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► To cite this version:

Soukaina Benchari, Cecilia Daquin, Yves Sallez, Emmanuelle Grislin-Le Strugeon. Modeling approaches of an industrial symbiosis: state-of-the-art. Congrès annuel de la SAGIP, May 2024, Villeurbanne (Lyon), France. hal-04639336

HAL Id: hal-04639336

<https://hal.science/hal-04639336>

Submitted on 8 Jul 2024

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Modeling approaches of an industrial symbiosis: state-of-the-art

Soukaina Benchari¹, Cecilia Daquin¹, Yves Sallez¹, Emmanuelle Grislin-Le Strugeon^{1,2}

¹ UPHF, CNRS, UMR 8201 - LAMIH, Valenciennes, France

² INSA Hauts-de-France, Valenciennes, France

{soukaina.benchari,cecilia.daquin,yves.sallez,emmanuelle.grislin}@uphf.fr

Keywords : *Industrial symbiosis, Negotiation, Optimization, Multi-agent systems, Circular economy*

1 Introduction

The linear economy (LE) system, utilized since the beginning of the industrial era, has demonstrated its incapacity to fulfill the goals of sustainable development [4]. The linear production process, characterized by raw material extraction, production, consumption, and disposal, accelerated by economic growth, has led to increased waste production and resource consumption [1, 8]. This process put a significant pressure on the Earth system's global balance. The planetary boundaries concept provides a crucial scientific tool for measuring this massive anthropogenic effect. Presently, six out of the nine planetary boundaries have been exceeded, indicating that the Earth system is no longer in a state of safe and just development for humanity [10].

To address the challenges posed by the LE footprint, a transition became imperative, giving rise to the concept of Circular Economy (CE) [5]. According to the Quebec circular economy consultation center, CE is a "system of production, exchange and consumption aimed at optimizing the use of resources at all stages of the life cycle of a good or service, in a circular logic, while reducing the environmental footprint and contributing to the well-being of individuals and communities". Materials and used products are reintroduced into the production and usage cycle as much as possible. Hence as stated by the European Commission (EC), in a circular economy, products and materials retain value for as long as possible, thereby minimizing waste and resources consumed. Reuse and upcycling loops throughout a product's life cycle bring economic benefits, fostering innovation and job creation.[6].

Among the seven pillars of the CE, industrial ecology ,(IE) is a practice aiming to minimize industrial environmental impacts. For this, IE is based on exchanges and pooling of flows, materials or services between industries through industrial symbioses (IS) [2]. Industrial symbiosis involves collaboration networks between companies, focused on exchanging flows of materials, energy, and knowledge to enhance their environmental and economic performance [9].

Industrial symbioses are not easy to set up or operate. Thence, their study is a research area that has been increasingly studied in recent years (since the 2000s) to understand their evolution and their functioning in order to promote them, facilitate them and make them sustainable [2]. In this context, this article provides a state-of-the-art overview on the various works carried out in this domain, and focuses particularly on diverse approaches to modeling

industrial symbiosis. Our objective is to highlight gaps in this area and suggest prospects for future research.

2 State-of-the-art

To realize this state-of-the-art, we analyze three selected survey articles from 2021 to 2022, along with one article from 2023, to examine the works conducted within the field of industrial symbioses and more particularly of the modeling approaches of IS. The aim of our work is to identify existing gaps in this field and so to suggest some relevant perspectives for future works.

[3] classified the methodologies used in the context of industrial symbiosis, highlighting the characteristics, limitations, and applications of each. Their study revealed a significant gap in the development of models that address all three objectives: economic, social, and environmental. Additionally, the article identified a gap regarding the hybridization between agent-based modeling approach (ABM) and System Dynamics (SD). The ABM approach is well suited to capture the complex and dynamic behaviors of industrial symbiosis by modeling the micro-interactions, while the SD approach can be utilized to model the macro-interactions as flows within the networks. Building on this, [7] introduced two methods: process integration (PI) and mathematical optimization. The article presented various variations of these approaches, breaking them down into categories such as energy, water, power, carbon, and waste. The authors identified a lack in existing models, specifically noting that many do not take into account seasonality and variability of both demand and supply. Moreover, among the mentioned models, most remain theoretical and lack implementation in real case studies. [11] classified methods used in the industrial symbiosis context into three primary axes: (1) Multi-Criteria Decision Making (MCDM), (2) Deterministic, Non-Deterministic and Heuristic, (3) Simulation approaches. The authors methodically outlined the sectors where these methodologies find application. However, their study revealed significant gaps in the existing literature. It highlighted a restricted focus on operational processes within the industrial symbiosis (IS) network. The article underscored a notable scarcity of studies using fuzzy methods, a mathematical approach designed to address uncertainty and imprecision in decision-making and problem-solving. Instances of goal programming and dynamic programming in the literature are identified as rare. Finally, [2] aimed to optimize production planning optimization for industrial symbiosis partners by proposing a centralized approach with a mixed-integer linear programming model. The authors identified key gaps in the literature, including the lack of focus on tactical and operational decisions. They emphasized the importance of decentralized approaches through negotiation, and highlighted the need to consider environmental and social factors. Additionally, they suggested expanding the proposed model to formalize industrial symbiosis as a network of synergies rather than a linear chain.

3 Conclusion

In the current world context, the transition from a linear to a circular economic model has proved crucial to mitigating the environmental impacts of industries. It is essential to encourage companies to engage in industrial symbiosis collaborations, highlighting the economic, social, and environmental benefits inherent in this transition. In this paper, we proposed a study of articles in the literature that are interested in modeling approaches of industrial symbiosis. This state-of-the-art highlighted various gaps related to the subject, such as the need to integrate multi-objective aspects into the models developed, the need to develop decentralized approaches guaranteeing the confidentiality of economic players, and the proposal of hybrid approaches in the context of industrial symbiosis. These results underline the importance of filling these gaps to promote a more holistic and efficient transition towards sustainable industrial practices.

To go further, based on the identified gaps and considering the advantages and disadvantages of central planning, centralized decision making facilitates the search for a global optimum solution. However, it does require stakeholders to share all information, presenting a potential limitation. Conversely, a decentralized approach offers the flexibility needed to consider the heterogeneity of stakeholders' decision-making criteria and preserves the confidentiality of information. The challenge with decentralized decision making lies in achieving optimal exchanges. Thus, an attractive work would be to propose a decentralized approach integrating optimization algorithms with simulation models from the field of multi-agent systems [11]. The aim of this approach would be to allow negotiation among multiple actors involved in an industrial symbiosis. So that decision-making is not only guided by the economic aspect, the optimization models' objective functions could encompass environmental and social factors. Additionally, incorporating uncertainty and future variations into the models represents another potential perspective.

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