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A Symbiosis-Based Life Cycle Management Approach for Sustainable Resource Flows in the Industrial Ecosystem

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ARTICLE INFO	ABSTRACT
<p>Article History: Received 8 December 2024 Received in revised form 14 January 2025 Accepted 2 March 2025 Available online 14 March 2025</p>	<p>The foundation of sustainable industrial development lies in maintaining a continuous flow of resources from nature to the industrial ecosystem and their return to life cycles. Traditional management approaches, characterized by linear flows, lead to unstable resource streams, which are the primary causes of severe environmental degradation and resource scarcity. Shifting the resource flow paradigm from linear or intermittent patterns toward continuous and circular streams constitutes a major challenge for sustainable resource management in industrial ecosystems. Existing research has primarily focused on improving resource efficiency or reducing waste; however, systematic management studies on resource flows from the perspective of the industrial ecosystem remain scarce. To address this gap, this paper proposes a life cycle management approach grounded in the concepts and mechanisms of industrial symbiosis. By analyzing the life cycle system of resource flows and the symbiosis model, a framework for circular resource flows is developed. Based on this framework, a life cycle model is introduced that leverages the symbiosis of existing resource streams, coupled with an integrated assessment method that supports goal-oriented life cycle management while also addressing environmental impacts and sustainable utilization prospects. The case study demonstrates the capability of this approach to assist decision-makers in identifying key issues and formulating integrated, targeted strategies to facilitate sustainable resource flows within industrial ecosystems. To illustrate the evaluation and outcomes, the case study employs Nash theory.</p>
<p>Keywords: Life Cycle, Sustainable Flows, Industrial Ecosystem Resources, Symbiosis, Nash Theory</p>	

1. INTRODUCTION

Over the past 200 years, industrialization has brought significant benefits, such as the rapid expansion of property, improved living conditions, and the reduction of manual labor. However, traditional industrial development has also been accompanied by an unlimited increase in material consumption and waste emissions. Moreover, both natural resources and the Earth's environmental capacity are finite. As a result, since the Industrial Revolution, growing concerns have been expressed regarding resource scarcity and environmental degradation [1].

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In this article, the term resources refer to material resources, including natural resources and their transformed forms (i.e., products or waste). Even today, a large portion of the global economy relies on the extraction and use of natural resources. With ongoing globalization and growth trends, such industrial models are pushing human society toward real physical limits and constraints in environmental carrying capacity. Therefore, the sustainable use of resources has become an urgent issue for sustainable industrial development.

The traditional resource management model follows a linear pattern—from resource exploitation to waste discharge—which leads to low efficiency in resource utilization and severe environmental challenges. Thus, resource flow management must undergo a transformation toward a more sustainable paradigm, shifting resource streams from linear or intermittent patterns to continuous and circular ones. The circular model of material flows, inspired by natural ecosystems, provides a foundation for the paradigm of sustainable industrial development.

In 1989, Pearce and Turner introduced the concept of the circular economy based on Boulding's 1966 work [2]. Today, the circular economy has become a widely accepted alternative model for transitioning from traditional economies to sustainable ones, particularly in countries such as China, Germany, and Japan. Existing research describes concepts, principles, and implementation practices at three levels: micro (enterprise), meso (eco-industrial parks), and macro (cities or regions).

At the micro level, implementation includes cleaner production [3,4], green and optimized consumption [5], product recycling and reuse, and policy development [6]. At the meso level, efforts focus on eco-industrial systems, industrial symbiosis networks [7–9], and information sharing [10,11]. At the macro level, implementation is mainly associated with regional economic and industrial networks [12,13], municipal waste management [14,15], and privacy or regulatory frameworks [16,17]. Despite these developments, inter-organizational sustainability management still raises numerous challenging questions that require further attention [18]. Sustainable resource flow management within the industrial ecosystem is one of the most critical challenges.

The path of resource flows in industrial ecosystems constitutes a complex life cycle system. Circular flows emerge when the output streams of some firms become the input streams for others. Designing an efficient integrated circular resource management system and developing a systematic evaluation method through in-depth analysis are essential for transitioning from the traditional linear model to a circular one in decision-making processes [19]. Consequently, resource flow management must be approached from the perspectives of life cycle and symbiosis.

Symbiosis-based life cycle management offers a pathway toward sustainable resource utilization, characterized by high environmental efficiency and reduced ecological impacts. The Society of Environmental Toxicology and Chemistry defines symbiosis-based life cycle management as a flexible, integrated framework of concepts, techniques, and practices addressing the environmental, economic, technological, and social aspects of products and organizations to achieve continuous environmental improvement throughout their life cycles. The United Nations Environment Programme (UNEP) has proposed a general framework comprising strategies, systems, programs, tools, and data, aimed at maximizing economic and social value while minimizing environmental and economic burdens [20].

The remainder of this paper is structured as follows: Section 2 reviews the literature and research problem. Section 3 analyzes the structure and function of industrial ecosystems and examines the resource flow life cycle system to identify industrial symbiosis patterns. Based on this, a symbiosis-based life cycle management framework is proposed. Sections 4 and 5 introduce the symbiosis-based life cycle management approach, including the life cycle system model, index system, evaluation models, and symbiosis-based management strategies. Section 6 presents a case study to demonstrate that the proposed approach provides a flexible and effective management tool for achieving environmental benefits and sustaining resource flows in industrial ecosystems. Finally, Section 7 discusses the conclusions and key challenges.

2. LITERATURE REVIEW

Current research has primarily focused on either product manufacturing or waste management, both of which consider three key dimensions: environment (ecosystems and resources), economy (cost impacts), and society (social impacts). For example, many studies on symbiosis-based life cycle management have explored its role in controlling

energy consumption and the environmental impacts of products [21–26]. Other works have developed symbiosis-based waste management approaches [27–29], while some have examined social or economic impacts [30–33].

Symbiosis-based life cycle management has also been applied in various industries, including construction, electrical equipment, packaging, chemical production, and environmental protection. The company 3M was among the first to implement symbiosis-based life cycle management, adopting a chain model that generated substantial benefits and rewards [34]. 3M focused on the broader impacts of its products and processes across their entire life cycle, supporting the execution of programs such as pollution prevention to meet environmental targets in 2010. Following its adoption of symbiosis-based life cycle management, 3M achieved two main objectives: (1) identification and management of environmental, health, safety, regulatory risks, and opportunities; and (2) efficient resource utilization throughout the life cycle of 3M's products. Their models have since been applied by other companies such as Alan Packaging [35], Dow Chemical, and Eskom [36].

Beyond the chain model, Morone also discussed a pyramid-shaped model of symbiosis-based life cycle management in a Swiss fruit farm, consisting of a farm, a garden, and orchards [31]. Some researchers have further examined the implementation of life cycle management practices and symbiosis-based approaches, such as material flow analysis (MFA), to guide resource use in specific industries toward sustainable development [37–40].

However, from the perspective of industrial ecosystems, no practical and systematic symbiosis-based life cycle management approach has yet been introduced for resource flow management that simultaneously improves economic resource efficiency and reduces environmental pollution. To address this research gap, the present study develops a symbiosis-based life cycle management approach for managing resource flows in sustainable industrial ecosystems, aiming to minimize environmental burdens while maintaining continuous and sustainable resource streams.

3. CONCEPTS AND PRELIMINARY FRAMEWORK

3.1. Structure and Function of the Industrial Ecosystem

In 1935, Tansley introduced the concept of the ecosystem. Building on this, in 1989, Frosch and Gallopoulos predicted the idea of the industrial ecosystem in their seminal article published in a leading American scientific journal. In such a system, energy and material use are optimized, while the waste stream of one process becomes the input for another [41].

Broadly, an industrial ecosystem can be defined as a complex economic–environmental system composed of industrial communities (extractors, producers, consumers, suppliers, and decomposers) and environmental elements (biotic and abiotic) [42,43]. Extractors are mainly mining companies, while producers consist of raw-material and component manufacturers. Consumers include both production firms and end users, whereas decomposers primarily involve waste collection, disassembly, recycling, and disposal enterprises [42,43]. Given the critical role of logistics, suppliers are also considered an integral part of the industrial ecosystem.

Within the industrial ecosystem, each actor—such as a producer—is connected through resource flows, which together form industrial symbiosis networks. These flows are influenced by both market forces and policy frameworks. Market and policy fluctuations can cause resource flow volatility, affecting the type and scale of the industrial community and, in turn, driving the evolution of industrial networks. For instance, the “polluter pays” principle supports the development of green industries by accelerating the transition from linear flows in traditional industries to circular flows in sustainable ones. Since resource flows directly shape the development patterns of industrial ecosystems, resource flow management is crucial for enabling this transition.

From an ecological perspective, natural ecosystems perform functions of production, consumption, and decomposition. Similarly, industrial ecosystems exhibit functions of exploitation, production, transportation, consumption, and restoration. Among these, transportation—including logistics and delivery—is unique to industrial ecosystems, serving as a bridge between other functions. Each function is supported by flows of materials and energy, finance, and information, which together ensure system operation. The balance between resource supply and demand ultimately determines the quality of these functions [44].

3.2. Resource Flows in Industrial Ecosystems

3.2.1. Classifications

An industrial ecosystem encompasses a wide range of industries, including mining, manufacturing, services (e.g., transportation, trade, education, healthcare, finance, and postal services), and environmental industries. Resource flows link these industries together and sustain the normal functioning of their activities.

From a resource perspective, flows can be categorized into two groups: natural resource flows and obsolete or waste resource flows. Natural resource flows support the production and consumption functions of the industrial ecosystem but may also lead to environmental issues such as biodiversity loss or soil and water degradation if overexploited. Conversely, waste resources, if not properly treated or recycled, can be discharged under regulatory standards. Fortunately, waste can be converted into reusable resources through recycling and reintegration into the system. Linear resource flows, when redirected through waste recycling, can thus be transformed into circular flows.

The characteristics of resource flows directly affect the environmental efficiency of industrial ecosystems. Generally, ecosystems with circular flows are more efficient and impose fewer environmental impacts compared to those with linear flows, as waste is converted into usable materials [44].

3.3. Life Cycle Processes of Resource Flows

Natural resources provide the raw materials required for industrial ecosystem functions. The life cycle system of resource flows in an industrial ecosystem includes several stages: extraction and exploitation, production, transportation, consumption and services, and restoration (waste disposal, recycling, and discharge).

Extraction and Exploitation: Raw materials are sourced for production. Overexploitation at this stage can harm natural ecosystems and lead to resource shortages.

Production: A core industrial function, where raw materials are transformed into goods for consumers. Inefficient use of resources can cause severe environmental problems due to waste and pollutant discharges. Greater reuse and recycling can enhance resource efficiency.

Transportation: Connects all stages of the life cycle, delivering various materials while consuming energy.

Consumption and Services: Reflect the effectiveness of goods and services in use. Low efficiency at this stage leads to significant environmental stress due to waste and excessive energy consumption. The overall level of consumption determines the intensity of resource use.

Restoration: Ensures the industrial ecosystem can realign with natural ecosystems through processes such as disposal, recycling, and discharge.

Disposal aims to reduce environmental stress in three ways: (1) converting waste into reusable resources for consumers, (2) transforming hazardous waste into harmless materials, and (3) minimizing waste volume.

Recycling improves resource efficiency through reuse and recovery.

Discharge—via sanitary landfills or incineration—must comply with greenhouse gas emission standards.

Rational circulation of resources helps relieve environmental stress, as waste from one actor, through mechanisms of symbiosis, can serve as resources for others [45].

3.4. Symbiosis Patterns in the Industrial Ecosystem

As discussed in the preceding section, traditional linear resource flows can be transformed into circular flows through symbiotic mechanisms. Various factors influence symbiosis patterns, including: the degree of symbiosis, industrial structure, geographical proximity, economic level, policies, social culture, and others. Different countries or regions exhibit distinct symbiotic conditions shaped by diverse social, economic, and environmental contexts.

Moreover, varying symbiotic environments lead to the development of different symbiosis models. While geographical proximity is often associated with industrial ecology, it is not strictly necessary to focus exclusively on the exchange of physical resources [46].

3.5. Resource Flow Management Framework

3.5.1. Scales and Dimensions

Although UNEP/SETAC provides a flexible framework for life cycle management based on symbiosis, a number of pragmatic approaches are required to adapt management to different scales, since each scale involves distinct dimensions and models. Therefore, identifying the relevant scale is a critical prerequisite for developing an appropriate management approach to achieve desired goals.

For life cycle management underpinned by symbiosis, resource flows are considered at two primary scales: the individual (enterprise) and the system (industrial ecosystem). In the context of sustainable industry, three dimensions of sustainability are central to life cycle management:

1. **Environmental dimension** – focused on reducing environmental impacts.
2. **Economic dimension** – emphasizing green growth through symbiotic mechanisms.
3. **Social dimension** – addressing symbiotic relations and social responsibility.

At the enterprise scale, the environmental dimension addresses the main environmental impacts of a company's products and services throughout their life cycle. The economic dimension emphasizes eco-efficiency, achieved through green technologies and the adoption of green products. The social dimension focuses on broader product responsibility.

At the industrial ecosystem scale, the environmental dimension relates to the overall ecological impacts generated by material flow networks. The economic dimension emphasizes the eco-efficiency of the material flow network, while the social dimension concerns the symbiosis network and its social responsibility toward sustainable development. Consequently, a new life cycle management framework grounded in symbiosis is required to guide industrial ecosystems in achieving sustainable development objectives.

4. MANAGEMENT FRAMEWORK

Based on the preceding discussion, the primary goal of life cycle management of resource flows is to achieve sustainable resources by transforming traditional linear flows into circular ones. Drawing on the UNEP framework for life cycle management and the life cycle processes of resource flows, this study proposes a life cycle management framework based on symbiosis for industrial resource flow management, illustrated conceptually in Figure 1.

This framework focuses on managing the life cycle system of resource flows, which consists of five subsystems: extraction, production, consumption, logistics and delivery, and disposal/recycling. Each subsystem is supported by a set of integrated management strategies designed to help decision-makers secure sustainable resources by promoting circular resource flows within the life cycle system.

An assessment system is incorporated to evaluate resource use within the life cycle, relying on two categories of indicators: (1) environmental impacts and (2) sustainable use. Moreover, the assessment system includes a feedback mechanism that communicates evaluation results to decision-makers, enabling them to progressively adjust strategies in pursuit of the sustainability objective.

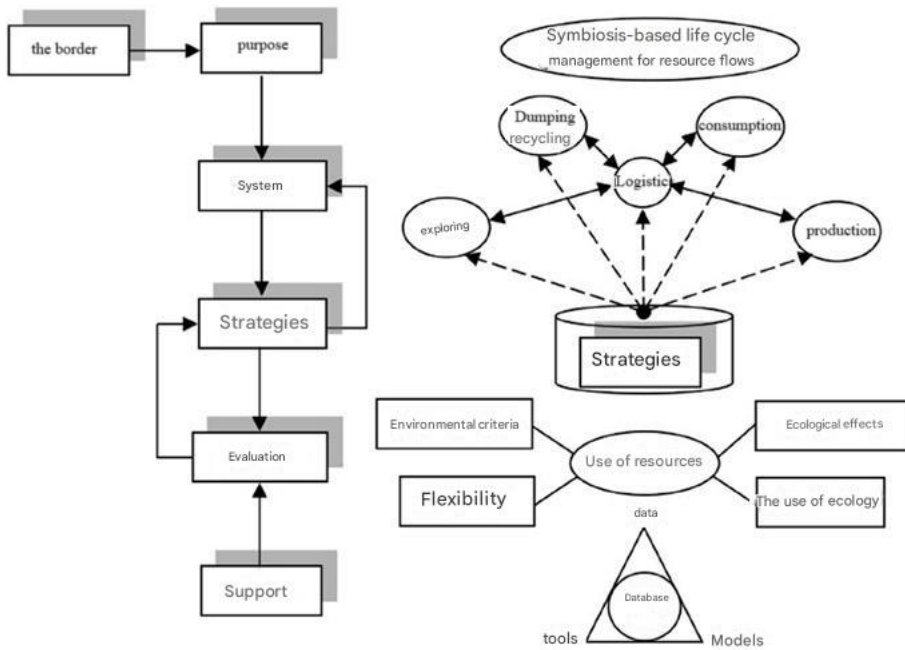


Fig. 1. Symbiosis-Based Life Cycle Management Framework for Managing Industrial Resource Flows

5. MANAGEMENT METHODS

The boundary of symbiosis-based life cycle management is primarily defined by the life cycle of the managed object. In this approach, the industrial ecosystem’s resource flow constitutes the system boundary of the resource life cycle, encompassing all stages previously described. The overarching objective of symbiosis-based life cycle management is to ensure sustainable chain management that promotes long-term development. Within the industrial ecosystem, resource flows embody the value chain. Thus, the central aim is to achieve sustainable resource support through the performance management of resource life cycle flows.

In this study, the goal of symbiosis-based life cycle management for industrial ecosystem resource flows is framed as the restricted use of resources within the thresholds of natural resource availability and the controlled release of waste within environmental capacity, guided by the principles of reduction, reuse, and limited recycling. To achieve this, efficient utilization of resources and effective recycling of waste are essential. Accordingly, a resource flow life cycle system model is developed to strengthen these two aspects. Resource flows link the four stages of the life cycle through logistics and transactions, forming a network that supports industrial ecosystem performance. Waste treatment and recycling systems serve as bridges for resource recovery, enabling the creation of closed-loop cycles. To realize circular resource flows, decision-makers must develop a set of management strategies, which will be discussed in detail later.

Currently, no fixed standards exist to evaluate whether resource flows are genuinely sustainable, considering that industrial sustainable development is inherently dynamic and the realization of symbiosis-based life cycle management represents a progressive and ongoing process. Therefore, it is essential to propose an evaluation method that can assess the impacts of management and provide timely information for further improvement.

Different stages of symbiosis-based life cycle management require different strategies. All stages are connected through a comprehensive system-wide strategy that supports efficient resource use and waste recycling throughout the entire life cycle. As previously stated, the industrial resource flow life cycle consists of five stages, each with its own specific strategies:

- Extraction stage: Strategies focus on economic benefits and environmental protection, including land cover

conservation, waste disposal, and ecosystem restoration.

- Production stage: Strategies emphasize economic efficiency, resource productivity, waste reduction, the use of renewable resources, recyclable materials, and minimal waste generation.
- Logistics stage: Strategies prioritize green packaging and energy-efficient delivery.
- Consumption and service stage: Strategies target sustainable consumption and environmentally friendly operations.
- Disposal, recycling, and discharge stage: Strategies highlight waste reuse, recycling, harmless disposal, discharge permits, and discharge standards.

Collectively, these strategies are designed to construct a symbiotic network system across all five stages.

The proposed life cycle management approach offers a systematic management solution based on a specific symbiotic system and a comprehensive evaluation of the life cycle, with the aim of achieving sustainable management of resource flows in the industrial ecosystem. The symbiotic system is designed to address environmental challenges and optimize resource use, while the comprehensive evaluation focuses on management impacts and identifying challenges at each life cycle stage.

The findings demonstrate that symbiosis-based life cycle management can significantly reduce environmental impacts and promote sustainable resource utilization. Meanwhile, mineral resource use is identified as the most critical challenge in the life cycle, with wastewater discharge recognized as the primary source of mineral resource impacts, due to the exploitation of certain ores (e.g., bauxite) for the production of chemical reagents. Based on these observations, decision-makers can encourage enterprises to adopt alternative reagents with minimal impacts by implementing targeted policies and actions.

As the results provide detailed insights into improvement levels and key challenges across different life cycle stages, decision-makers not only gain a clearer understanding of management impacts but also acquire the ability to implement targeted solutions to address unsustainable resource use. Therefore, symbiosis-based life cycle management of resource flows is both effective and feasible.

6. MODELING

The key concepts examined for symbiosis-based life cycle management include circular economy, Nash equilibrium theory, agent-based modeling, and multi-criteria analysis. In addition, scenario analysis, robust decision-making, integrated assessment modeling, and various hybrid approaches combining “circular economy” and “solid waste management” are considered as secondary elements of this study. A detailed but crucial distinction between the concepts of sustainability and circular economy has previously been discussed [47].

All the aforementioned methods—including agent-based modeling, multi-criteria decision analysis, scenario analysis, robust decision management, and integrated modeling—are valuable for analyzing the processes of decision-making management systems. However, these approaches generally fail to account for the strategic behavior of actors engaged in negotiation. In contrast, Nash theory provides a valuable perspective on how the preferences and decisions of actors influence not only their opponents’ choices but also their own subsequent decisions and the ultimate outcomes of strategic interactions. For example, if one participant proposes aggressively in order to discourage competitors from making further offers, the final selling price may differ significantly from a scenario in which two or more participants gradually bid until one reaches the maximum perceived value. Another advantage of Nash theory is its capacity to evaluate individuals’ behavior based on their self-interests while still aiming for optimal system-level outcomes emerging from self-serving actions.

Agent-based modeling (ABM) simulates the interaction between multiple independent agents and evaluates the impact of their actions on a system [48]. ABM is particularly suited to capturing systemic effects and interactions among agents and their behaviors. It enables the simulation of group dynamics resulting from individual interactions

within communities. ABM is especially useful when dealing with a large number of heterogeneous agents whose interactions are complex. The core characteristics of an agent in ABM are:

1. pursuing a set of defined objectives,
2. interacting with the environment and other agents according to a given set of social rules, and
3. influencing the behavior of other agents through pre-defined communication mechanisms.

Unlike traditional top-down modeling, ABM generates complex system behaviors from bottom-up interactions among agents and between agents and their environments. Agents are capable of learning from their environment and adapting to new conditions or data. In the context of economic systems, ABM can effectively simulate macro-level dynamics emerging from simple individual actions [49]. Rather than attempting to predict a single future, ABM explores multiple possible futures arising under alternative conditions [50]. It has also been applied to understand the relationships between diffusion processes and consumer purchasing decisions, as well as to study industrial cooperation and supply chain networks. Importantly, defining rules within ABM is critical, as even minor changes in rules can lead to fundamental shifts in agent behavior and system outcomes.

Multi-criteria decision analysis (MCDA) organizes alternative options hierarchically and prioritizes criteria effectively. This operational tool is particularly useful for studying issues characterized by high uncertainty, multiple stakeholder interests, and conflicting objectives. MCDA allows for the ranking of policy alternatives using stakeholder perspectives and cost–benefit information. It is often employed to address complex and ambiguous decision-making problems. A complementary weighting method is commonly applied to rank options. MCDA is most effective when multiple parameters simultaneously influence task performance. Its most recognized application lies in tackling decision-making problems influenced by conflicting criteria.

Scenario analysis examines how a specific goal in the future (normative) might be achieved through uncertain developments (exploratory), or how a shift from an exploratory scenario to a targeted (normative) scenario—referred to as a transition scenario—may occur [51]. This method is used to test a wide range of development strategies and identify the most suitable plans through optimization techniques. The analysis is conducted with consideration of technical, social, economic, environmental, and political criteria. In this context, uncertainty is understood as a set of potential future outcomes. In other words, scenario analysis generates models where uncertainty becomes the foundation for decision-making systems [52]. Importantly, scenario analysis should not be confused with forecasting. Rather, it provides plausible pathways through which the future may unfold. It offers valuable insights for policymakers when assessing the long-term consequences of current and planned practices [53]—for instance, analyzing the implications of increasing or reducing recycling rates.

To mitigate the risk of poor decision-making, scenario analysis incorporates agent-based methods by evolving statistically independent scenarios into temporally consistent trajectories, thus ensuring robust choices. By considering both short- and long-term costs and benefits of expected outcomes, scenario analysis helps identify the most promising options [54].

To illustrate the complementary potential of Nash theory in highlighting key points within decision-making systems for symbiosis-based life cycle management of sustainable industrial ecosystem resource flows, an example demonstrating the application of Nash theory to advance circular economy principles in industrial life cycle management is provided using the framework presented in [55]. This framework integrates three decision-making methods—cost–benefit analysis, life cycle assessment, and multi-criteria decision analysis—with Nash theory principles to identify optimal solutions for negotiation or equilibrium problems.

Consider a negotiation scenario between a city council member representing citizens and a manager of a waste recycling company regarding the cost of recycling services. Using cost–benefit analysis, the operational cost of the waste recycling plan is calculated at 3,000,000 IRR per ton, while, via multi-criteria decision analysis weighting methods, citizens' willingness to pay is estimated at 10,000 IRR per ton. Both parties understand that the cost is less than 10,000 IRR per ton and the value paid is greater than 3,000,000 IRR per ton. A surplus exists per ton, which must be shared through negotiation regarding service costs.

It is assumed that both participants are rational and always seek to maximize their preferred outcomes. Similarly, it is assumed that they are intelligent—they possess the same information, understand the situation, and can make logical inferences. Table (2) presents the payoffs of their decisions given the choices of their counterpart. The value on the left represents the payoff to the recycling company, while the value on the right corresponds to the city council. These surplus values indicate the per-ton share allocated to stakeholders.

If both parties agree on sharing the surplus, each receives a payoff of 7,500 IRR. If one agrees while the other disagrees, the consenting player receives 5,000 IRR, while the dissenting player receives nothing. Conversely, if both parties disagree, the outcome is zero (i.e., $(d_1, d_2) = (0,0)$). Stability in this context is defined as the absence of incentive for either party to deviate from the strategy in pursuit of a better payoff.

Suppose the Nash equilibrium is initially at (d_1, d_2) . In this case, the city council has incentives to deviate due to a preferred surplus of 10,000 IRR per ton, and likewise, the recycling company has incentives to adjust its strategy. If the deviation scenarios (d_1, u_2) and (d_2, u_1) are considered unstable for the recycling company or city council respectively, the system transitions to the state (u_1, u_2) . Therefore, the state (u_1, u_2) is stable for both players because deviation would result in a lower preferred payoff for the city council ($(u_1, d_2) = (5,000, 0)$) or for the recycling company ($(d_1, u_2) = (0, 10,000)$), which constitutes the Nash equilibrium.

This illustrates the solution concept in Nash theory, which asserts that participants have no incentive to further deviate once an equilibrium is reached.

Table 1. Negotiation Model for Life Cycle Management Service Costs in Symbiosis-Based Management of Sustainable Industrial Ecosystem Resource Flows

Symbiosis-Based Life Cycle Management for Sustainable Industrial Ecosystem Resource Flows	City Council Oppose (d2)	City Council Agree (u2)
Oppose (d1)	0, 0	10,000, 0
Agree (u1)	5,000, 5,000	0, 10,000

As illustrated in Figure (2), both stakeholders possess symmetric payoff functions. Accordingly, the Nash bargaining solution for surplus division occurs at $(u_1, d_2) = (5,000, 5,000)$, indicating that the agreed service cost should be 7,500 IRR per ton.

This example clearly demonstrates the potential of Nash theory to enhance stakeholder participation in waste management and circular economy initiatives. By supporting fair allocation of benefits and costs among stakeholders—in this case, a city council representing citizens and a waste management company—the model can be applied to achieve results consistent with the objectives and approach of this study.

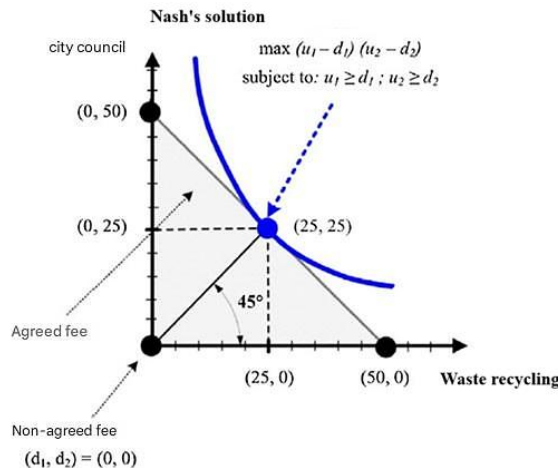


Fig. 2. Nash Theory-Based Solution for the Negotiation Model of Life Cycle Management Service Costs in Symbiosis-Based Management of Sustainable Industrial Ecosystem Resource Flows

7. CONCLUSION

Traditional, isolated management approaches often lead to unsustainable resource use and significant environmental challenges. Developing an effective method for managing resource flows is essential to achieve sustainable industrial transformation, as the industrial ecosystem's resource flows represent a complex life cycle system.

This study aimed to implement life cycle thinking and symbiosis mechanisms to develop a symbiosis-based life cycle management approach for achieving sustainable resource flows within industrial ecosystems. The approach introduces several key advancements:

1. The symbiosis-based life cycle management framework provides sustainable resource management through a symbiosis-oriented system coupled with targeted life cycle assessment.
2. The symbiosis-based life cycle model facilitates the transition from linear to circular flows, thereby promoting sustainable resource use.
3. The system evaluation method helps decision-makers identify critical issues at each life cycle stage and develop targeted strategies, ensuring sustainable management impacts from both environmental and resource utilization perspectives.

Finally, the case study confirmed the effectiveness of the proposed approach in improving environmental performance and promoting sustainable resource utilization compared to traditional methods. Thus, the proposed framework offers a flexible and efficient management solution based on Nash theory for achieving sustainable resource flow management in industrial ecosystems.

Nevertheless, due to the complex nature of system life cycles, several limitations remain. This study still represents a partial system implementation with hypothetical conditions rather than a full reflection of a real-world system. Establishing a database to collect annual data from a real system is necessary for further validation. Moreover, the dynamic nature of resource flows remains a critical challenge, and gaps exist in predicting future trends. Consequently, further research focusing on developing data-support and trend analysis systems to complement the current work would be highly valuable.

Declaration

We acknowledge that we used ChatGPT to enhance the academic writing of our manuscript while ensuring the originality and integrity of our work.

Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

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Declaration of Interest

The authors declare that they have no competing interests.

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