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Optimizing Resource Utilization in Industrial Symbiosis: A DEMATEL and FAHP Approach for Sustainable Manufacturing

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Abstract: Industrial symbiosis (IS) represents a strategic framework for collaboration among companies through innovative partnerships, which aimed at optimizing resource utilization, reducing environmental impact, and promoting sustainable development in line with the principles of circular economy. This study conducted a systematic literature review (SLR) and a quantitative analysis of the effectiveness of IS tools in resource management. Publications from January 2020 to December 2024 were retrieved from the established databases such as SpringerLink, ScienceDirect, EBSCO, and DOAJ, with a focus on industrial engineering, environmental management, circular economy, sustainable development, resource conservation, and recycling. Advanced methodologies including the Fuzzy Analytic Hierarchy Process (FAHP) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) were applied to evaluate four key dimensions, i.e., Decision-Making (DMD), Geographical Location (GLD), Strategic Planning (SD), and Lean Manufacturing (LMD), along with 21 subcriteria. The results indicated that DMD and GLD functioned as causal dimensions influencing SD and LMD, while alternatives such as Intelligent Waste Recycling Systems (IWRS) and Life Cycle Assessment (LCA) were considered to be highly efficient in resource utilization. The identification of dominant relationships via the threshold value of α = 0.58 highlighted strategic leverage points for implementing sustainable manufacturing practices. These findings emphasize that effective DMD, combined with strategic planning based on geographical considerations and application of technological tools, is critical for optimizing resources, enhancing environmental protection, and fostering economic and social development, thus providing clear guidance for the implementation of IS strategies in industrial settings.

Keywords: Industrial symbiosis; Lean manufacturing; Circular economy; Decision-Making; Environment; Resources

1. Introduction

Climate change and rapid population growth have intensified the need to transition from traditional linear production models to circular economy (CE) frameworks, which emphasize sustainability and efficient resource use (Mura et al., 2020). With the global population expected to surpass 10 billion by 2050, pressures on food, energy, and water systems are increasing (Dodson et al., 2020; Samberger, 2022), while climate change poses systemic risks that demand fundamental shifts in production and consumption patterns (Durán-Romero et al., 2020). The CE paradigm offers promising strategies to address these challenges, particularly in developing urban contexts (Bellezoni et al., 2022; Filho et al., 2022), by promoting organized and waste-reducing systems that align with sustainable development goals (Knäble et al., 2022; Singh et al., 2022). CE is conceived as a model that enables economic development, while preserving environmental integrity through responsible and cyclical use of resources, supported by partnerships and governance structures that facilitate long-term resilience (Corona et al., 2019; Moraga et al., 2019).

Companies traditionally operating under the linear “take-make-consume-dispose” model have increasingly recognized the relevance of sustainability principles in their strategies (Superti et al., 2021). In this context, CE has gained prominence as a key approach to achieving sustainable development (Neves & Marques, 2022; Prieto-Sandoval et al., 2018). Forming the basis for resource efficiency and environmental preservation, CE is commonly associated with the principles of reducing, reusing, and recycling (Bongers & Casas, 2022; Kirchherr et al., 2017). The Ellen MacArthur Foundation, established in 2010, is one of the most influential initiatives in promoting this transition and it has played a critical role in accelerating the global adoption of CE practices (Korhonen et al., 2018).

The transition from linear economic models to sustainable production systems has placed CE at the forefront of global environmental strategies. Within this framework, regulatory approaches and operational tools such as sustainable resource extraction, eco-design, functional economy, responsible consumption, efficiency of life cycle, and industrial symbiosis (IS) are increasingly recognized as key enablers of resource sustainability (Hallioui et al., 2022; Hotte et al., 2022). In particular, technological advancement acts as a fundamental driver of material savings and supports more informed and strategic decision-making processes which aimed at mitigating environmental degradation (Heshmati & Rashidghalam, 2021).

Recent literature has highlighted the strategic relevance of circular product design in fostering material recovery and reuse (Diaz et al., 2022; Mortensen & Kørnøv, 2019). IS, through the establishment of inter-firm synergies, facilitates the exchange and reintegration of by-products, thus contributing to more efficient resource utilization and extending product life cycles (Carolin C et al., 2023; Smol et al., 2017). These collaborative practices serve not only to reduce waste generation but also to prevent further depletion of natural resources, thereby supporting biodiversity and environmental resilience (Mura et al., 2020).

IS represents a core component of the CE paradigm, defined by the physical exchange of materials, energy, water, and by-products between industrial actors located within a defined geographic area (Azevedo et al., 2021; Fraccascia & Giannoccaro, 2020). These interactions enable firms to lower production costs, improve resource efficiency, and capture mutual economic and environmental benefits (Aamer & Al-Awlaqi, 2022; Galvan-Cara et al., 2022; Shahid et al., 2024). However, the implementation of IS requires robust coordination mechanisms across technical, economic, informational, and regulatory domains to ensure stable and effective partnerships (Mallawaarachchi et al., 2020; Saraceni et al., 2017).

Despite its great potential, IS faces significant challenges due to the uneven distribution of benefits, which incur higher costs or lower gains of some companies (Wadström et al., 2021). Nevertheless, IS remains a prominent strategy for promoting circularity and enhancing industrial productivity. It facilitates the conservation of finite resources (Alakaş et al., 2020), fosters value retention across the production chain (Holgado et al., 2018), and supports the transition from linear to circular business models (Demartini et al., 2022). In particular, IS has shown successful applications in urban contexts, where collaborative exchanges and shared infrastructure can generate significant energy savings and environmental benefits (Godina et al., 2022; Low et al., 2018).

However, the effective implementation of IS remains complex and depends on the ability to accurately identify and prioritize opportunities of reusing resources. Despite advancement in research, there is still a lack of robust methodologies that can adequately address the interdependencies and inherent uncertainties in industrial systems. The absence of appropriate decision-making tools to prioritize these opportunities limits companies’ ability to fully leverage the advantages of IS. In this regard, the combined use of the Fuzzy Analytic Hierarchy Process (FAHP) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) approaches emerges as a promising solution to effectively model and evaluate the causal and hierarchical relationships among the various factors influencing the implementation of IS.

The objective of this study is to apply the FAHP and the DEMATEL approaches to prioritize IS and resource reuse opportunities, based on a detailed analysis of industrial case studies. Through this methodology, the study aims to identify the barriers and key opportunities for the successful implementation of IS across various industrial sectors. This approach will enable companies to make more informed and strategic decisions, optimizing resource use, minimizing environmental impacts, and enhancing their competitiveness, thereby contributing to the transition towards a more sustainable and efficient CE.

2. Methodology

2.1 Systematic Literature Review (SLR)

SLR is a rigorous and structured methodology that enables the collection, evaluation, and synthesis of available evidence on a specific topic, aiming to provide a comprehensive and coherent understanding of the current state of knowledge within a particular field (Mengist et al., 2020). Unlike traditional reviews, which may be biased or selective, SLR is characterized by a methodological framework that ensures greater objectivity and transparency in the selection and analysis of studies, thereby increasing the validity and reliability of the conclusions (MacLure et al., 2016).

This methodology is essential for identifying patterns, trends, and gaps in the literature, making it a key tool for advancing knowledge in complex and multidisciplinary areas. In the context of IS and resource reuse, SLR enables the integration of diverse approaches—such as circular economy models, industrial waste management, and sustainable development—to better understand systemic interactions and identify opportunities for improvement in the implementation of such strategies.

For this study, an extensive literature search was conducted for publications dated between January 1, 2020, and December 31, 2024, using well-established academic databases: SPRINGER LINK, SCIENCEDIRECT, EBSCO, and DOAJ. The search was refined through thematic filters related to industrial engineering, natural resources, circular economy, sustainable development, and conservation, and limited to studies published in the last five years in the English language.

Moreover, in SPRINGER LINK and SCIENCEDIRECT, advanced search strategies were implemented using key terms such as:

- “Industrial Symbiosis” AND “Sustainable Development”
- “Industrial Symbiosis” AND “Resource Use”
- “Industrial Symbiosis Framework” AND “Natural Resource Use” AND “Industrial Re-waste”

These search strategies yielded a robust body of relevant literature addressing the relationships between IS, efficient resource use, and sustainable practices. To ensure the methodological rigor and scientific relevance of this review, inclusion criteria were defined to select only studies that explicitly addressed IS, circular economy, or sustainable resource management. The selected studies in English language were peer-reviewed and published between 2020 and 2024, thereby ensuring alignment with the study’s conceptual framework, scientific validity, and consistency in result interpretation. This approach focused the analysis on current and high-quality evidence, in order to avoid biases from outdated or less rigorous sources. Complementarily, to ensure analytical coherence, reproducibility, and methodological integrity, exclusion criteria were established and studies were removed if they were not relevant to the focus of the research, non-peer-reviewed, published prior to 2020, or written in other languages. The systematic application of these criteria enabled the construction of a reliable and up-to-date literature corpus to provide a solid foundation to identify patterns, trends, and gaps in the implementation of IS and resource reuse strategies. The synthesized evidence reflects scientific rigor, contemporaneity, and relevance for both practice and future research.

2.2 Application of Decision-Making Methods: FAHP and DEMATEL

Based on the findings obtained from SLR, this study adopted a hybrid analytical approach that integrated the FAHP and DEMATEL methods. This methodological combination is particularly suitable for contexts involving multiple qualitative criteria and complex causal relationships.

The FAHP method is employed to assign relative weights to various sustainability criteria under conditions of uncertainty, effectively capturing the ambiguity inherent in human judgments through fuzzy logic. This technique enhances the accuracy and robustness of factor prioritization compared to traditional deterministic approaches. Meanwhile, the DEMATEL method identifies and models cause–effect relationships among critical factors, thus revealing the structural interdependencies within the system and allowing the determination of which elements could act as drivers or consequences in the framework of IS. The integration of FAHP and DEMATEL provides a comprehensive and strategic assessment of the elements involved in the adoption of sustainable practices, in order to support policy design, industrial decision-making, and transition toward circular and sustainable models.

2.2.1 Data collection process

The data collection process was designed to ensure the reliability, consistency, and relevance of expert judgments, following a multi-stage approach:

Expert Selection: Nine experts with recognized experience in IS, resource optimization, and manufacturing sustainability were selected. The participants included (1) senior engineers; (2) academic researchers; and (3) industrial managers from diverse sectors to ensure a balanced representation of technical, managerial, and strategic perspectives. Each expert had a minimum of ten years of experience in sustainability projects and prior participation in industrial optimization initiatives.

Questionnaire Design: Two instruments, one for the FAHP and another for the DEMATEL, were developed. The FAHP questionnaire focused on pairwise comparisons of 21 sub-criteria grouped into four dimensions: decision-making, strategic, geographical location, and lean manufacturing. Experts evaluated the relative importance of each criterion using a linguistic scale, which was subsequently converted into triangular fuzzy numbers to capture uncertainty. The DEMATEL questionnaire assessed causal relationships among dimensions and sub-criteria, asking experts to rate the influence of each element on the others using a five-point scale (0 = no influence; 4 = very high influence).

Data Collection Procedure: Data were obtained from structured online surveys and follow-up interviews to clarify ambiguous responses and ensure consistency. Detailed instructions and illustrative examples were provided to minimize interpretation errors. After the initial collection, responses were checked for completeness and consistency using the FAHP consistency index and cross-validation in the DEMATEL.

Data Processing: The fuzzy pairwise comparison matrices were aggregated using the geometric mean to generate a consensus judgment. For the DEMATEL, the direct influence matrices from each expert were normalized and averaged, in order to construct a combined matrix that was used to calculate the total influence and cause–effect relationships among dimensions.

This rigorous process ensures that the FAHP and DEMATEL analyses are grounded in expert knowledge, adequately capturing uncertainty and providing robust inputs for multi-criteria decision-making and subsequent causal analysis.

3. Results

This study determined 394 references in the search performed, then eliminated the 94 duplicates to obtain 300. Left behind after the excluded records, 150 reports were searched for retrieval and the reports not retrieved were 55 subsequently. For evaluation, we filtered 95 eligible ones and finally we excluded reports from Mining industries = 30, Arid and construction = 20, Industry of biological bases = 10, Area of the medicinal sector = 10, Area of the pharmaceutical industry = 6.

The titles and abstracts of the references were reviewed and 19 articles were selected for full-text review. The 19 articles retrieved were evaluated for inclusion in the literature review as shown in Figure 1.

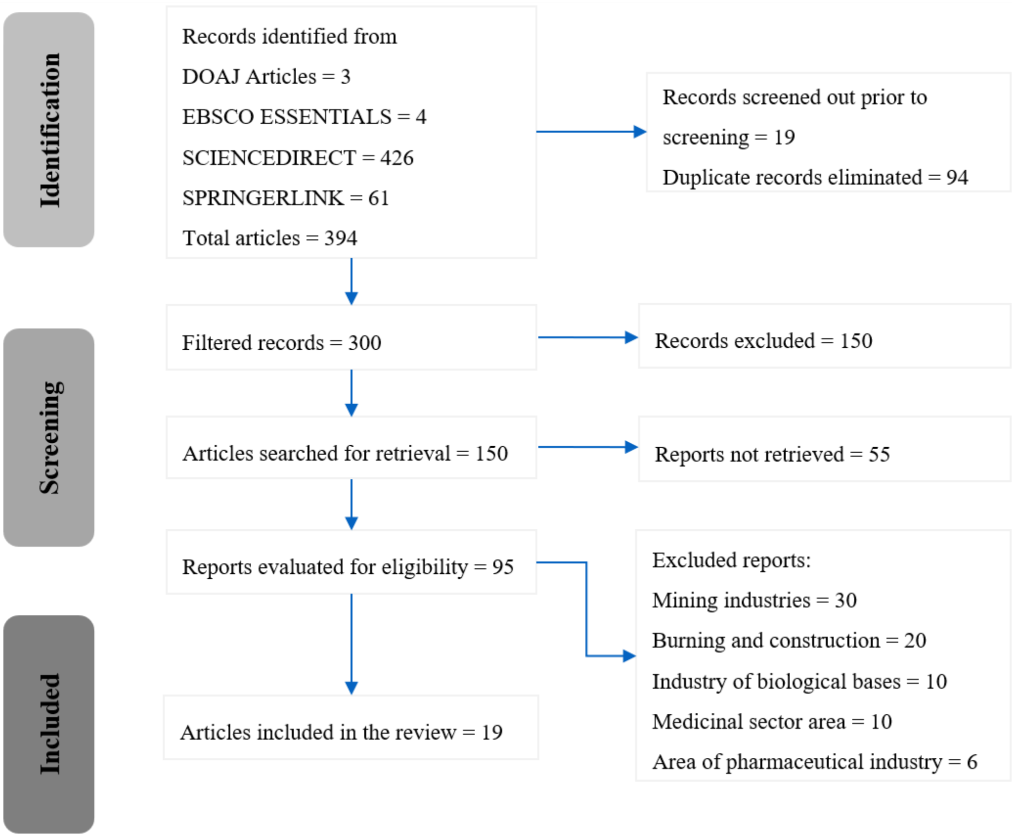

Figure 1. Process of identification, selection, and inclusion of studies in the SLR

Table 1 presents a diverse set of tools and strategies aimed at optimizing resource use in industrial settings, encompassing regulatory approaches, analytical methodologies, emerging technologies, and simulation models. These tools enable the analysis of material flows, assessment of environmental impacts, product redesign, improvement of energy efficiency, and promotion of synergies within IS. Collectively, the reviewed studies highlight an integrative approach that combines environmental criteria, technical capabilities, and organizational strategies, in order to facilitate effective implementation of circular economy and sustainability principles across various industrial sectors.

Table 1. Tools for resource utilization

Tools and Strategies	Description	Utilization	Sources
Environmental criteria and methodology for the establishment	Environmental legislation and environmental regulations.	Rational use of natural resources and resource sustainability.	Shahid et al., 2024
Ecological network analysis methods	The system can be represented as a network composed of nodes (sectors or components).	It helps analyze the distribution of the structure and functional relationships within the ecosystem.	Tian et al., 2022
Eco-efficiency	Saving and reduction of water consumption and ecological sustainable development.	Empirically examines the impact on the eco-efficiency of water resources.	Zhang et al., 2021
Geographical distribution of business strategy	Geographical location, assumed to be constant over the course of time, as a function of supply and demand.	Ability to model the geographical layout of the enterprise.	Raimbault et al., 2020
Zoning method		Establishes a measure of the productive potential of different areas.	Xie et al., 2021
Taxonomy of SI indicators	Division of the earth's surface into areas representing different degrees.	SI synergy allows to reduce waste quantities.	Fraccascia & Giannoccaro, 2020
Capacity rate	Structural features of IS and generate adoption.	Measures the proportion of installed capacity of the industrial sector.	Wang & Li, 2021
Discursive collisions	Development of high-quality manufacturing industry.	Material recovery and product redesign.	Ortega-Alvarado et al., 2021
Virtual reality strategy implementation	Vision of better product design and waste sorting technologies.	Process focused on facilitating the adoption of VR strategies during product development.	Diaz et al., 2022
The value chain	Corporate sustainability strategies, results aligned with the company's sustainability objectives.	The value chain provides the possibility to look for the strategy at the base of the CE.	Muyulema-Allaica & Tapias-Molina, 2024.
Networked analytical process	It is a succession of actions carried out with the objective of installing and valorizing a product in the market.		Alakaş et al., 2020
IS results analytical framework	To understand the mechanisms of how results are derived in IS.	It is to categorize the results, key players and elements in IS research by placing them in well-established concepts.	Wadström et al., 2021
Life cycle assessment	Analyze environmental impacts.	Extraction of raw material to the end of product life.	Demartini et al., 2022
Material flow	Use input/output streams, including material and economic data.	Quantify stock and flow of materials and energy.	
Value stream mapping (VSM)	The VSM approach is widely implemented for waste management purposes.	Map losses and misuses throughout the production process.	Serafim-Silva et al., 2024
Agent-based modeling	They are heterogeneous and autonomous with their own behavioral rules.	Simulate material flows and the IS process.	Han et al., 2022
Multi-agent systems modeling	System composed of multiple intelligent agents interacting with each other.	It serves to solve problems that are complicated to determine for an agent.	Zhou & Fu, 2020
Game theory	It is related to their ability to solve problems involving multiple strategies.	Represents synergies between two or more companies sharing resources.	Jato-Espino & Ruiz Puente, 2021
Energy efficiency analysis	The potential for energy savings in industrial sectors.	Use the least possible amount of energy resources.	Jabari et al., 2024
Materials quality management system	Set of actions and tools aimed at avoiding possible errors or deviations.	To guarantee the quality of the process for which these products are obtained.	Ammar et al., 2021

A review of the existing literature on IS and resource utilization was conducted to identify research areas that remain underexplored (Muyulema-Allaica & Tapias-Molina, 2024; Shahid et al., 2024). Ecological networks aim to preserve ecological functions to sustain biodiversity and ensure sustainable use of ecosystems (Tian et al., 2022). Ecological efficiency encompasses more convenient use of resources, bringing order about greater value and lowering the detrimental impact of the environment (Zhang et al., 2021).

The main study of industrial organizations is location, which strives to take care of and develop the potential of area productivity and environmental impact (Raimbault et al., 2020). The zoning method is the division of area surfaces to establish an efficient measure in production and waste (Xie et al., 2021).

The taxonomy of indicators, with the sole objective of providing their adoption and proper use in practice, answers three main questions: what to measure, where to measure, and how to measure (Fraccascia & Giannoccaro, 2020). In addition, the capacity rate is a fundamental indicator to determine the efficiency of use and management of a company's resources (Wang & Li, 2021).

Waste could be envisioned as a resource for better product design with waste management technologies and more efficient recycling. Shared economics is a vision of IS and new businesses for the supply of trades, reuse and repair of recycled or waste products. The limitation of individual consumption is to envisage individual changes in consumption style, together with the services and purchase of products for repair and reuse (Ortega-Alvarado et al., 2021).

Figure 2 presents a strategic management perspective on design activities, to propose a process model focused on facilitating the adoption of virtual reality (VR) strategies during product development. The implementation of the VR strategy is organized into distinct categories, based on the theory of essential factors for successful strategies. These categories include the strategic context, the strategic process, and the strategic outcomes. Management factors play a crucial role in enabling circular product design at various stages of product planning and development, in order to ensure that VR strategies are effectively integrated throughout the design process. This model highlights how strategic management principles can guide the incorporation of VR technologies into product development, thus promoting sustainability and circularity in design activities.

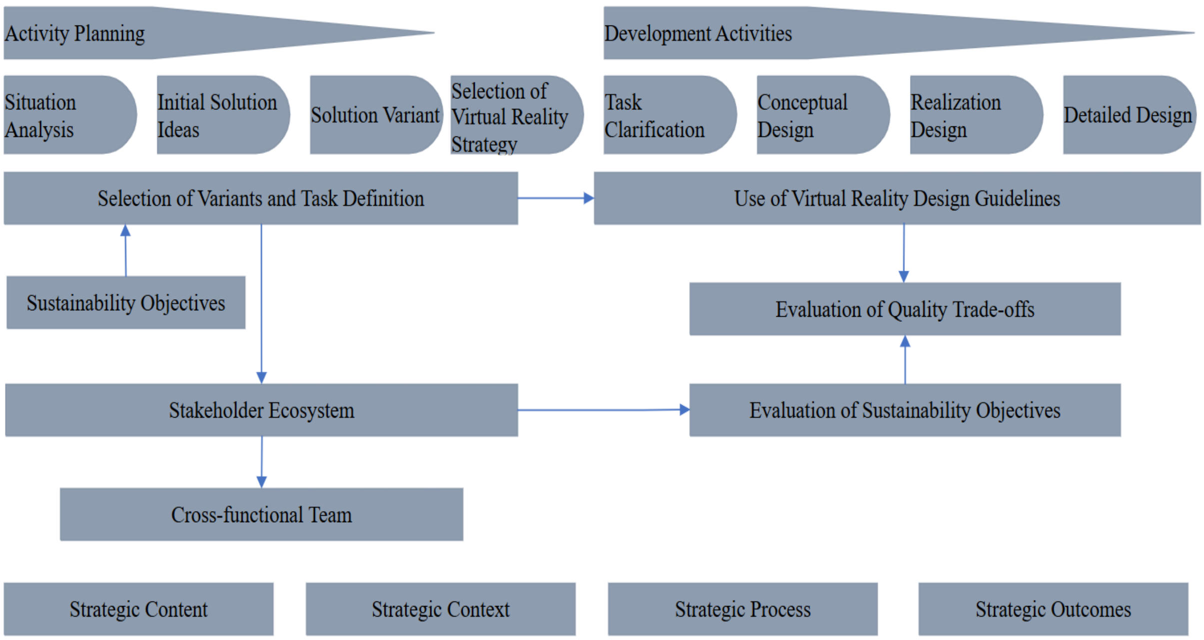

Figure 2. Management factors that influence the design of circular products

Product selection and evaluation are typically carried out at an early stage of development in which product systems add relatively low levels of design. Environmental and social studies have found that several sustainable assessment methods are suitable for protecting the assessment in the early stages of the process (Diaz et al., 2022).

Figure 3 indicates that the industrial economy, restorative by intent, aims to rely on renewable energy, minimize, track and eliminate the use of chemicals, as well as eradicating waste through careful design; a CE increases the value derived from the existing economic structure, products, and materials (Muyulema-Allaica & Tapias-Molina, 2024).

Table 2 highlights the diverse strategies and methods employed in the implementation of the CE, illustrating the complexity of sustainability concepts and the integration of practices often borrowed from other fields. These strategies encompass various stages of the product life cycle, from design to recycling and recovery, with an emphasis on reducing resource consumption, minimizing waste, and fostering collaboration across industries. The strategies outlined include establishing industry standards, designing products tailored to customer needs to prevent overproduction, implementing energy-efficient manufacturing processes, and promoting voluntary community involvement in consumption and repair activities. Moreover, the table underscores the importance of innovative approaches, such as utilizing by-products in manufacturing and incentivizing recycling, to close material loops and ensure the sustainability of the production cycle.

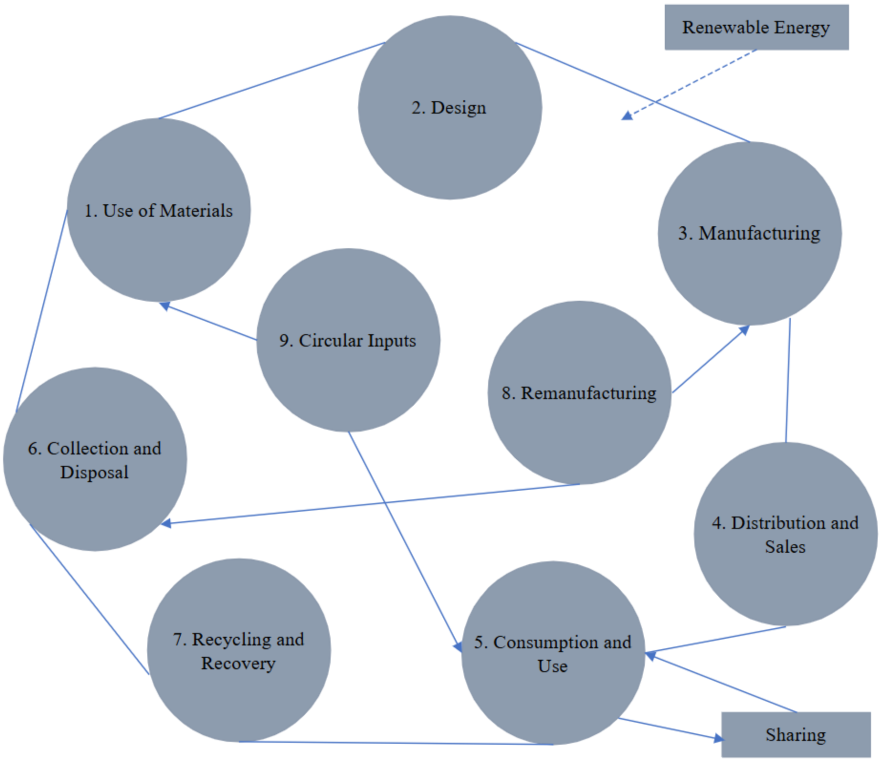

Figure 3. Resource flows through a circular value chain

Table 2. Strategies of the circular economy

No.	Terminology	Description
1	Use of materials	Establishment of industry standards to promote cross-sector collaboration through transparency, financial and risk management tools, regulation and infrastructure development, and education.
2	Design	Tailor-made products to meet customer needs and preferences, can reduce waste and prevent overproduction.
3	Manufacturing	Required services provided with reduced energy input, which can be achieved through reduced energy consumption and process.
4	Distribution and sale	Efficient packaging design strategies that comply with regulations and utilize end-of-life packaging material.
5	Consumption and use	Voluntary participation of the community and different stakeholders in organizing exchange platforms and providing guidance on product repair and replacement.
6	Collection and disposal	A method to reward consistent and repeated recycling of recyclable materials, e.g., a deposit refund. Facilities to promote cost-effective, time-saving, and environmentally safe post-consumer collection and disposal.
7	Recycling and recovery	By-products from other manufacturing processes and their corresponding value chains are used as raw materials for the manufacture of new products.
8	Remanufacturing	Rebuilding a producer by replacing defective components with reusable ones.
9	Circular entries	Resource inputs or materials that last more than one life cycle and can be easily regenerated.

In Figure 4, the Analytical Network Process (ANP) method represents an interaction between the criteria and sub-criteria within a hierarchical structure. This approach provides more realistic and effective results by considering the interrelationships and feedback between various elements. The ANP algorithm consists of six fundamental steps, as outlined by Alakaş et al. (2020).

Figure 5 shows multilayer flow mapping, which is a resource efficiency assessment methodology designed according to Lean value and waste principles (Serafim-Silva et al., 2024). It is based on Value Stream Mapping (VSM), a well-known Lean tool aimed at identifying and quantifying value-added and non-value-added activities at each stage of the production system. It identifies all types of losses (e.g., time, energy, water, raw materials, etc.) associated with each process unit with a particular focus (Holgado et al., 2018).

Figure 6 shows the classification of environmental outcomes with respect to the value-benefit approach. Such outcomes can be, for example, reductions in greenhouse gas emissions, waste discharge, and water use. The environmental value should originate from an identified symbiosis and be clearly distinguishable from others (Wadström et al., 2021).

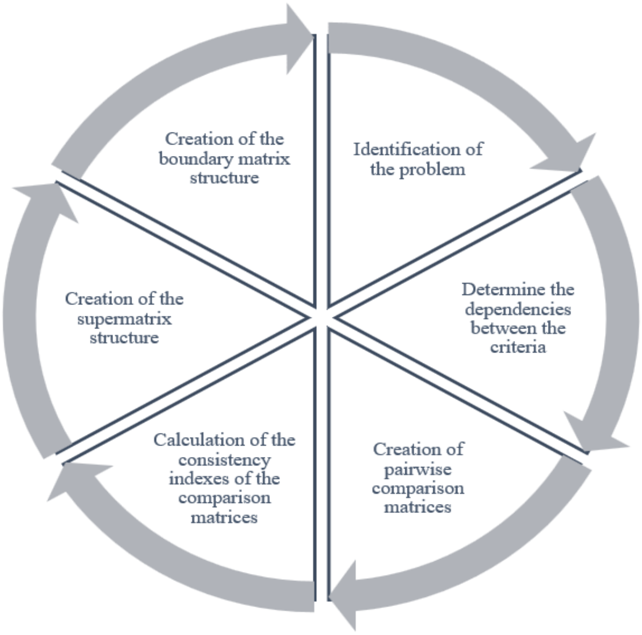

Figure 4. Steps in the analytical network process (ANP)

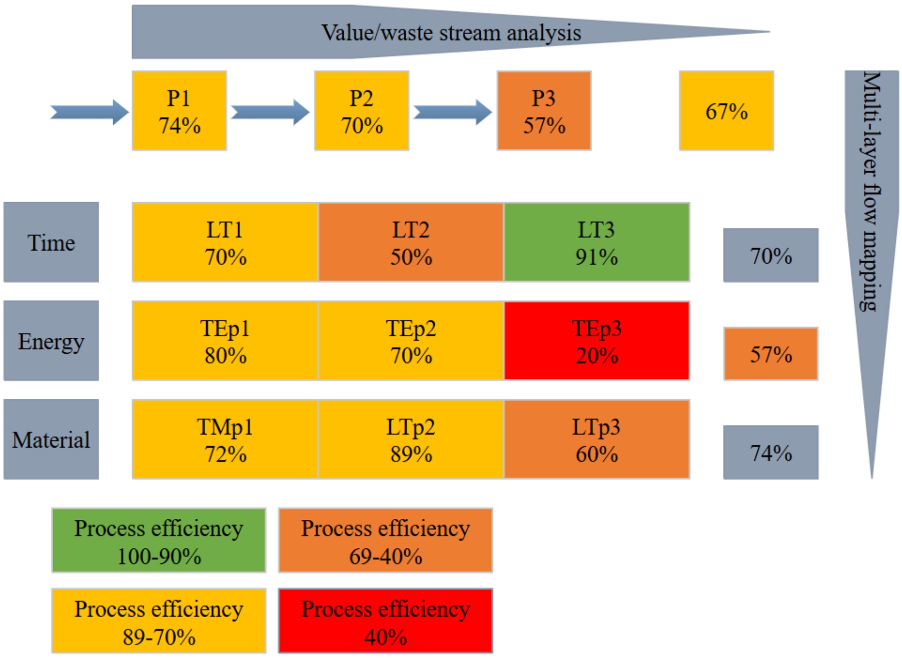

Figure 5. Conceptual example of a multi-layer flow mapping dashboard

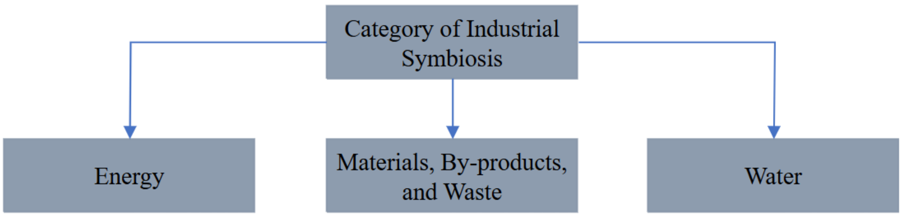

Figure 6. Categories of IS

Regarding the application of material flow analysis to IS, there are some specific aspects that need to be considered: 1) need to integrate material, water, and energy flow analysis; 2) indirect flows of enterprises; and 3) evaluation of both subsystems and whole IS network (Demartini et al., 2022).

It is relatively easy for the agent-based model to state how agents emerge from individual actions through computational models of a complex system and understand their evolution over the course of time (Han et al., 2022). Multi-agent systems help determine problems that are difficult for an agent to solve by means of a simulation model for decision making (Zhou & Fu, 2020). Game theory studies the situations that individuals perform as the outcomes depend on the decision-making of other individuals (Jato-Espino & Ruiz-Puente, 2021).

Energy efficiency is quantified as the ratio of the minimum energy required to accomplish a specific activity to the actual energy consumed during the process (Jabari et al., 2024). The quality management system allows companies to comply with standardized parameters and thus meet the needs of customers (Ammar et al., 2021).

3.1 Application of the FAHP and the DEMATEL

Figure 7 shows the dimensions of the tools for resource utilization.

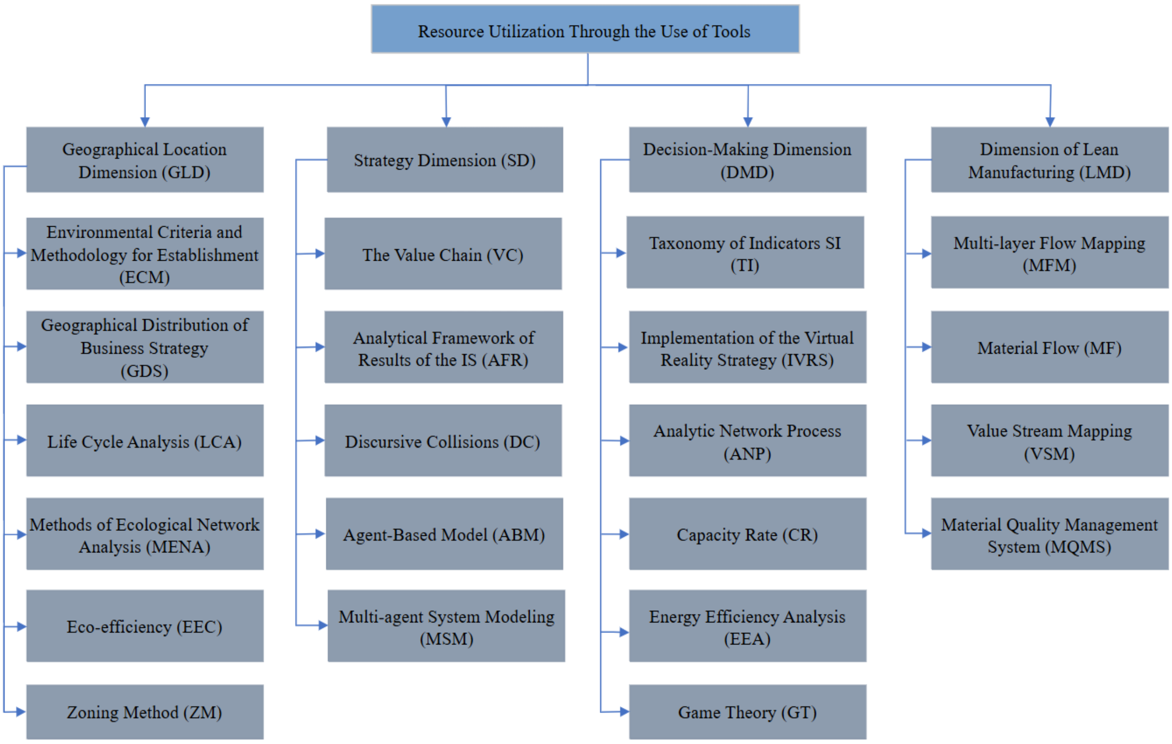

Figure 7. Dimension diagram

3.1.1 Resource utilization through the use of tools

Table 3 shows the DEMATEL analysis applied to the tools for resource utilization and identifies the efficiency of decision-making. In this process, 4 dimensions and 21 sub-criteria were identified. From another point of view, the threshold value was determined by the total ratio values. The calculated values above the threshold value were dominant over the other values. The results reflected that the decision-making and geographical location dimensions were the causes; on the other hand, the effect was mirrored in the strategic and lean manufacturing dimensions. It was determined that the decision-making and geographical location dimensions had a greater influence on the strategic and lean manufacturing dimensions.

Table 3. Standardized matrix of dimensions

Criteria	Comparison of Criteria				Standard Matrix				Balancing
	GLD	SD	DMD	LMD	GLD	SD	DMD	LMD	
GLD	1	5	1/3	3	0.221	0.313	0.184	0.409	0.282
SD	1/5	1	1/7	1/3	0.044	0.063	0.079	0.045	0.058
DMD	3	7	1	3	0.662	0.438	0.553	0.409	0.515
LMD	1/3	3	1/3	1	0.074	0.188	0.184	0.136	0.145
Total	4.53	16.00	1.81	7.33					

Table 4 shows the comparative weights and evaluation of each criterion, i.e., the tool for resource utilization. Table 5 presents the matrix of direct and indirect relationships among the analyzed dimensions (GLD, SD, DMD, and LMD), along with the threshold value (α = 0.58) used to distinguish the most relevant interactions within the model. This value was obtained by calculating the average of all elements in the total relationship matrix, thus providing an objective reference point for identifying the strongest connections. In this analysis, only relationships with values equal to or greater than 0.58 were considered significant, as they represent strong and direct influences between dimensions. Conversely, relationships with lower values were excluded due to their limited impact on the system. This procedure allowed the refinement of the interaction network and facilitated the interpretation of results by clearly highlighting the dimensions with dominant influence and those with higher dependence. The use of the threshold value contributed to a more coherent and comprehensible representation of the DEMATEL model, hence reinforcing the causal relationships among the studied dimensions.

Table 4. Comparative weights of dimensions and criteria

Dimension	Weights	Alternative	λ max	Reliable Change Index (RCI)	Alternative Weight	Total Alternative Weight	Position
		ECM			0.104	0.0293	8
		GDS			0.104	0.0293	9
GLD	0.282	LCA	6.587	0.095	0.340	0.0958	2
		MENA			0.044	0.0124	14
		EEC			0.340	0.0958	3
		ZM			0.067	0.0189	12
		VC			0.138	0.0079	16
		AFR			0.086	0.0050	17
SD	0.058	DC	5.397	0.089	0.053	0.0031	18
		ABM			0.341	0.0197	11
		MSM			0.382	0.0221	10
		TI			0.157	0.0811	5
DMD	0.515	IWRS	6.544	0.088	0.384	0.1979	1
		ANP			0.071	0.0364	6
		MFM			0.207	0.0302	7
LMD	0.145	MF	4.225	0.083	0.081	0.0118	15
		VSM			0.091	0.0132	13
		MQMS			0.620	0.0902	4

Table 5. Matrix of direct and indirect relationships of dimensions

Indicator	Direct Relationship				Standardized Direct Relationship				Total Relationship				Direct-Indirect Relationship			
	GLD	SD	DMD	LMD	GLD	SD	DMD	LMD	GLD	SD	DMD	LMD	R	C	R+C	R-C
GLD	0	2	2	3	0.00	0.18	0.18	0.27	0.37	**0.61**	0.53	**0.62**	2.13	1.64	3.76	0.49
SD	3	0	2	1	0.27	0.00	0.18	0.09	0.55	0.40	0.48	0.45	1.88	2.51	4.39	-0.63
DMD	3	4	0	4	0.27	0.36	0.00	0.36	**0.75**	**0.92**	0.53	**0.85**	3.05	1.66	4.72	1.39
LMD	1	3	3	0	0.09	0.27	0.27	0.00	0.48	**0.69**	**0.60**	0.41	2.17	2.01	4.18	0.17
					Sum C_j				1.64	2.51	1.66	2.01	valor umbral (α) = 0.58			

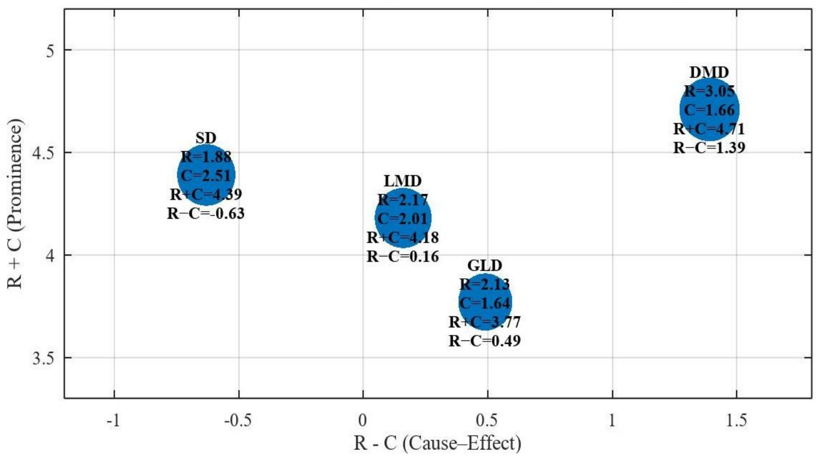

Figure 8. Dimension ratio graph

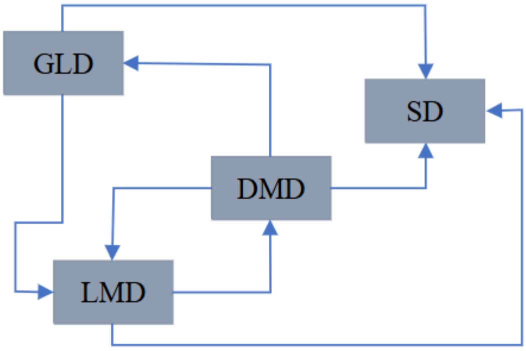

Figure 9. Drive and controller dimensions

Figure 8 shows the direct and indirect relationship of the dimensions, indicating the decision-making dimension as the driver before the other dimensions.

Figure 9 shows the relationships among the dimensions, and also identifies which dimension has more value according to the rating. In this case, the decision-making dimension is more important than the other dimensions.

4. Discussion

In the acquired databases, the importance of tools for the use of resources in the implementation of sustainability improvement was determined. This research was comprised of the dimensions of decision making, geographic location, strategies, and lean manufacturing with their respective criteria, in order to solve problems.

Likewise, virtual reality technology has been determined as an important information technique in product development (Diaz et al., 2022), with respect to the competitive analysis of the company in the redesign of products with the purpose of promoting sustainability in the development of new manufacturing alternatives (Ortega-Alvarado et al., 2021)

The life cycle assessment is a methodology that determines the environmental impacts and aspects of a company's product (Muyulema-Allaica & Ruiz-Puente, 2022). The assessment is part of the determination throughout the life of the product (Reyes-Soriano et al., 2022); that is, from the extraction of raw materials to the final disposal of the products. The purpose of this tool is the quantitative evaluation of materials, energy, and environmental impacts.

The other tools are adapted to the needs of the companies according to the prospects of solving the problems. In addition, eco-efficiency is the fulfillment of legal and environmental commitments, with respect to the objective of sustainable development. It proposes measures to save water and energy, to minimize the impact on the natural environment, and to reduce the risks of waste in industries.

The results showed that the DEMATEL model was a valuable tool for understanding the interaction between factors that influenced sustainability within industrial settings. The application of the threshold value $\alpha = 0.58$ could help identify the most significant relationships among the analyzed dimensions, by filtering out those with lower impact and highlighting the most influential ones. This value, calculated from the average of direct and indirect relationships, allowed a more accurate interpretation of dependencies and a better prioritization of strategic actions. Consequently, the dimensions related to decision-making and the implementation of Lean Manufacturing principles were found to have a dominant effect over others, thus providing essential insights for optimized planning and resource allocation in sustainable manufacturing processes.

For future research, it is important to validate the model through case studies in various industrial sectors to test the consistency of the threshold value and adapt its application to the specific characteristics in each context. Further progress should also be made toward integrating more advanced multi-criteria methods or predictive analytics and artificial intelligence tools to enhance the anticipation and change management in complex production environments. Finally, it would be beneficial to include new dimensions related to digitalization, circular economy, and organizational resilience, thereby broadening the scope of the model and reinforcing its role as a practical instrument for continuous improvement and sustainability in industrial management.

5. Conclusions

IS constitutes a strategic framework for collaboration among companies through innovative partnerships aimed at optimizing resource use, minimizing environmental impact, and promoting sustainable development, in alignment with circular economy principles. Based on the SLR of publications from January 2020 to December 2024 in established databases like SpringerLink, ScienceDirect, EBSCO, and DOAJ as well as quantitative analysis of IS tools, this study observed that effective implementation of IS relied on the integration of critical dimensions, such as DMD, GLD, SD, and LMD, along with 21 specific subcriteria. The application of advanced methodologies, including the FAHP and the DEMATEL, revealed that DMD and GLD acted as causal dimensions and exerted significant influence on SD and LMD. Meanwhile, alternatives such as IWRS and LCA offered high efficiency in resource management and utilization. The use of a threshold value (α = 0.58) facilitated the identification of dominant relationships among dimensions, to highlight critical strategic leverage points for implementing sustainable manufacturing practices. These findings emphasize that targeted decision-making, combined with strategic planning based on geographic positioning and the adoption of appropriate technological tools, is essential for optimizing resource efficiency, enhancing environmental sustainability, and fostering economic and social development. Consequently, this study not only provides a robust conceptual framework for adopting IS strategies but also offers practical guidance for integrating circular economy principles into industrial processes, thus contributing to the design of innovative policies and practices that promote comprehensive sustainability in global industrial contexts.

Author Contributions

Conceptualization, J.C.M.-A. and P.M.P.-M.; methodology, J.C.M.-A.; software, F.X.A.-F.; validation, P.M.P.-M. and J.C.M.-A.; formal analysis, J.E.B.-C.; investigation, J.C.M.-A.; resources, J.E.B.-C.; data curation, P.M.P.-M.; writing—original draft preparation, J.C.M.-A.; writing—review and editing, P.M.P.-M.; visualization, J.C.M.-A.; supervision, F.X.A.-F.; project administration, J.C.M.-A.; funding acquisition, J.E.B.-C. All authors have read and agreed to the published version of the manuscript.

Data Availability

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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