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Design for sustainability of industrial symbiosis based on emergy and multi-objective particle swarm optimization

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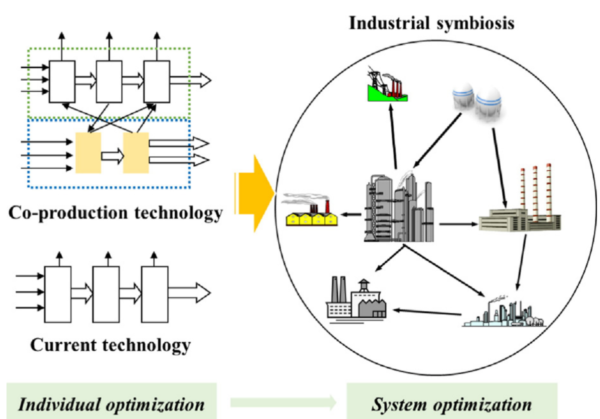
HIGHLIGHTS

- A model for sustainability design of industrial symbiosis has been developed.
- Emergy sustainability index has been used to measure sustainability performance.
- Multi-objective Particle Swarm Algorithm is proposed to solve the model.

GRAPHICAL ABSTRACT



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ABSTRACT

Industrial symbiosis provides novel and practical pathway to the design for the sustainability. Decision support tool for its verification is necessary for practitioners and policy makers, while to date, quantitative research is limited. The objective of this work is to present an innovative approach for supporting decision-making in the design for the sustainability with the implementation of industrial symbiosis in chemical complex. Through incorporating the emergy theory, the model is formulated as a multi-objective approach that can optimize both the economic benefit and sustainable performance of the integrated industrial system. A set of emergy based evaluation index are designed. Multi-objective Particle Swarm Algorithm is proposed to solve the model, and the decision-makers are allowed to choose the suitable solutions form the Pareto solutions. An illustrative case has been studied by the proposed method, a few of compromises between high profitability and high sustainability can be obtained for the decision-makers/stakeholders to make decision.

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1. Introduction

Design for sustainability has become an evolving hot spot for sustainable industrial development. It is a philosophy which aims achieving the full consequence of a particular economic objective with least negative impacts on environmental issues and social concerns (Othman et al., 2010; Jayswal et al., 2011). The "industrial symbiosis" strategy provides practical pathway to the design for sustainability, through closing the loops of material and energy flows inner and among plants (Allenby, 1992; Diwekar and Small, 1998; Dong et al., 2013). It is reported that with implementation of industrial symbiosis, flows can be optimized in the network and significant economic and environmental benefits can be achieved in process synergies (Zhang et al., 2013), industrial parks or complex (Lambert and Boons, 2002; Park et al., 2008) and industrial cities (Van Berkel et al., 2009; Dong et al., 2014).

The chemistry industry as a key consumer of fossil energy and a tremendous emitter of GHG in manufacturing industries is responsible for product stewardship and sustainable development (Jayswal et al., 2011). In order to achieve sustainable development, many implements are put into effect in chemical engineering such as integrated industrial system (Ren et al., 2013a) and integrated industrial park (Midthun et al., 2012). But it does not mean that all the integrated systems and integrated industrial parks are sustainable, Li et al. (2011) has pointed that process system engineering should be positioned to address the sustainability of chemical engineering in the early design stage. Sustainable design with industrial symbiosis implementation is an emerging methodology for sustainable planning in the early design stage.

To verify and optimize the designed industrial symbiosis, analytical methodologies and design approach is necessary for practitioners and policy makers (Dong, 2014). While in the field of industrial ecology, there are several prevailing approaches, e.g. life cycle assessment (Hertwich et al., 2000; Guinée et al., 2010), material/energy flow analysis (Ayres, 1989; Sendra et al., 2007) and input–output analysis (Leontief, 1936; Giljum, 2009), innovative index for sustainability and design approach for industrial symbiosis integrating with effective model is still an area to be explored.

In past studies, sustainability performance of industrial systems was usually measured by using multi-criteria method to investigate the three pillars of sustainability including economic performances, environmental issues and social concerns (Othman et al., 2010; Mele et al., 2011; Liu and Huang, 2012). Besides these, there are also some studies using single indicator approach to measure sustainability, i.e. emergy sustainability index (Singh and Lou, 2006; Ren et al., 2013b), ecological footprint (Ren et al., 2013c) and the extended indices. Emergy based indicator was proved to be effective indicators to present the essence of sustainability, while rather few applications in industrial symbiosis. For instance, Singh and Lou (2006) defined two new emergy-based sustainability indices including index of economic performance and index of environmental performance to assess the sustainability of industrial ecosystems. Ren et al. (2013b) used the emergy-based indices such as the emergy sustainability index (ESI) to assess the sustainability of different crop-based biofuel production systems. These works have established the foundation for the sustainability assessment of industrial complex. But most of the works are about assessing the sustainability of industrial process, and few studies focus on sustainability design for industrial symbiosis which is a hot spot in chemical engineering and environmental engineering. In addition, although the criteria or indices used in sustainability assessment of industrial systems can be referred in sustainable design, consider the repeatability and relevancy in the criteria system, there is still research gap of setting proper objectives for industrial symbiosis. Therefore, to develop a multi-objective model for sustainable design of industrial symbiosis is quite important.

With such circumstance, this paper aims to develop an innovative approach for sustainable design for an industrial symbiosis in a chemical complex. Innovative emergy based indicators are incorporated so as to better illustrate the objectives of sustainability. A mathematical model for sustainable design of integrated industrial system has been developed. Both economic performance and sustainability of the industrial symbiosis have been considered in the objectives, and Particle Swarm Algorithm is proposed to solve the multi-objective problem. To test its availability, a sustainable design for an industrial symbiosis in one chemical complex is presented. Our approach and results are critical to practitioners and policy makers in sustainable industrial planning.

The reminder of this paper is organized as: Section 2 illustrates our design idea with the implementation of industrial symbiosis strategy; Section 3 presents the detail of model, including emergy indices and mathematical model; Section 4 the depicts the case study in one chemical industrial symbiosis; finally, Section 5 draws the conclusion and policy implications.

2. Design for the sustainability with industrial symbiosis

In this study, industrial symbiosis (IS) is applied to design for the sustainability. The hypothesis of the application of industrial symbiosis is shown as Fig. 1: Industrial symbiosis could enhance the resource efficiency through increasing the exchange of material/energy flows in the industrial process and between industries (Chertow, 2000, 2007). What is more, compared with process synergies, the IS can also consider supply and demand chain so as to maximize energy, resource, environmental efficiency. It provides a way to optimize the material/energy flow network to achieve sustainability.

To support to design a more sustainable IS system, investigate its impacts and make optimization is important and practical (Zhang et al., 2008). Different pattern and scale of synergies and related physical and monetary flows would have positive or negative impacts on the sustainability of the symbiosis. Proper objective for sustainability and modeling approach to support design will be necessary to the optimal design.

3. Methodology

In this part, we firstly introduced the traditional emergy indices; then, developed the extended emergy indices for industrial systems; finally, proposed the developed model for sustainability design of industrial symbiosis.

3.1. Emergy indices

This part firstly introduced the traditional emergy indices, and then presented the extended emergy indices for industrial systems.

3.1.1. Traditional emergy indices

Emergy, spelled with an 'm', which represents the energy memory or the total energy embodied in any product or service, can measure both the work of nature and that of human in generating products and services (Giannetti et al., 2006).