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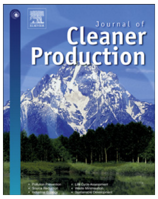

Fuzzy mixed integer non-linear programming model for the design of an algae-based eco-industrial park with prospective selection of support tenants under product price variability

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ABSTRACT

Eco-industrial parks provide a platform for the application of industrial symbiosis where the synergistic network of companies reuse portions of their by-products to reduce disposed waste, reduce environmental emissions, and improve plant efficiency. However, designing a complex network of material and energy exchanges between companies in an industrial park while satisfying multiple conflicting objectives require a systematic design methodology. In addition, strategic decision-making in an eco-industrial park involves the selection of prospective companies (i.e., support tenants), which complement the existing companies (i.e., anchor tenants). In this study, a fuzzy mixed-integer non-linear programming model is proposed to select prospective support tenants in an eco-industrial park while satisfying the product demand, minimizing the environmental footprint of the eco-industrial park, and also maximizing the annualized profit of each company in the eco-industrial park. A hypothetical but realistic case study involving an algae-based eco-industrial park is used to demonstrate the application of the model. The results demonstrate the selection of the appropriate support tenants for the algae-based eco-industrial park together with the optimal plant configuration. Sensitivity analysis is used to assess the performance of the algae-based eco-industrial park with respect to the changes in prices of the by-products. The developed model thus aid the planners of an eco-industrial park in assessing which among the prospective support tenants would best complements an existing anchor tenant. Furthermore, the model can also identify price negotiation points between tenants for some product streams which may show sensitivity on the plant capacity of each tenant.

1. Introduction

Anthropogenic climate change due to greenhouse gas (GHG) emissions is widely regarded as a serious environmental issue. In particular, carbon dioxide (CO_2) emissions from energy use and industrial activities account for 62% of the total (IEA, 2014). The current atmospheric CO_2 concentration is approximately 400 ppm (NOAA, 2015) and exceeds the safe limits of 350 ppm (Rockstrom et al., 2009). With the increasing awareness on environmental impact of the industry, clustering of industries into eco-industrial parks (EIPs) was adopted in the last portion of the 20th century (UNEP, 1996). EIPs are clusters of industrial plants seeking synergistic collaboration with one another leading to improved economic benefit and reduced environmental impact (Lowe et al., 1996). For EIP to work, the concept of industrial ecology (IE) is applied where companies re-use another company's by-products and excess energy. Benefits of EIPs include reducing virgin

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material resource input and waste disposal as well as increasing energy efficiency and the generation of additional high-value product streams (Gertler, 1995). Historically, many examples of industrial symbiosis (IS) emerged without the benefit of rigorous, systematic planning (Chertow, 2007). On the other hand, it has been noted in recent literature that there is significant potential for process integration (PI) methodology to be applied towards systematic planning of EIPs. PI methods were originally developed to facilitate the synthesis of heat exchanger networks (HENs) to increase the energy efficiency of process plants (Linnhoff et al., 1982). Over the past four decades, PI for heat integration and related applications gained mainstream acceptance, and has been integrated into many modern textbooks (e.g., Smith, 2005) and reference books (e.g., Klemeš et al., 2011). Other PI extensions were developed based on analogous problem structures. For example, mass integration (El-Halwagi and Manousiothakis, 1989) was proposed based on the analogy between heat and mass transfer. Besides, PI has also been applied in various areas, such as water integration (e.g., Wang and Smith, 1994), property integration (Shelley and El-Halwagi, 2000), carbon constraint planning (Tan and Foo, 2007), integrated biorefinery (Ng, 2010), resource conservation network (e.g., Foo, 2012), risk management (Tan et al., in press), etc. A recent review article gives an account of key PI developments, and in particular discusses the diversification of PI (Klemeš et al., 2013). Insight-based pinch analysis techniques have also co-evolved with mathematical programming, initially as competing schools of thought, but more recently as complementary strategies (Klemeš and Kravanja, 2013). A handbook has also been published which covers all major areas of PI theory and industrial applications (Klemeš, 2013). In particular, total sites (TS) methodology has been extensively documented to be an effective approach to designing heat integration in industrial clusters to achieve reductions in fuel use and combustion emissions (Dhole and Linnhoff, 1993). A recent description of the methodology is found in Perry (2013), while some successful industrial cases in Japan (Matsuda, 2013) and Thailand (Matsuda et al., 2014) are also documented in PI literature. Practical aspects of implementing TS considering various operational aspects, as well as the interactions of individual companies with each other and with regulatory authorities, are discussed extensively by Chew et al. (2013). Practical experiences of carbon emissions reduction from EIPs was reported by Ban et al. (2016) which aid the development of guidelines and policies to facilitate the reduction of carbon emissions among the EIP participants in South Korea.

A typical EIP consists of previously established *anchor tenants* that serve to attract other companies to join the EIP, to act as either supplier or customer of these anchor tenants. These new plants are known as *support tenants*, whose entry creates new opportunities for integration. In considering the candidates for support tenants, a planning committee may be formed to assess the compatibility of the candidate support tenants in the EIP, as proposed by Lowe (1997). One of the major assessment steps of the recruitment process is to assess the by-product trading between the anchor tenants and the prospective support tenants, and to evaluate the potential for integration. Process systems engineering (PSE) approaches were proposed in previous studies to support decision-making in the development of an efficient EIP. For example, a life cycle optimization approach was utilized by Castaño et al. (2015) for the optimal operation of a petrochemical industrial cluster. A linear programing model coupled with a cooperative game theory approach was used by Tan et al. (2016) in systematically allocating the costs and benefits of interplant integration in an EIP. A graphical approach via pinch technology using Total Site Profile and R-curve was proposed by Matsuda et al. (2014) in assessing the performance of heat integration in industrial parks. The total site profile was also used by Varbanov and Klemeš (2010) for realistic heat recovery targets in an EIP context. A non-linear programming (NLP) model was used by Lovelady and El-Halwagi (2009) to design water networks in EIPs. Fuzzy linear programming (FLP) was proposed by Aviso et al. (2010a) to model the self-interest of each plant in an EIP, while a subsequent work used bi-level optimization to represent the role of a regulatory authority (Aviso et al., 2010b). A fuzzy multi-objective optimization model was adapted in evaluating various scenarios for the optimal design of an integrated biorefinery (Tay et al., 2011) and rice mill complex (Lim et al., 2014). Ng et al. (2013a) also adapted fuzzy optimization approach to synthesize a sustainable integrated biorefinery with consideration of economic, inherent process safety, inherent health and environmental aspects. Recently, a generalized mixed-integer nonlinear programming model was developed by Kantor et al. (2015) for the optimal design of an EIP to lower costs and emissions. An extensive literature review of optimization methodology was reported by Boix et al. (2015) for the design of EIPs. Despite the methodologies presented in enhancing the EIP for cleaner production, the industry seeks ways in using energy efficiently while reducing its environmental footprint. An alternative to achieve this is through the use of biomass. Partnership across firms for biomass use has been proposed by Pehlken et al. (2016) and has been proven to enhance the sustainable production of bioenergy streams. With the increasing demand for liquid fuels which is expected to grow by 40% by 2035, the production of biofuels in an EIP framework presents a promising solution to current environmental concerns and growing demand in the transportation sector. A palm biomass-based EIP was proposed by Ng and Ng (2013) to produce biofuels with other bioenergy products and developed a mixed-integer linear programming (MILP) model for its optimal design assuming single proprietorship. Ng et al. (2013b) later extended the MILP model to fuzzy multi-objective optimization for multiple owner scenarios of the palm biomass-based EIP. A stochastic programming-robust optimization model has been developed by Shabani and Sowlati (2016) to design a forest biomass-based supply chain network considering uncertainties in biomass availability and quality. Among the biomass available for the production of biofuels, microalgae present a potentially sustainable alternative as it has a very high oil yield per hectare of land (Chisti, 2007). Fuels derived from microalgae are known as algal biofuels. A review study by Bahadar and Khan (2013) revealed 43 start-up companies working on commercializing algal biofuels from various countries. However, commercialization challenges have been encountered by most of these companies, especially due to considerations of economic viability, energy consumption, and environmental impact. A recent life-cycle assessment study on algal systems was published by Medeiros et al. (2015) suggested that it has slightly lower performance compared to the matured fossil-fuel energy with respect to carbon footprint and energy balance. To address such concerns, the application of IS concept has been proposed recently for algae-based firms such as the integration of algal systems with sewage treatment (Ledda et al., 2016) and carbon dioxide capture and utilization (Cuellar-Bermudez et al., 2015). At the heart of the EIP is the algae-based firm which acts as the anchor tenant and provides synergistic collaborative network between various industries on specific by-product streams. As IS provides a platform for various companies to reuse by-product streams in the EIP, it then leads to increased profit, increased process efficiency, reduced virgin resource inputs, and reduced waste disposal. A special case of an EIP is an algal bioenergy park (ABP), which utilizes microalgae biomass to produce various bioenergy products such as biofuels, biochemicals and bioenergy streams in the network of shared streams between companies in the industrial park. Various PSE techniques were previously applied for designing algae process networks. A

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