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An agent-based model for establishing a symbiotic system in manufacturing companies

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ABSTRACT

Manufacturing companies currently use linear production systems, which are detrimental to sustainability in the short, medium, and long term. In this context, there is a need for means of transitioning from linear to circular economies that adhere to more environmentally friendly operating practices. This research was undertaken with the objective of designing an agent-based model for establishing a symbiotic system in manufacturing companies. The methodology was grounded in scientific principles, enabling a concrete and useful procedure carried out in a clear manner. The process began with the real-world system, moving to a conceptual model through abstraction, followed by the creation of an analytical model through formalization, and finally the implementation of a computational model; Subsequently, the validation of this model will enable future research related to the creation of a model or, alternatively, the continuation of research milestones by expanding the database of this study.

1. Introduction

The growth of industries generates an environmental impact, as mentioned by Beltrami et al., [1], which has significantly affected the secondary sector and logistical connections such as marketing, creating an intrinsic correlation with industrialization. The objective is to explore a model that allows for understanding the transition from a linear to a circular model, with the aim of minimizing environmental impact.

Consequently, Puentes-Cociña [2] states that there is no compatibility in the existence of a linear economic model grounded in the environment and the parameters of resources whether extraction, production, consumption, or solid waste disposal which were limited and easily obtained within industrialization.

Industrialization emerges in a transitional and recovery-focused environment centered on the Circular Economy (CE), as noted by Tamara, [3]. When this model is applied within the theoretical

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framework of the system, the adoption of circular economy principles, which incorporates the circular aspect and the foundations for designing sustainable industrial processes.

In the context of Hernández-Marquina et al., [4], the CE is described as an approach to innovation involving the transition from a linear model to a circular model with the aim of reducing pollution from generated waste and achieving zero waste. This approach establishes three principles: 1) The elimination of waste and pollution, 2) The sustainability of products and materials in use, and 3) The regeneration of natural systems, as mentioned in [5], [6].

As stated by Vega-Guerrero et al., [7] manufacturing is a component of circularity, in which, when preserving the reuse of resources in the form of materials and energy, within a socio-technical design and with verified information, the lack of resources in waste generation leads to a shortfall within the context of product lifecycle management at the end of production.

The existence of the CE and manufacturing is evident in the principle of nature's metabolism, indicating that each element has a specific function and objective within the production process; consequently, production processes generate waste, which becomes raw material for others, yielding sustainable benefits within the context of complex systems [7].

Understanding complex systems over time has hindered progress, but technological advancements now enable the study of behaviors and cross-industry analysis, which is sparking interest in manufacturing processes, among other areas. Consequently, to assess and characterize different behaviors within various scenarios for understanding circular analysis, models are digitized within a computational system [8],[9],[10],[11],[12].

The complexity of today's models is being developed through computational systems, which requires collaboration among different related teams capable of addressing a specific problem using various paradigms within the real system. Based on different hypotheses, an analytical model is proposed, which supports a real system that gives way to the digital component—a crucial aspect for simulation. In this way, conceptualizing the different computational languages to incorporate into simulation processes grounded in an Agent-Based Modeling (ABM) allows for the use of computational resources and the reduction of real-world resources [13],[14],[15].

2. Literature Review

A Systematic Literature Review (SLR) is a method that allows for the transparent and reproducible identification, evaluation, and synthesis of the available scientific evidence on a specific topic. Unlike a traditional narrative review, an SLR follows a predefined protocol that reduces bias in the selection of studies and provides a comprehensive overview of the current state of knowledge [16].

Systematic reviews are currently one of the most rigorous methodological approaches for consolidating scientific knowledge, as they employ explicit inclusion and exclusion criteria, structured search strategies, and quality assessment procedures. According to Snyder [16] , this type of review helps build a solid foundation for future research, identify knowledge gaps, and generate new lines of inquiry. Consequently, the SLR not only summarizes existing evidence but also facilitates an understanding of emerging trends within a scientific field.

In research related to ABM where disciplines such as engineering, sustainability, computer science, logistics, and economics converge systematic reviews are particularly relevant given the diversity of existing methodological approaches. This heterogeneity makes it difficult to obtain a comprehensive overview through conventional reviews. SLR allows for the integration of results from different contexts, the identification of common patterns, and the establishment of relationships among previously conducted research

According to Carrizo & Moller, [17], the purpose of a systematic review is to identify all relevant evidence related to a research question using objective and reproducible procedures. This approach ensures that the results obtained can be replicated by other researchers, thereby strengthening the scientific reliability and validity of the study

Likewise, Neumann & Suen [18] note that a systematic review should be conducted in accordance with clearly defined stages: formulating research questions, identifying databases, applying inclusion and exclusion criteria, assessing the quality of the studies, and synthesizing the evidence found. These stages help minimize researcher bias and ensure that only relevant, high-quality studies are included.

The Figure 1 illustrates the workflow followed during the SLR used to identify, screen, and select studies on ABM for sustainability. The process follows a structured sequence that ensures transparency, reproducibility, and methodological rigor in the selection of scientific literature.

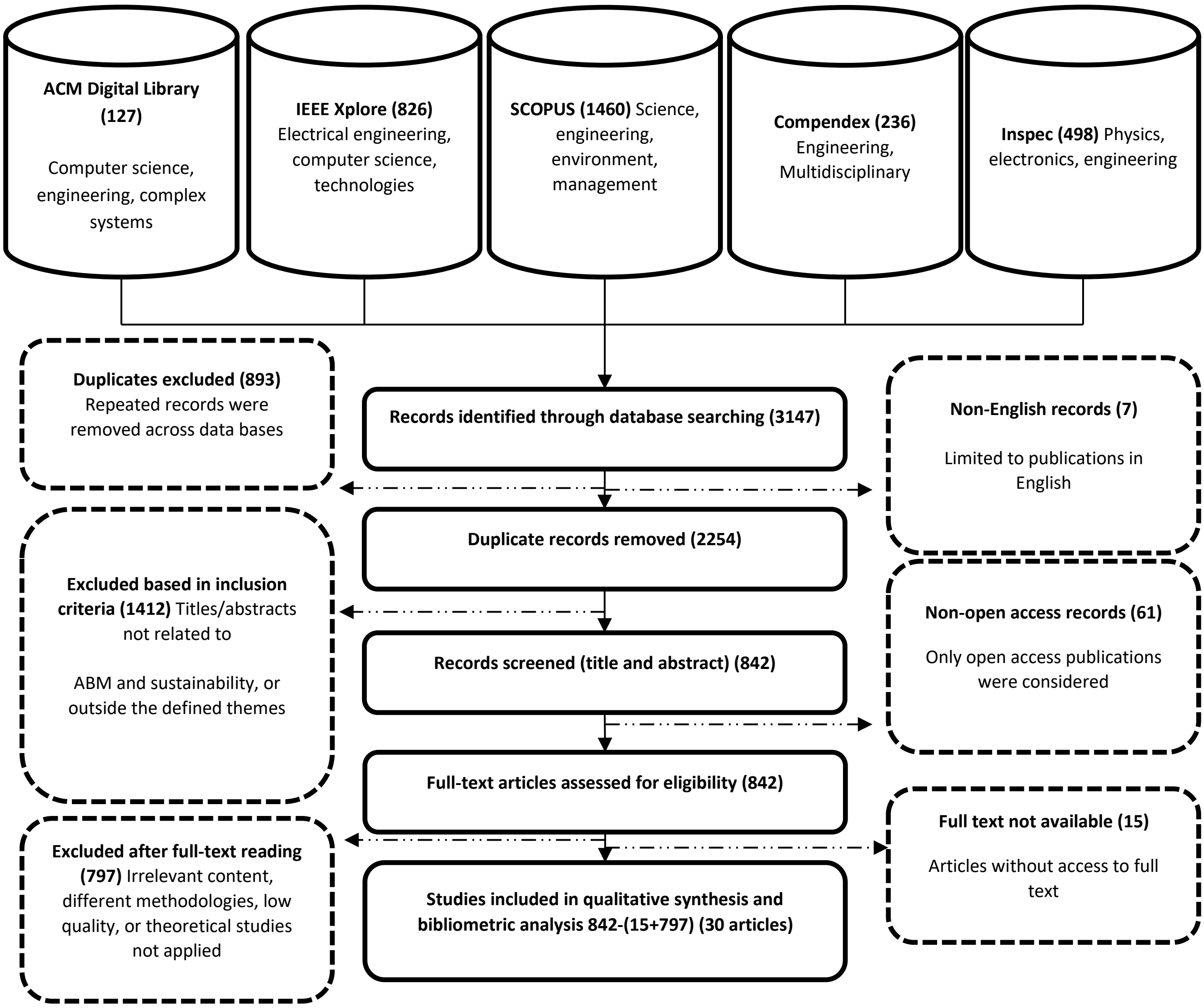

Figure 1. Systematic Literature Review

The review began with the identification of publications from five major scientific databases: ACM Digital Library (127 records), IEEE Xplore (826 records), Scopus (1460 records), Compendex (236 records), and Inspec (498 records), resulting in a total of 3147 records retrieved through database searching.

The first filtering stage consisted of removing 893 duplicate records, leaving 2254 unique publications for further evaluation. Subsequently, titles and abstracts were screened according to predefined inclusion and exclusion criteria. During this phase, 1412 records were excluded because they were unrelated to ABM, sustainability, or the predefined research themes.

The remaining studies underwent a full-text eligibility assessment. At this stage, 61 non-open-access publications and 7 non-English articles were excluded to ensure accessibility and language consistency throughout the review.

A detailed full-text review was then performed on the eligible publications. During this process, 797 studies were excluded because they addressed different methodologies, lacked sufficient methodological quality, or were considered theoretical works without practical application to the research objectives.

After completing all screening and eligibility stages, 30 studies satisfied all inclusion criteria and were incorporated into the qualitative synthesis and bibliometric analysis. These selected articles constituted the scientific foundation for analyzing publication trends, research themes, collaboration networks, methodological approaches, and the application of ABM to sustainability-related problems.

Overall, the flow diagram demonstrates a rigorous and transparent study selection process, ensuring that only high-quality, relevant, and accessible scientific publications were included in the final analysis. This systematic procedure strengthens the reliability, reproducibility, and scientific validity of the bibliometric review

The SLR allowed for a rigorous selection of articles related to ABM applied to sustainability, while bibliometric analysis made it possible to quantitatively examine scientific output, identify the most influential authors, the institutions with the highest levels of collaboration, the leading countries in research, and the journals with the highest impact. This methodological integration is widely recommended because it combines qualitative analysis of the literature with quantitative indicators of scientific output. [19].

In accordance with the article under review, the literature search was conducted using a structured strategy based on previously established inclusion and exclusion criteria, considering only open-access publications related to ABM and sustainability within the selected study period.

The Table 1 details the results of the selected articles, mentions the authors and objectives, in order to identify the tools used in the research and the results.

Table 1.
Referential matrix of the selected articles

Methodological Stage	Tools Applied	Representative Authors	No. of Articles (n=30)	Percentage (%)
Characterization of agents, behaviors, and interactions	Agent-Based Modeling (ABM), Behavioral Modeling, Social Simulation, Network Analysis, Stakeholder Analysis, Blockchain	[20], [21], [22], [23], [24], [25], [26], [27]	14	46.7
Design of the simulation environment and scenarios	Geographic Information Systems (GIS), System Dynamics, Scenario Analysis, Space Syntax, Simulation Modeling	[28], [29], [30], [31], [32]	5	16.7
Definition of decision-making and adaptation rules	Artificial Intelligence (AI), Machine Learning, Decision Support Systems (DSS), Optimization Algorithms	[33], [34], [35], [36]	4	13.3
Selection of model variables and performance indicators	Sustainability Assessment, Multi-Criteria Decision Analysis (MCDA),	[37], [38], [39]	3	10

	Statistical Analysis, Performance Indicators			
Model validation and evaluation	Statistical Analysis, Sensitivity Analysis, Scenario Comparison	[16], [40]	2	6.7
Integration with complementary computational tools	GIS, Blockchain, Internet of Things (IoT), Big Data, Bibliometrix, Biblioshiny	[19], [41]	2	6.6
Total			30	100

The most frequently identified component was the characterization of agents, behaviors, and interactions, representing 46.7% (14 out of 30 articles) of the reviewed studies. This finding highlight that the core of an ABM lies in defining autonomous agents, their behavioral rules, objectives, and interaction mechanisms. Studies such as Marvuglia et al., [20], [21] demonstrated that representing heterogeneous agents and their adaptive interactions enables the simulation of emergent behaviors that cannot be adequately captured using conventional analytical or optimization models. Likewise, Meng et al., [22], [23] concluded that ABM is particularly suitable for analyzing sustainability-related problems because it explicitly represents heterogeneous stakeholders, decentralized decision-making, and nonlinear interactions.

The second most relevant component corresponds to the design of the simulation environment and scenarios (16.7%), supported by tools such as GIS, System Dynamics, Space Syntax, and Scenario Analysis. These methodologies contribute to representing the physical or virtual environment in which agents interact. However, the literature indicates that these tools primarily define the simulation context, while the behavioral dynamics remain governed by the Agent-Based Model itself. For example, Yamu et al., [28] used Space Syntax to characterize spatial configurations, whereas Vinayak et al., [29] combined GIS and predictive models to represent land-use dynamics, providing spatial information that can be incorporated into an ABM.

The definition of decision-making and adaptation rules accounted for 13.3% of the selected studies. Although techniques such as Artificial Intelligence, Machine Learning, and Decision Support Systems improve the adaptive capacity of computational models, they are mainly employed to strengthen the agents' decision-making processes rather than replacing the ABM structure. This is evident in studies by Alam et al., [33], [34], where intelligent algorithms were integrated to enhance autonomous decisions within complex systems.

Similarly, the selection of variables and performance indicators (10%), model validation and evaluation (6.7%), and integration with complementary computational tools (6.6%) represent methodological stages that improve model quality and reliability. Sustainability Assessment, MCDA, Statistical Analysis, GIS, Blockchain, IoT, Big Data, Bibliometrix, and Biblioshiny were identified as complementary techniques that support calibration, validation, visualization, or data processing. Nevertheless, none of these methodologies independently represents the autonomous behavior, interaction, and adaptation of multiple heterogeneous actors, which constitute the defining characteristics of ABM.

Overall, the evidence obtained from the SLR demonstrates that although numerous computational models and analytical techniques have been applied to sustainability-related problems, the Agent-Based Model provides the most comprehensive framework for representing complex adaptive systems. Consequently, the proposed research focuses on the development of an Agent-Based Model, while incorporating complementary methodologies such as GIS for environmental representation, Artificial Intelligence for adaptive decision-making, and Statistical Analysis for calibration and validation. This integrated approach enables the model to capture individual behaviors, interactions among agents, emergent system dynamics, and scenario-based analysis, thereby providing a robust computational framework for addressing the research problem.

The use of a systematic review made it possible to construct a robust theoretical framework for ABM, identify the main international research trends, and scientifically justify the need for the subsequent bibliometric analysis. Thus, the combination of these two methods provides a comprehensive understanding of scientific developments in the field, allowing us to identify not only the quantitative evolution of academic output but also the main thematic areas, international collaborations, and opportunities for future research. In this context, it is important to explore the development of an agent-based model how it is constructed and the processes involved in its creation.

2. Methodology

According to Göhlich et al., [27] the procedure for creating the agent-based model consists of the following key steps: 1) Abstraction of the real system, 2) Definition of the conceptual model, 3) Interactions and constraints, 4) Development of the analytical model, 5) Formalization of the model, 6) Computational implementation, and (7) Verification, validation, and testing. This methodological framework facilitates the systematic representation of system components and their dynamic interactions, ensuring the reliability and robustness of the simulation outcomes. Figure 2 presents the overall modeling process.

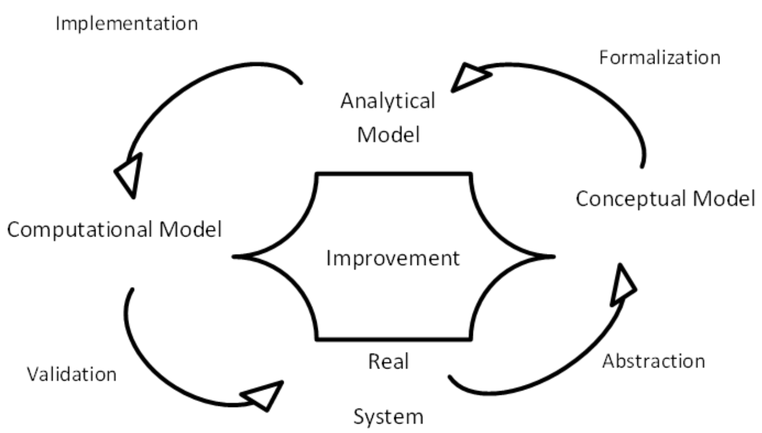

Figure 2. Basic structure of the complex systems modeling process

Abstraction of the Real System: The process begins by identifying and understanding the real system to be modeled. This involves analyzing its main characteristics and relevant properties to represent its behavior. The parameters that will limit the model to measure the evolution of the phenomenon are defined.

Definition of the Conceptual Model: A conceptual model is created based on the modeler's creativity. At this stage, the system under study is conceptualized, separating it from its environment and defining the model's objectives.

Interactions and Constraints: The conceptual model must allow for economic and environmental interactions among the companies involved. The goal is to transform traditional linear processes into more sustainable circular models, particularly in manufacturing industries.

Development of the Analytical Model: The conceptual model is documented through scientific literature, and the analytical model is defined using mathematical logical expressions. This analytical model reproduces the behavior of the real system over time.

Model Formalization: A formal representation of the abstract model is constructed, characterizing the system under study, its properties, and the paradigms selected for analytical formalization.

Computational Implementation: The analytical model is coded in a formal programming language and implemented in a simulator (e.g., NetLogo). This allows for the analysis of the system's behavior and its evolution under different proposed scenarios.

Verification, Validation, and Testing: The computational model is verified to ensure it complies with the established paradigms, and any potential flaws are resolved. The accuracy of the simulation results is validated, and tests are conducted to evaluate different operational conditions, analyzing the model's sensitivity and robustness.

3. Results

3.1. Real System

The model was developed for exploratory purposes to observe the trajectory of how CE practices have evolved, focusing primarily on waste reduction and improving operational efficiency and effectiveness within the concept of sustainability. The CE framework is shown, which aims to reduce material input as well as waste production using the Lean philosophy, as shown in the Figure 3. This is a Lean Circular model that focuses on economic, equity, social, political, and environmental growth within a company's value chain.

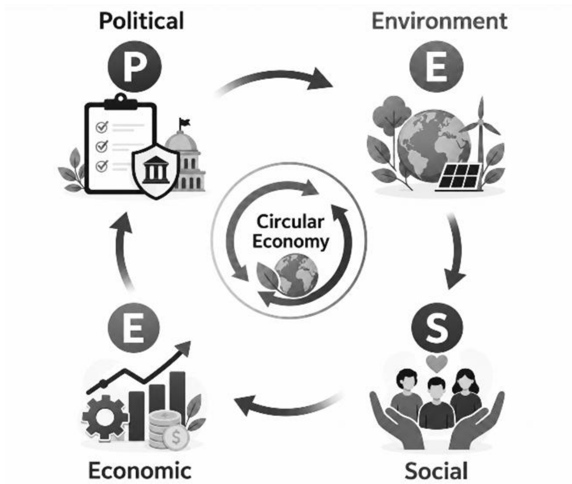

Figure 3. The Four Pillars of Sustainability

Under the concept of sustainability and guided by the corresponding environmental, economic, social, and political principles that serve as a framework for constructing the conceptual model, the study incorporates various logical aspects into the modeling process and uses these as a foundation, thereby demonstrating the sustainability of manufacturing industries; thus drawing on specific and concrete situations that provide a broader view of reality, with the aim of demonstrating the existence of industrial symbiosis, which is evident in the conceptualizations of CE.

3.2. Conceptual Model

The elements of the industrial system were identified through the analysis of individual companies, which exhibit the characteristics of a complex system, since each operates autonomously within hierarchical organizational structures; these companies typically base their operations on market demand and their own strategies, utilizing prior studies, which leads to a considerable increase in economic benefits. By forming part of a union among agents, growth is considered--meaning a greater number of agents and stronger relationships-with the aim of achieving more environmentally responsible operations and greater economic benefits.

The complex nature of establishing trust-based relationships or agreements does not affect each agent's investment capital, as this would not be necessary; only working capital would be exchanged. The implementation of the conceptual model began by outlining the natural environment, including all influential factors for future simulation, highlighting the traditional ABM model, which requires the application of analytical techniques.

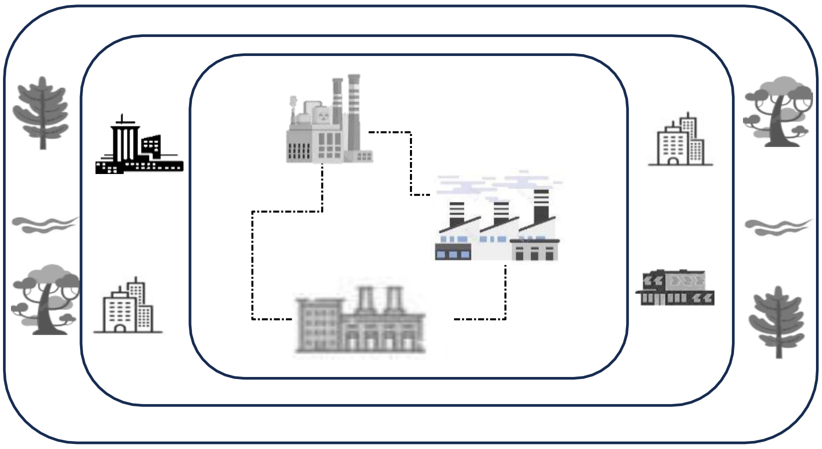

Figure 4. Conceptual Model

3.3. Analytical Model

To develop the analytical model, we must have the foundations of the conceptual model, which highlights the various technical characteristics of the agents. It is evident that, influenced by the conceptual model, we have moved on to the creation of an analytical model so that it can be modeled in computer language, in this case using NetLogo software.

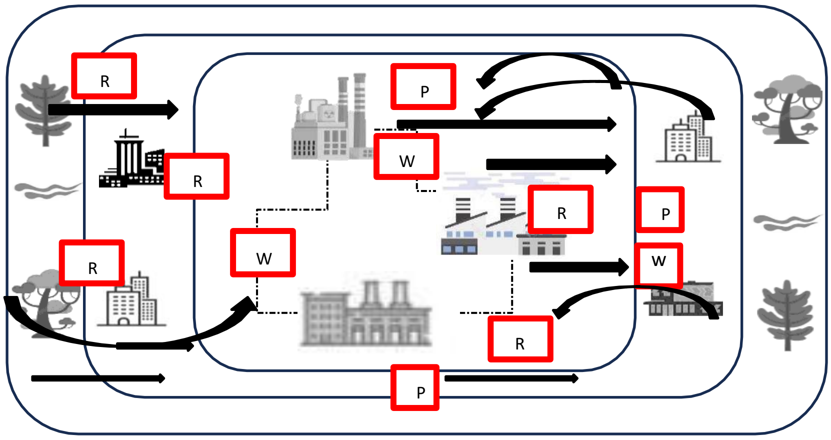

Figure 5. Analytical Model

It also outlines the elements entering the various points, as shown in the following figure, which illustrates the input and output points—that is, the input and output s—which represent resources, products, and waste; it is worth noting that these points include qualitative, quantitative, and economic aspects.

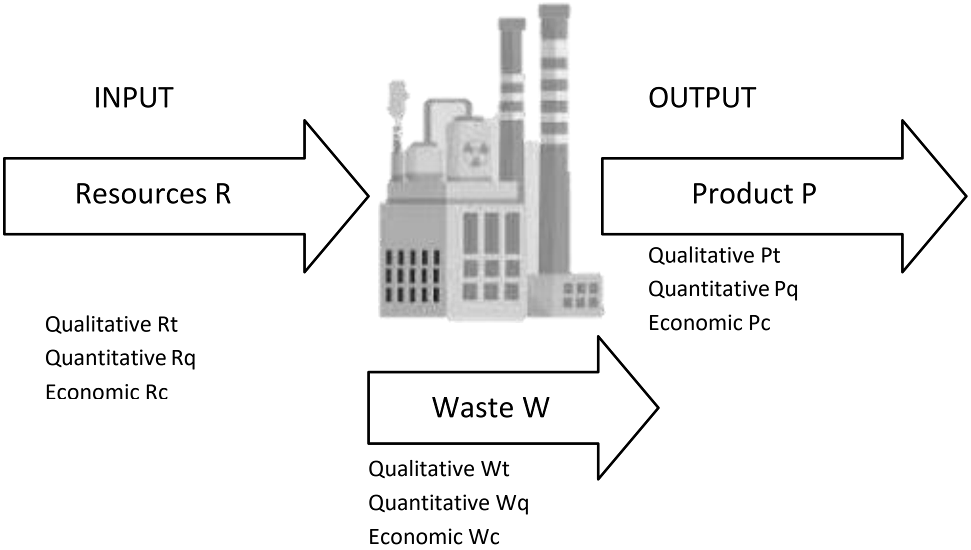

Figure 6. Types of elements that companies have

The acronyms of the analytical model correspond to the variables and subvariables; subsequently, the interpretation of the following Figure 7 is presented, and the structural component is illustrated graphically to provide a better understanding of the formulation of interrelationships.

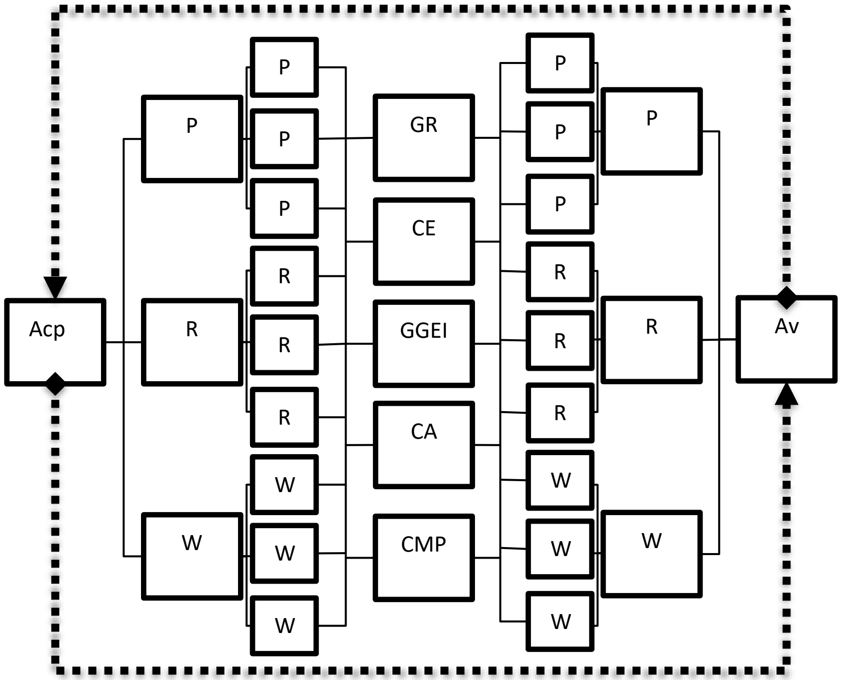

Figure 7. Agent Collaboration Structure

Los acrónimos que representan las variables y subvariables del modelo analítico se presentan en la Tabla 2.

Table 2.
The acronyms in the analytical model correspond to the variables and subvariables

P	Product	SR	Real System
Pt	P Qualitative	Acp	Buying Agent
Pq	P Quantitative	Av	Selling Agent
Pc	P Economic	GR	Waste Generation
R	Resources	CE	Energy Consumption
Rt	R Qualitative	GGEI	GHG Generation
Rq	R Quantitative	CA	Water Consumption
Rc	R Economic	CMP	Raw Material Consumption
W	Waste		
Wt	W Qualitative		
Wq	W Quantitative		
Wc	W Economic		

The natural system is defined as the primary environmental category of influencing factors, determining what changes can affect each flow of natural and waste resources. This includes inputs associated with production and outputs for raw materials, as well as the environment's capacity to absorb these output flows (waste). The social factor is the source of the influencing factors in the social category, including behaviors and relationships that arise spontaneously or through norms.

The economic factor originates from monetary flows, thereby influencing the economic system (through buying and selling). This category is considered influential within the market environment regarding agents and the prices of byproducts within the framework of an exchange network in an industrial park setting. Likewise, the technical category encompasses factors associated with production processes and service delivery, providing the operational basis for the implementation of sustainable strategies. The specific agents, categories, and corresponding activities are presented in Table 3 [42],[43].

Table 3.
Category and Subcategory of the Analytical Model

Category	Subcategory	Definition
Environmental factor	Natural Environment	Real System
	Resources	Inputs from the natural system to the real system
	Waste stream	Outputs from the real system to the natural system
Social factor	Legal and Political	Laws and policies that promote behaviors
	Organizational	Behaviors with norms that support the real system
	Educational	Operational doctrines
Economic factor	Market	Related to economic development
	Innovation and Competitiveness	Business practices for continuous improvement
Technical Factor	Infrastructure	Implementation of sustainable systems
	Technological	Machinery to expand operations
	Procedural	Sustainable practices

Where the variables and agents were identified, as seen in the acronyms, structure, and analytical model, defining the following interrelationship formulas through symbiosis:

$$\sum Fma + \sum Fs + \sum Fe + \sum Ft = SR \qquad \text{(EC.1)}$$

$$P1 + P2 + P3 + P4 \ldots = \sum Pn \qquad \text{(EC.2)}$$

$$W1 + W2 + W3 + W4 \ldots = \sum Wn \qquad \text{(EC.3)}$$

$$R1 + R2 + R3 + R4 \ldots = \sum Rn \qquad \text{(EC.4)}$$

$$\sum Pn + \sum Wn + \sum Rn = A \qquad \text{(EC.5)}$$

Where it is taken into account that

$$EC1 + EC2 + EC3 \neq EC1 + EC2 + EC3$$

But if the following constraints

$$EC1 + EC2 + EC3 = EC2 + EC3$$

$$EC1 + EC2 + EC3 = EC1 + EC3 \qquad \text{(EC.6)}$$

$$EC1 + EC2 + EC3 = EC1 + EC2$$

3.4. Validation of the Computational Model

To verify the computational model, the model was developed and implemented. As the programming language was introduced, the adequacy of the computational positions and structures was verified, and the results of these verifications led to a validation procedure, as shown in the Figure 8.

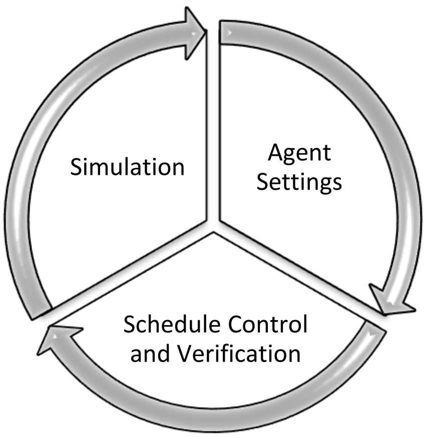

Figure 8. Validation procedures

Using the NetLogo platform, a computational model was developed to replicate the behavior of the real-world system and its evolution across different scenarios, thereby collecting data to observe collaboration among agents and how they interacted. The Kalundborg (Dynamic) case study, used for validation, focuses on global industrial symbiosis, which has been in operation since the 1970s; which highlights how the cooperation network implemented to improve the economic and environmental situation influences various aspects of material exchange that is, within the global context, industrial cooperation is implemented such that one agent’s waste serves as another agent’s raw material [44], [45], [46].

Agent configuration: We began by creating a computational language using commands that would enable simulation; this resulted in commands such as “to, end” for command input and output, the creation of actions or procedures to be performed, for example “setup, go, go1, go2,” and “create-turtle” for creating turtles (so named due to the program’s configuration); “link-wint” for the network between agents if there is any collaboration; “if ConsumoMP” for raw material consumption; “if ConsumoA” for water consumption; “if ConsumoGEI” for GHG generation; “if ConsumoE” for energy consumption; “if GeneracionR” for waste generation; (“let”, “if”, “clear-all”, “count”, “ask”, “show”, among others)—these are used to implement the observations from the points mentioned above (Figure 9).

Figure 9. Agent configuration

Programming control and verification: Subsequently, in the following process, this allowed for control and verification (Source: if for any reason the language does not match or is incorrect, the simulator will not run and an error will occur). Click on “Verify” to ensure the commands were correct (Figure 10).

Figure 10. Programming control and verification

Simulation: The computational model is initialized in the real-world scenario, where all observations are set to “off” (1), ensuring that no agents are active; This is done to verify that the computational model is suitable for predicting its evolution. Subsequently, the “Go” button (2) is pressed, which will result in an increase in agents; to clear the agents, the “Setup” button (3) is pressed, which will return the global environment to state 0, as shown in the figure 11.

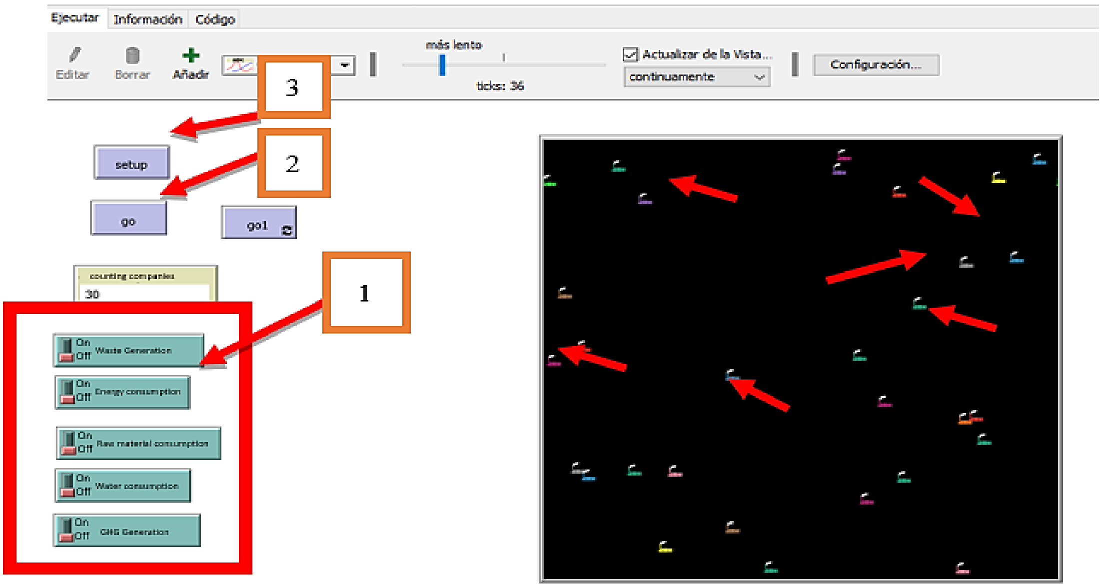

Figure 11. Simulation

3.5. Proposed statistical results

To evaluate the effectiveness of the proposed agent-based model in promoting industrial symbiosis and CE practices, several simulation scenarios were designed considering different numbers of agents and activated environmental, economic, and technical parameters. The results obtained allow the analysis of collaboration levels among industrial actors, waste reduction, resource consumption, and sustainability indicators. Table 4 summarizes the level of collaboration achieved under the different simulated scenarios.

The following results were obtained from exploratory simulations carried out with the proposed NetLogo model. Different scenarios were created by varying the number of participating companies and the activation of the environmental, economic, and technical parameters. The objective was to observe how collaboration evolves under different conditions. Therefore, the values presented in this section correspond to simulation results and should not be interpreted as data collected from real manufacturing companies.

3.5.1. Level of collaboration among industry players

The results presented in Table 4 show a clear and consistent upward trend in the level of collaboration among industrial actors as the number of agents increases and environmental and economic parameters are progressively activated across the simulated scenarios. This pattern highlights a strong dependence on interaction density and the degree of integration of management variables within the system.

Table 4.
Collaboration level among industrial actors under different simulation scenarios

Level of collaboration among industry players Scenario	Number of agents	Activated parameters	Level of collaboration (%)	Existence of symbiosis
Scenario 1	5	2	35%	Low
Scenario 2	10	3	58%	Medium
Scenario 3	15	4	82%	High
Scenario 4	20	5	100%	Complete

At the highest level, Scenario 4 reaches 100% collaboration, corresponding to complete industrial symbiosis. This outcome is associated with 20 agents and the activation of five parameters, resulting in a fully integrated network in which resource exchange flows operate continuously and in a structured manner. At this stage, cooperation among actors is no longer partial but becomes a fully interdependent system. At the next level, Scenario 3 records 82% collaboration, classified as high. This scenario involves 15 agents and four activated parameters, leading to a robust cooperative network, although not yet fully consolidated. Systematic behavior is observed in the exchange of by-products and resources, suggesting an advanced stage of inter-organizational integration. Scenario 2 shows a 58% collaboration level, classified as medium, with 10 agents and three activated parameters. In this case, interaction among actors remains partial, reflecting a system in the process of consolidation, with limited exchange flows and an emerging level of inter-firm coordination. Finally, Scenario 1 presents the lowest value, at 35% collaboration, classified as low. This scenario includes 5 agents and two activated parameters, indicating a weakly developed network in which inter-firm connections are limited and industrial symbiosis has not yet taken a functional structure.

3.5.2. Waste reduction through the circular economy

The implementation of industrial symbiosis strategies generates significant improvements in waste management. As presented in Table 5, increasing collaboration among agents enables a higher proportion of waste to be reused as raw material in other production processes, reducing the amount of final waste disposed of in the environment.

Table 5.
Waste reduction through the circular economy

Scenario	Initial waste generated (t)	Reused waste (t)	Waste reduction (%)
Scenario 1	120	25	20.8%
Scenario 2	150	58	38.7%
Scenario 3	180	97	53.9%
Scenario 4	210	150	71.4%

When the results are analyzed from higher to lower performance, Scenario 4 exhibits the most significant outcome, with a waste reduction rate of 71.4%. In this case, 150 tons of waste are reused from an initial generation of 210 tons, reflecting a highly efficient circular flow of materials supported by strong inter-organizational exchange. Scenario 3 follows with a reduction rate of 53.9%, where 97 tons are reused out of 180 tons generated. Although the system does not yet reach its maximum efficiency, it shows a consolidated level of circularity, with a considerable portion of waste being reintegrated into productive cycles. Next, Scenario 2 presents a moderate performance, achieving a 38.7% reduction. Here, 58 tons are recovered from 150 tons of generated waste, indicating that resource exchange is active but still limited in scope, with partial integration among participating agents. Finally, Scenario 1 records the lowest efficiency, with a waste reduction rate of 20.8%, corresponding to 25 tons of reused waste out of 120 tons generated. In this initial configuration, the limited level of collaboration restricts the capacity for material recovery, resulting in a predominantly linear flow of resources.

3.5.3. Resource consumption before and after applying the model

Table 6 presents a comparison of resource consumption before and after the implementation of the proposed model. The results demonstrate reductions in raw material consumption, water use, and energy demand, highlighting the potential of industrial symbiosis to improve resource efficiency and support sustainable manufacturing practices.

Table 6.
Resource consumption before and after applying the model

Indicator	Before the model	After he model	Variation (%)
Raw material consumption (kg)	5,000	3600	-28%
Water consumption (m^3)	1,200	870	-27.5%
Energy consumption (kWh)	9,500	7,200	-24.2%
Greenhouse gas emissions (kg CO_2-eq)	4,300	2,950	–31.4%

The agent-based model promotes a significant reduction in the use of natural resources by 28% and pollutant emissions by 31.4%, strengthening the sustainability of manufacturing companies. Likewise, energy consumption is reduced by 24.2% and water consumption by 27.5%, highlighting the model's impact before and after implementation.

The sustainability indicators shown in Table 7 were used to evaluate the overall performance of the proposed model. These indicators measure operational efficiency, waste utilization, business integration, and global sustainability, providing a comprehensive assessment of the impact generated by industrial symbiosis within the manufacturing system.

Table 7.
System Sustainability Indicators

Indicator	Initial value	Final value	Improvement (%)
Operational efficiency	62%	88%	41.9%
Waste utilization	18%	74%	311%
Business integration	30%	85%	183%
Global Sustainability	45%	90%	100%

As the results are analyzed, the most significant improvement is observed in waste utilization, which increases from 18% to 74%, representing a 311% relative growth. This reflects a substantial strengthening in the capacity to reintegrate waste into productive processes, reducing dependency on virgin raw materials. Likewise, business integration shows a marked rise from 30% to 85% (183%), indicating a higher level of coordination and collaboration among participating firms. Operational efficiency also exhibits a consistent improvement, rising from 62% to 88%, which corresponds to a 41.9% increase. This suggests that the system becomes progressively more optimized as symbiotic relationships are strengthened. Finally, global sustainability doubles its initial value, increasing from 45% to 90% (100%), reflecting a balanced and consolidated improvement in the overall performance of the system. In general terms, the results confirm that the progressive incorporation of industrial symbiosis mechanisms leads to a clear enhancement of all evaluated sustainability dimensions, with particularly strong gains in resource recovery and inter-firm integration, which act as the main drivers of system-wide improvement.

The validation of the computational model developed in NetLogo confirms that the system appropriately reproduces the dynamics of industrial collaboration within a CE framework, under the simulation parameters defined in Table 8. The results obtained show consistent and coherent behavior across the different scenarios, reflecting how the progressive activation of environmental and economic variables influences the interaction patterns among agents. In this sense, the model captures the expected transition from low to high levels of cooperation, as well as the strengthening of resource exchange mechanisms associated with industrial symbiosis, demonstrating its suitability for representing and analyzing collaborative structures in complex industrial systems.

Table 8.
Computational model validation results

Evaluated variable	Result obtained	Status
Agent configuration	Correct	Validated
Connection between agents	Stable	Validated
Scenario simulation	Successful	Validated
Code verification	No errors	Validated
Replication of the actual system	Adequate	Validated

To complement the validation process, the model was executed under different simulation scenarios to verify that its behavior remained consistent. In all cases, increasing the number of participating agents resulted in higher levels of collaboration and greater resource exchange among companies. Likewise, the model responded consistently when the environmental and economic parameters were modified, providing additional confidence in its stability for representing industrial symbiosis processes.

4. Discussion

The results show that the application of the agent-based model promotes the creation of industrial collaboration networks, allowing waste generated by one company to become useful resources for another. This increases operational efficiency, reduces environmental impact, and strengthens sustainability within manufacturing chains.

Likewise, the model demonstrates that as long as there is greater interaction among agents and the activation of environmental, economic, and technical parameters, industrial symbiosis achieves higher levels of effectiveness. The simulation developed in NetLogo allowed us to validate the system's dynamic behavior and verify the viability of the CE approach within the manufacturing sector.

Mathematical models are a key tool for addressing current challenges in industry, such as process optimization, sustainable resource management, and adaptation to climate change, which makes them highly important, as noted by [47]. Studies related to guidelines derived from model findings have required an approach focused on high-quality data that is not always available for analysis, leading to the implementation of hybrid designs that combine artificial intelligence systems with traditional knowledge [48], [49].

After running the software, it was concluded that for the model to function and for collaboration to exist between "Acp" and "Av" agents (buyer and seller agents), all parameters of the study must be activated, since only then can the full extent of collaboration between agents be demonstrated; on the other hand, if all the study's parameters are activated, a 100% activation rate is shown; that is, there is a symbiosis among all industries, which aligns with the principles of sustainability; It follows that as time passes and, consequently, the number of new agents increases and decreases, the number of parameters (Eq.5) also increases, where Eq.5 demonstrates that to fulfill this, Eq.6 must be carried out.

To understand and analyze the behavior of collaborative relationships between agents within a real-world system, where complex analyses of collaborative networks require specific techniques and must be framed within a complex system understanding the degree of this complexity leads to the ABM, which allows for a better understanding of it , through the relationship known as the Science of Science, which aims to gather data through very meticulous techniques such as the SLR as a tool that enables bibliometric analysis, thanks to the aid of artificial intelligence, complex systems, and mathematical models, which allow for a deep understanding of the behavior of the aforementioned agents, as their behavior is observed digitally [50], [33], [51], [52], [53].

On the other hand, there are platforms that help understand new management systems, which enable the performance and optimization of processes to make them more agile and comprehensible, with the aim of understanding complex mathematical model systems [54], [55]. This is evident both in the methodology and in previous studies, which allows for a more concise compilation of information to understand the systematic literature review, as mentioned in [56], [57], [58], [59]. This has been reflected in new collaborative platforms for the redesign of authors and, at the same time, new strategic models for innovation in industries and significant impact, with the aim of exploring the balance between complexity and accessibility for small-scale producers [60], [61], [62].

Although the proposed model shows adequate results, this study has certain limitations: it relied on exploratory scenarios rather than calibration using data from actual manufacturing companies, and it assumes uniform behavioral rules for all agents, whereas real-world industrial environments may involve more diverse conditions. These limitations present opportunities for future improvements and practical applications.

4. Conclusions

Within this context, a fundamental procedure was established, laying a solid foundation to support the study's progress; the Systematic Literature Review (SLR) enabled the systematic identification and measurement of the quality and scope of existing research in the Agent-Based Modeling (ABM) field, thereby providing a robust contextual framework. This analysis helped reinforce the importance and understanding of the tools used. Framed within a transactional or cross-sectional research design.

Within the model-building approach, the steps to create the conceptual and analytical model were analyzed, emphasizing abstraction, which allowed for the sketching of the real system, along with formalization, which enabled the determination of agents, followed by the implementation of the mathematical model, and finally the validation of the model; This follows the three most important points: agent configuration, which enables the construction of the model using a programming language; model verification and validation; and finally, simulation.

Using this as a basis for future research, which will allow for the collection of more accurate data on the agents, this enables the model to incorporate weights, thereby highlighting its importance within sustainable industrial processes.

Future research will focus on applying the proposed model to incorporate industrial data in order to improve its accuracy. Likewise, it would be valuable to evaluate the model across different manufacturing sectors and within larger-scale industrial networks to determine its collaborative network.

Author Contributions

For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, J.C.M.-A. and S.A.M.-M.; methodology, J.C.M.-A.; software, S.A.M.-M.; validation, S.A.M.-M., J.C.M.-A. and I.R.B.-R.; formal analysis, S.A.M.-M.; investigation, J.C.M.-A.; resources, J.C.M.-A.; data curation, S.A.M.-M.; writing—original draft preparation, S.A.M.-M.; writing—review and editing, J.C.M.-A. and S.A.M.-M.; visualization, I.R.B.-R.; supervision, J.C.M.-A.; project administration, S.A.M.-M.; funding acquisition, I.R.B.-R. All authors have read and agreed to the published version of the manuscript." Authorship must be limited to those who have contributed substantially to the work reported.

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The authors declare that there are no known competing financial interests, personal relationships, or conflicts of interest that could have appeared to influence the work reported in this paper.

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