches are inadequate to capture this complexity, as they tend to oversimplify decision contexts or overlook qualitative factors that are critical for implementation success [7].

MCDA offers a structured and transparent framework to address these challenges. MCDA enables the integration of heterogeneous criteria (both quantitative and qualitative) into a coherent evaluation model by assigning relative importance (weights) to each criterion and aggregating performance scores into composite indicators. This approach has been widely applied in sustainability assessment, environmental management, and technology selection, where trade-offs between competing objectives are unavoidable [9].

In the context of industrial symbiosis, MCDA is particularly valuable for three reasons. First, it allows the simultaneous consideration of multiple readiness dimensions that jointly determine the feasibility and maturity of IS solutions. Second, decision quality is enhanced through participatory processes in which stakeholder knowledge and preference are integrated into the weighting process. Third, it produces transparent and reproducible results that can be communicated to diverse audiences, including policymakers, industry practitioners, and funding bodies.

Building on these strengths, the SYMBA project adopted MCDA as the methodological approach to evaluate and prioritise IS solutions across Europe. The methodology was designed not only to rank solutions, but also to provide insights on what actions are needed to improve the maturity of the IS solution.

Definition of Readiness Levels as Evaluation Indicators

To operationalise the evaluation of IS solutions within the MCDA framework, the SYMBA methodology adopts a readiness-based indicator system. The use of readiness levels allows the assessment of IS solutions not only in terms of their potential benefits, but also according to the conditions required for their effective implementation, continuity, and replication. This approach recognises that the success of IS initiatives depends on a combination of technical, environmental, organisational, regulatory, and societal factors.

As illustrated in Figure 1, the SYMBA framework is structured around five complementary readiness dimensions: Symbiosis Readiness (SymRL), Environmental Readiness (ERL), Organisational Readiness (ORL), Legal and Ethical Readiness (LRL), and Societal Readiness (SRL). Together, these dimensions provide a holistic representation of IS maturity, capturing both the core characteristics of symbiotic exchanges and the enabling conditions that support their deployment in real-world contexts.

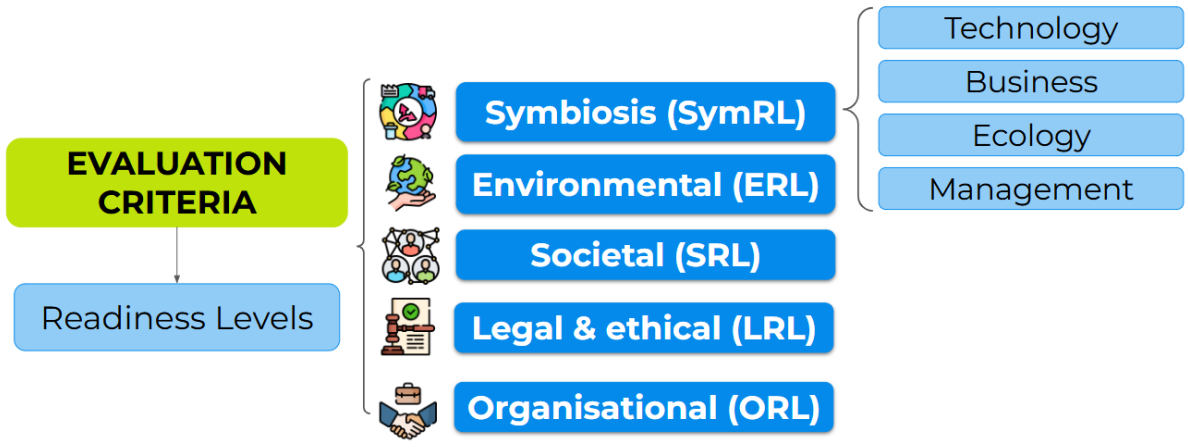

Figure 1. Readiness levels used in the MCDA

SymRL represents the core dimension of the framework and reflects the extent to which an IS solution achieves effective and stable integration of resource exchanges. This readiness level captures the maturity of the symbiotic relationships themselves, considering aspects such as the technical feasibility of exchanges, the integration of material, energy, or water flows, and the coherence of the overall system configuration [10].

Given its central role, SymRL is assessed using a more granular scale than the other readiness dimensions. The evaluation criteria and scoring levels used to assess SymRL are presented in **Table 1**, which outlines progressive stages of symbiotic maturity, from early conceptualisation to fully operational and replicable solutions. This differentiation allows the framework to distinguish between IS initiatives that are still exploratory and those that demonstrate consolidated, system-level integration.

While SymRL captures the core functionality of IS solutions, successful implementation also depends on a set of enabling conditions addressed through four complementary readiness dimensions.

Table 1. Evaluation Criteria of the Symbiosis Aspects

SymRL	Technology	Business	Ecology	Management
9	Commercialisation	Business case continuously controlled, reported, and shared	Sustainability benefits proven	Resilient partnership
8	Extended operation	Finalise legal framework	Benefits routinely monitored and reported	Practical operation and management start
7	Demonstration	Partners committed	Monitoring and reporting begin	Senior management is involved and supports IS case
6	Prototype demonstration "looks like"	Business case with all details	Permits applied	Concept for joint management is developed
5	Breadboard demonstration "acts like"	Evaluate competitiveness	Sustainability assessment finalised	Partners start joint evaluation of industrial symbiosis potential
4	Proof of concept validation	Check resources and criteria	Sustainability assessment in progress	Partners indicate interest
3	Proof of concept research (bench scale)	Check fit with strategies of partners	Thorough data collection	First contact with partners
2	Academic research	Develop concept	Rough estimate	Potential partners identified
1	Initial ideas			

ERL evaluates the extent to which an IS solution delivers environmental benefits and aligns with sustainability objectives **[11]**. This includes considerations related to resource efficiency, emissions reduction, and contribution to circular economy goals. The criteria and scoring levels for ERL are summarised in **Table 2**:

Table 2. Environmental Readiness scale used in SYMBA

ERL	DESCRIPTION
1	Basic principles - Concept formulated.
2	Proof of concept – Preliminary technical evaluation.
3	Scale-up validation of initial assessments – Full-scale feedstock impact evaluation.
4	Full-scale producer impact evaluation – Commercialization.
5	Sustainable feedstock and material supply established.

ORL reflects the capacity of the involved actors to manage, coordinate, and sustain IS activities over time. This dimension captures aspects such as governance structures, coordination mechanisms, and organisational capabilities required to support symbiotic exchanges [12]. The corresponding evaluation criteria are presented in **Table 3**.

Table 3. Organisational Readiness scale used in SYMBA

ORL	DESCRIPTION
1	Identification of the organisational needs (infrastructures, capabilities, skills) and associated organisational readiness aspects. Formulation of proposed solution concept and potential impacts; appraisal of organisational readiness issues; identification of relevant roles, processes, functions, and structures for the solution.
2	Comprehensive description of the proposed solution's impacts within the organisation in terms of roles, competencies and skills, physical infrastructures required. Solution validated through simulation of major induced changes to substantiate proposed impacts and organisational readiness. The organisational developing the solution starts to acquire roles, competencies, and skills, physical infrastructures required.
3	Proposed solution validated through pilot testing in real or realistic organisational environments. The organisation developing the solution achieves roles, competencies and skills, physical infrastructures required. Solution demonstrated in real-world environments and in co-operation with relevant stakeholders to gain feedback in order to improve roles, processes, functions, and infrastructures required.
4	Refinement of the roles, processes, functions and infrastructures required and retesting of the solution in relevant organisational environments. Targeted solution, as well as a plan for organisational embedment, complete and qualified: roles, processes, functions and infrastructures are available.

LRL addresses the regulatory and normative context in which IS solutions operate. This includes compliance with existing legislation, legal feasibility of resource exchanges, and alignment with ethical and safety considerations [12]. The criteria used to assess LRL are detailed in **Table 4**, ensuring that regulatory constraints and ethical considerations are explicitly accounted for in the evaluation.

Table 4 . Legal & Ethical Readiness scale used in SYMBA

LRL	DESCRIPTION
1	Generic consideration of legal and ethical compliance aspects is observed, but nothing has yet been done for the development of the solution. Formulation of the need to enhance the legal normative, laws, rules, and guidelines, and solution concept; appraisal of legal and ethical compliance issues.
2	Abstract description of the proposed solution's legal and ethical compliance. Solution's legal and ethical compliance prospects validated against any required or recommended changes in the legal and/or regulatory system.
3	Definition of the proposed solution's legal and ethical compliance status after pilot testing in real or realistic organisational environments. Detailed description of the required or recommended changes in relevant laws, regulations, or organisational rules to ensure full compliance with the proposed solution.
4	Refinement of the solution within the existing legal and ethical system and, if needed, proposals for required or recommended changes to some aspects of it. Targeted solution, as well as a legal and ethical compliance audit, complete, qualified, and ready to be launched on the market.
5	Actual solution proven legally and ethically compliant after launch on the market.

SRL focuses on social acceptance, stakeholder engagement, and broader societal implications of IS solutions [13]. This dimension captures factors related to public perception, stakeholder support, and social value creation. The assessment criteria for SRL are provided in Table 5:

Table 5. Social Readiness scale used in SYMBA

SRL	DESCRIPTION
1	Identifying problem and identifying societal readiness. Formulation of problem, proposed solution(s) and potential impact, expected societal readiness; identifying relevant stakeholders for the project.
2	Initial testing of proposed solution(s) together with relevant stakeholders. Problem validated through pilot testing in a relevant environment to substantiate proposed impact and societal readiness.
3	Proposed solution(s) validated by relevant stakeholders in the area. Solution(s) demonstrated in a relevant environment and in cooperation with relevant stakeholders to gain initial feedback on potential impact.
4	Refinement of the project and/or solution and, if needed, retesting in a relevant environment with relevant stakeholders. Proposed solution(s) as well as a plan for societal adaptation complete and qualified.
5	Actual project solution(s) proven in a relevant environment.

Together, the five readiness dimensions form an integrated indicator system that supports consistent and transparent evaluation of IS solutions. Rather than assessing individual aspects in isolation, the readiness framework acknowledges that IS maturity emerges from the interaction between technical integration and contextual readiness. The use of differentiated scoring scales allows the framework to capture varying degrees of maturity while maintaining comparability across solutions.

The scoring of the readiness indicators was based on a structured qualitative–quantitative assessment combining available project data and expert judgement. Specifically, each IS

solution was evaluated using information derived from the SYMBA mapping exercise and associated documentation, including technical descriptions, implementation status, and contextual conditions [14]. Where direct quantitative data were not available, scores were assigned through expert-based evaluation guided by predefined criteria to ensure consistency across cases. As such, the resulting scores should be interpreted as indicators of relative readiness and maturity rather than precise measurements of environmental or economic performance.

Multi Criteria Decision Analysis Implementation and Aggregation Logic

The SYMBA MCDA methodology follows a stepwise process that translates the evaluation of individual readiness dimensions into a single composite score for each IS solution (Figure 2). First, each solution is assessed independently against the defined readiness levels, resulting in a set of criterion-specific scores. These scores reflect the degree to which a solution meets the requirements associated with each readiness dimension, based on available information and expert judgement.

Second, weighting factors are applied to each readiness level to represent their relative importance in the overall evaluation. The weighted scores are then aggregated to compute a single composite score for each IS solution. This aggregation enables direct comparison across solutions while preserving the contribution of each individual criterion.

Finally, composite scores are interpreted using predefined maturity ranges that classify IS solutions into three categories: beginner, intermediate, and advanced. This classification supports a shift from purely comparative ranking towards a more actionable assessment, as it links evaluation results to targeted recommendations for improvement, scaling, or replication.

The MCDA framework was implemented consistently across all evaluated IS solutions, ensuring methodological coherence and comparability.

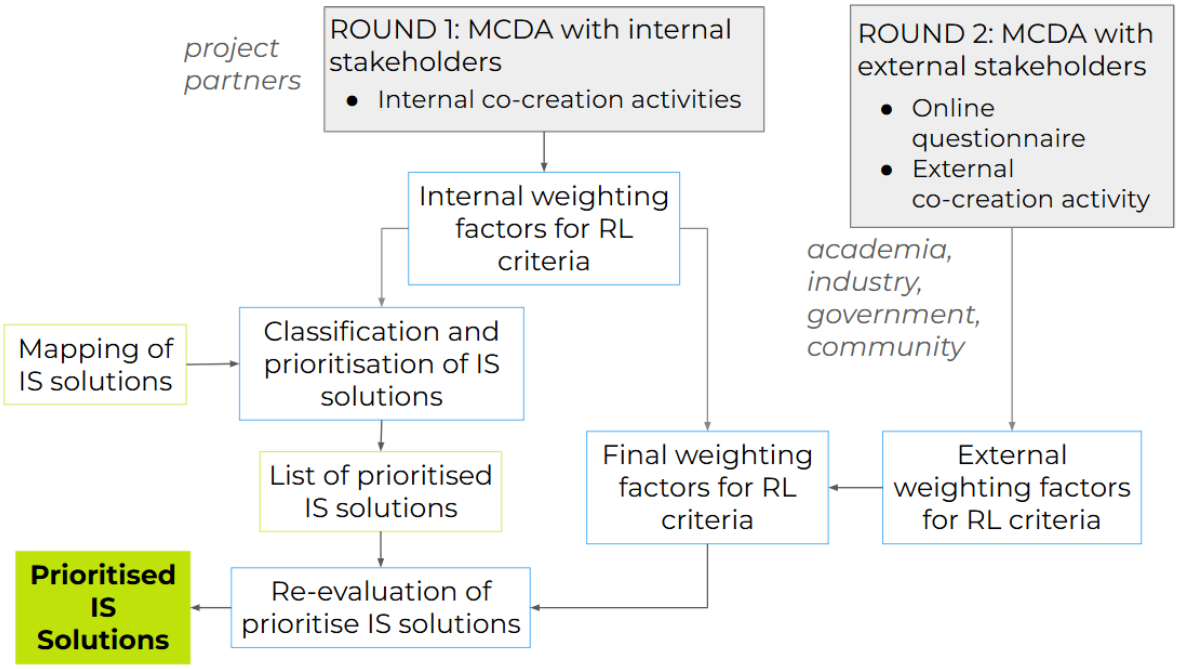

Figure 2. MCDA methodology with steps for its development

STAKEHOLDER-DRIVEN WEIGHTING AND PRIORITISATION

A key objective of the SYMBA methodology is to ensure that the prioritisation of IS solutions reflects not only technical or environmental considerations, but also the perspectives and priorities of the stakeholders involved in their development and implementation. To this

end, the MCDA framework incorporates a participatory weighting process designed to enhance transparency, legitimacy, and practical relevance.

The stakeholder-driven approach was structured in two iterative rounds. The first round involved internal stakeholders associated with the SYMBA project, while the second round expanded the consultation to external stakeholders representing a broader set of interests. This two-step process allowed the methodology to be refined internally before being validated and adjusted through external perspectives, ensuring both methodological robustness and wider applicability.

Internal Stakeholder Weighting

The weighting process began with an internal expert consultation exercise aimed at capturing informed perspectives on the relative importance of the readiness dimensions used in the MCDA framework. This internal step was designed to reflect expert knowledge on IS evaluation and to contribute one of the two complementary inputs to the overall weighting process.

Internal stakeholders involved in this exercise represented expertise in industrial symbiosis implementation, circular economy strategies, sustainability assessment, and decision-support methodologies. Their input was collected through a combination of collaborative discussions and a structured survey-style consultation. First, a joint meeting was held to introduce the readiness framework, clarify the interpretation of each dimension, and ensure a shared understanding of the evaluation scope. This was followed by an individual consultation in which participants assessed the relative importance of the readiness dimensions by assigning weights according to their expert judgement.

The resulting internal weighting factors express a consolidated expert perspective on the key dimensions influencing the maturity and feasibility of IS solutions. The outcomes of the internal weighting exercise were subsequently considered alongside input from external stakeholders. The following subsection describes the external stakeholder consultation process used to complement and broaden the weighting of the readiness dimensions.

External Stakeholder Consultation and Validation

External stakeholder engagement was conducted through a structured, two-step process combining an online questionnaire with a subsequent interactive workshop (**Figure 3**). First, an online questionnaire was distributed to external stakeholders representing academia, industry, public authorities, and civil society reflecting a quadruple-helix perspective, **[15]**. The questionnaire was designed to capture expert judgement on the relative importance of the defined readiness levels using two complementary approaches: a ranking exercise, in which participants ordered the readiness dimensions according to perceived importance, and a weighting exercise, in which participants assigned relative weights to each dimension.

The responses to the questionnaire were aggregated and analysed to derive preliminary external weighting factors. These preliminary results were then used as input for an online co-creation workshop, where stakeholders collectively reviewed, discussed, and interpreted the outcomes of the questionnaire. The workshop provided an opportunity to clarify differing perspectives, validate the consistency of the results, and refine the weighting scheme through discussion and consensus-building. The final external weighting factors were defined based on this combined quantitative and qualitative process, ensuring alignment between individual expert judgement and shared stakeholder understanding.

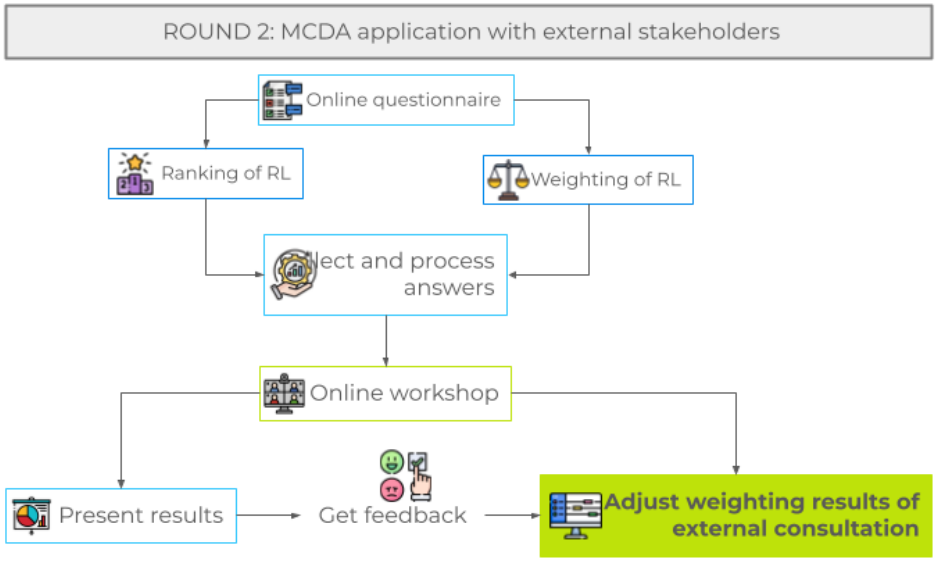

Figure 3. Steps for round 2 of stakeholder consultation

Following the completion of both weighting rounds, the internal and external weighting outcomes were jointly analysed to identify convergences and differences in the relative importance assigned to the readiness dimensions. On this basis, a consolidated set of weighting factors was defined, integrating expert knowledge and external stakeholder perspectives into a single weighting scheme used in the MCDA application.

Taken together, the internal and external stakeholder consultations described above provided two complementary perspectives on the relative importance of the readiness dimensions used in the MCDA framework. Rather than treating one input as a validation of the other, the SYMBA methodology integrates expert knowledge and broader stakeholder perspectives to derive a balanced and transparent weighting scheme. This combined approach enhances the legitimacy and robustness of the weighting process while ensuring that the resulting priorities reflect both technical considerations and contextual values. The final set of weighting factors derived from this process constitutes a core input to the subsequent application of the MCDA framework, where they are used to evaluate, prioritise, and interpret the maturity of IS solutions.

APPLICATION OF THE SYMBA FRAMEWORK: RESULTS AND DISCUSSION

Application to European Industrial Symbiosis Solutions

The SYMBA MCDA framework was applied to a dataset of over 150 IS solutions identified across Europe as part of the project's systematic mapping activities [14]. The solutions encompass a wide range of sectors (agri-food, plastic and packaging, textile, waste and wastewater valorisation) and bio-based industrial ecosystems which were classified into three main categories according to their operational nature: approaches, methodologies, and platforms. This classification captures systematic differences in governance structures, coordination mechanisms, and typical levels of technological maturity, thereby enabling comparative analysis across heterogeneous IS initiatives.

The mapped solutions address diverse forms of resource exchange, including material by-products, energy, water, infrastructure, and shared services. The mapping exercise thus provided the empirical basis for applying the MCDA and testing its capacity to differentiate solutions according to their readiness and maturity. Each solution was evaluated using a structured set of readiness indicators, based on available project data and expert-informed assessment following the criteria defined in the methodological framework section.

Prioritisation Results and Maturity Classification

The application of the MCDA framework resulted in composite scores for each IS solution, derived using a stakeholder-informed weighting scheme and used for prioritisation and maturity classification. The final weighting factors assigned to the five readiness dimensions are summarised in **Table 6**, reflecting the integration of internal expert input and external stakeholder perspectives.

Table 6. Average weightings for the criteria generated in the two rounds (internal and external) and final weighting

Criteria	Internal weighting factor [%]	External weighting factor [%]	Final weighting factor [%]
SymRL	30	27	**28**
ERL	25	18	**22**
LRL	15	21	**18**
ORL	15	21	**18**
SRL	15	12	**14**

SymRL emerged as the most influential criterion in the composite evaluation, reflecting its central role in determining the technical and systemic feasibility of IS solutions. ERL was assigned the second-highest weight, underscoring the importance attributed to environmental performance and circularity outcomes. ORL and LRL occupied intermediate positions in the final weighting scheme, indicating their relevance as enabling conditions for implementation. SRL, while consistently weighted lower, remained an integral component of the evaluation framework.

These results highlight both convergence and nuance in stakeholder priorities. While the overall hierarchy of readiness dimensions was broadly consistent across stakeholder groups, differences in emphasis were observed, particularly with respect to environmental and organisational considerations. Such variations underline the value of incorporating multiple stakeholder perspectives within the MCDA framework.

Using the final weighting factors, composite scores were calculated for each IS solution using Equation (1), where individual readiness scores were aggregated into a single indicator of overall maturity.

$$\alpha = \frac{\sum X_n \times Y_n}{100} \quad (1)$$

where X is the score of each readiness level, Y is the weight given by the MCDA method, and α is the final value for each readiness.

These scores enabled the ranking and prioritisation of solutions within and across the three solution categories. Rather than relying solely on ordinal rankings, the results were further interpreted through a maturity-based classification that groups solutions into three levels: beginner, intermediate, and advanced (**Figure 4**).

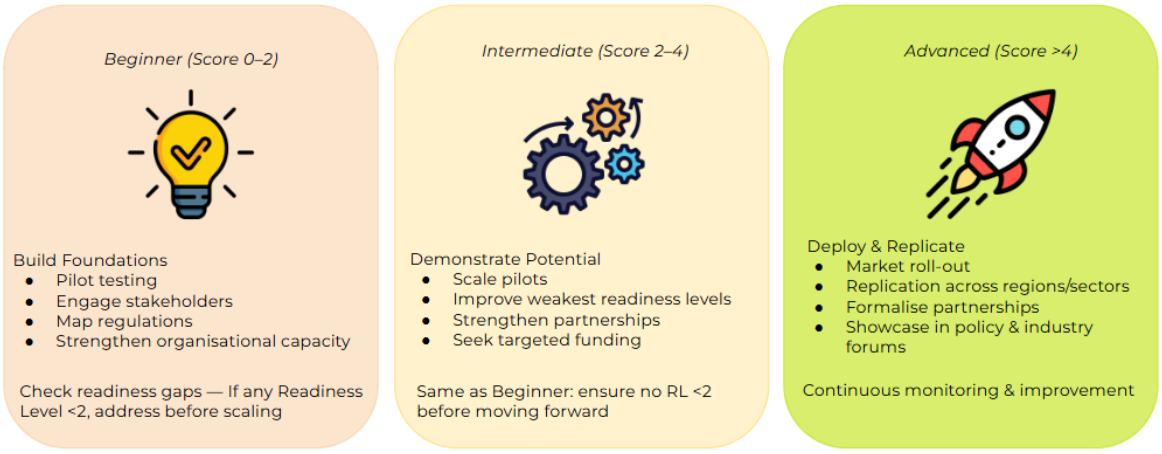

Figure 4. Recommendations based on maturity

Beginner solutions are characterised by low composite scores (lower than two) and typically exhibit significant gaps in one or more readiness dimensions. These solutions often correspond to early-stage initiatives or concepts that require foundational development before scaling can be considered. Intermediate solutions (scores between two and four) demonstrate more balanced readiness profiles, with functioning symbiotic exchanges but identifiable weaknesses that may constrain broader deployment. Advanced solutions (scores higher than four) achieve high scores across most readiness dimensions and are generally suitable for replication, scaling, or transfer to new contexts.

A cross-case analysis of the evaluated solutions reveals several consistent patterns. Solutions classified as platforms tend to achieve higher scores in symbiosis and organisational readiness, reflecting more advanced coordination mechanisms and established stakeholder networks. In contrast, approaches and methodologies generally exhibit lower levels of implementation maturity, often remaining at conceptual or pilot stages. Environmental readiness scores are relatively high across most cases, indicating strong potential for resource efficiency improvements, while legal and societal readiness dimensions show greater variability, suggesting that regulatory conditions and stakeholder acceptance remain context-dependent factors. These patterns highlight the uneven development of IS solutions across different dimensions and reinforce the need for multidimensional evaluation frameworks.

Interpretation and Implication for Industrial Symbiosis Decision-Making

Beyond prioritisation, the SYMBA MCDA framework was designed to inform action. For each maturity category, a set of indicative implementation guidelines was derived based on the readiness dimensions contributing most strongly to the composite score. These guidelines aim to support stakeholders in identifying targeted actions to improve readiness and advance solutions along the maturity spectrum.

In this context, the prioritisation outcomes highlight the central role of symbiosis-related and environmental considerations in shaping stakeholder perceptions of the feasibility of IS solutions. At the same time, the intermediate weighting assigned to organisational and legal dimensions underscores their function as enabling conditions rather than primary drivers of implementation. Taken together, these patterns reinforce the view that successful IS deployment depends on a combination of robust technical integration and supportive institutional contexts.

For beginner solutions, recommendations focus on building foundational capacities, such as strengthening organisational structures, clarifying regulatory conditions, and engaging key stakeholders. Intermediate solutions are encouraged to address specific readiness gaps, improve coordination mechanisms, and seek targeted support to enhance robustness and

scalability. For advanced solutions, guidance emphasises replication, formalisation of partnerships, and integration into regional or sectoral strategies.

These findings are consistent with previous studies highlighting governance, economic, and regulatory barriers as key constraints to the implementation of industrial symbiosis. Henriques et al. [16] discuss sector-specific barriers, whereas Södergren and Palm [5] underline the importance of local governance and institutional conditions.

By linking evaluation results to practical guidance, the framework reinforces its role as a decision-support tool rather than a purely analytical exercise. This feature is particularly relevant for policymakers, cluster managers, and funding bodies seeking to allocate resources effectively and support the strategic development of industrial symbiosis initiatives.

Methodological Contribution and Added Value

The SYMBA framework contributes to the growing body of decision-support tools for industrial symbiosis by operationalising a stakeholder-driven MCDA approach that integrates multiple readiness dimensions into a coherent evaluation model. A key methodological strength lies in the use of readiness levels as structured indicators that support both comparison and diagnosis. By translating qualitative and quantitative information into comparable scores, the framework enables systematic prioritisation while preserving transparency regarding the factors driving overall performance. Furthermore, the maturity-based interpretation of results moves beyond simple ranking, allowing stakeholders to understand not only which solutions perform better, but also why they do so and what actions may be required to improve readiness.

Compared to existing MCDA applications in sustainability, Bystrzanowska [8] notes the reliance on predefined indicator structures and analyst-driven evaluation processes. More recent studies, such as Caruso [9], incorporate multiple sustainability dimensions but continue to depend primarily on expert-defined weighting schemes. In contrast, the SYMBA framework introduces a combined readiness-based indicator system and a participatory weighting process integrating both internal and external stakeholder perspectives, thereby enhancing both the diagnostic capacity of the framework and the legitimacy of the prioritisation outcomes. The observed weighting patterns reflect shared priorities while also capturing nuanced differences linked to organisational, legal, and societal contexts. This approach addresses well-recognised challenges in sustainability-oriented MCDA applications, particularly regarding the transparency and justification of weighting choices and the integration of stakeholder preferences [17].

From a governance and decision-making perspective, the results highlight the potential of the SYMBA framework to support strategic planning across different stages of IS development. By linking prioritisation outcomes to maturity-based interpretation, the framework enables stakeholders to move beyond static rankings and focus instead on identifying development pathways tailored to the readiness profile of each solution. This feature is particularly relevant for policymakers, regional authorities, and funding bodies seeking to allocate resources effectively and design support measures aligned with the maturity and needs of IS initiatives.

At the same time, the application of the framework reveals inherent limitations associated with readiness-based evaluations. While the approach provides valuable insights into implementation conditions and maturity, it does not replace detailed quantitative assessments of environmental or economic performance. Rather, the results underscore the complementary role of the SYMBA framework alongside tools such as life cycle assessment or cost–benefit analysis.

Importantly, addressing this limitation constitutes a core next step of the SYMBA project. Building on the prioritisation results presented in this study, subsequent project activities aim to integrate the MCDA framework with environmental, economic, and circularity assessment tools. This integration is intended to enable a more comprehensive evaluation of selected IS solutions, combining readiness-based prioritisation with quantified sustainability performance

and thereby strengthening the robustness and applicability of decision-support for implementation, scaling, and replication.

CONCLUSIONS

This paper presented a stakeholder-driven MCDA framework developed within the SYMBA project to evaluate and prioritise IS solutions in bio-based industrial ecosystems. By integrating five complementary readiness dimensions into a coherent indicator-based structure, the framework provides a transparent and systematic approach to assess the maturity of IS solutions and support informed decision-making.

The two-step stakeholder engagement process, combining internal expert input with external validation, proved instrumental in enhancing the legitimacy, robustness, and practical relevance of the weighting scheme underpinning the MCDA.

Rather than focusing solely on ranking, the SYMBA approach emphasises learning, improvement, and strategic prioritisation. By identifying specific readiness gaps, the framework supports targeted interventions aligned with the development stage of each solution, thereby facilitating more effective implementation, scaling, and replication of industrial symbiosis practices.

While the framework primarily addresses readiness and maturity, it is designed to complement, rather than replace, detailed quantitative sustainability assessments. Its integration with environmental, economic, and circularity evaluation tools represents a key next step within the SYMBA project and will further strengthen its value as a comprehensive decision-support system.

Overall, the SYMBA MCDA framework contributes to the advancement of sustainability indicators and participatory decision-support methodologies for industrial symbiosis. Its replicable and adaptable structure makes it a valuable tool for policymakers, practitioners, and researchers seeking to promote resilient and resource-efficient industrial systems in support of Europe's circular economy objectives.

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NOMENCLATURE

Abbreviations

ERL	Environmental Readiness Level
IS	Industrial Symbiosis
LRL	Legal & Ethical Readiness Level
MCDA	Multi Criteria Decision Analysis
ORL	Organisational Readiness Level
SRL	Societal Readiness Level
SymRL	Symbiosis Readiness Level

REFERENCES

1. Faria, E., Caldeira-Pires, A. and Barreto, C.,Social, Economic, and Institutional Configurations of the Industrial Symbiosis Process: A Comparative Analysis of the Literature and a Proposed Theoretical and Analytical Framework, *Sustainability*, Vol. 13, No. 13, 2021, https://doi.org/10.3390/su13137123.

2. Verkic, B., Göbbels, L. and Greiff, K., Analysis of environmental indicators assessing industrial symbiosis and urban symbiosis for an improved indicator selection process: A scoping review, *Cleaner Environmental Systems*, Vol. 19, p 100363, 2025, https://doi.org/10.1016/j.cesys.2025.100363.
3. EUR-Lex, EUR-Lex - 52020DC0098 - EN, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0098, [Accessed: Jan. 07, 2026].
4. European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Strategic Framework for a Competitive and Sustainable EU Bioeconomy, *SWD(2025) 895 final,* https://environment.ec.europa.eu/strategy/bioeconomy-strategy_en, [Accessed: May. 08, 2026].
5. Södergren, K. and Palm, J., The role of local governments in overcoming barriers to industrial symbiosis, *Cleaner Environmental Systems*, Vol. 2, p 100014, 2021, https://doi.org/10.1016/j.cesys.2021.100014.
6. Ramírez-Rodríguez, L. C., Ormazabal, M. and Jaca, C., Mapping sustainability assessment methods through the industrial symbiosis life cycle for a circular economy, *Sustainable Production and Consumption*, Vol. 50, pp 253-267, 2024, https://doi.org/10.1016/j.spc.2024.08.005.
7. Harfeldt-Berg, L., Wallin, E., Löwgren, A. and Sommarin, P., Industrial symbiosis readiness level assessment - A stakeholder co-designed matrix tool for guidance and evaluation, *Resources, Conservation & Recycling Advances*, Vol. 27, p 200270, 2025, https://doi.org/10.1016/j.rcradv.2025.200270.
8. Bystrzanowska, M. and Tobiszewski, M., How can analysts use multicriteria decision analysis?, *TrAC Trends in Analytical Chemistry*, Vol. 105, pp 98-105, 2018, https://doi.org/10.1016/j.trac.2018.05.003.
9. Caruso, M., Buttazzoni, M., Passoni, C., Labò, S., Marini, A. and Pinho, R., An updated multi-criteria decision-making method for the sustainable renovation of buildings including environmental, economic and social life-cycle metrics, *Journal of Building Engineering*, Vol. 98, p 110967, 2024, https://doi.org/10.1016/j.jobe.2024.110967.
10. Publications Office of the EU, Study and portfolio review of the projects on industrial symbiosis in DG Research and Innovation, https://op.europa.eu/en/publication-detail/-/publication/f26dfd11-6288-11ea-b735-01aa75ed71a1/language-en, [Accessed: Jan. 19, 2026].
11. Scimita Ventures, How Environmental Readiness Level (ERL) Accelerates and De-Risks Innovation, https://scimitaventures.com/insights/how-environmental-readiness-level-erl-accelerates-and-de-risks-innovation, [Accessed: Jan. 19, 2026].
12. Bruno, I., Lobo, G., Covino, B. V., Donarelli, A., Marchetti, V., Panni, A. S. and Molinari, F., Technology Readiness Revisited: A Proposal for Extending the Scope of Impact Assessment of European Public Services, *Proceedings of the 13th International Conference on Theory and Practice of Electronic Governance (ICEGOV 2020)*, pp 369-380, Athens, Greece, September 23-25, 2020, https://doi.org/10.1145/3428502.3428552.
13. Cresswell, K. M., Bates, D. W. and Sheikh, A., Ten key considerations for the successful implementation and adoption of large-scale health information technology, *Journal of the American Medical Informatics Association*, Vol. 20, No. e1, pp e9–e13, 2013, https://doi.org/10.1136/amiajnl-2013-001684.
14. Villanueva-Rey, P., Robles Dopazo, E., Hernández Martín, D., González Monjardin, L. and Pereira Ferrer, M., SYMBA project Industrial Symbiosis mapping, Dataset, Zenodo, Jun. 2025, https://doi.org/10.5281/zenodo.15703413.

15. Carayannis, E. G. and Campbell, D. F. J., 'Mode 3' and 'Quadruple Helix': Toward a 21st century fractal innovation ecosystem, *International Journal of Technology Management*, Vol. 46, No. 3-4, pp 201-234, 2009, https://doi.org/10.1504/IJTM.2009.023374.
16. Henriques, J., Ferrão, P., Castro, R. and Azevedo, J., Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers, *Sustainability,* Vol. 13, No. 4, Art. 1723, 2021, https://doi.org/10.3390/su13041723.
17. Marttunen, M., Lienert, J. and Belton, V., Structuring problems for Multi-Criteria Decision Analysis in practice: A literature review of method combinations, *European Journal of Operational Research*, Vol. 263, No. 1, pp 1-17, 2017, https://doi.org/10.1016/j.ejor.2017.04.041.

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