Resources, Conservation and Recycling 119 (2017) 89–96

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

An MILP model for optimizing water exchanges in eco-industrial parks considering water quality

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ARTICLE INFO

Article history:
Received 29 January 2016
Received in revised form 4 June 2016
Accepted 6 June 2016
Available online 18 August 2016

Keywords:
Industrial symbiosis
Industrial ecology
Eco-industrial parks
Goal programming
Multi-objective optimization

ABSTRACT

Unlike other resources that may come in multiple energy forms, there is no substitute for freshwater. Therefore, Eco-Industrial Parks (EIPs) have been designed to encourage interplant water exchange networks in order to minimize the consumption of freshwater as well as the generation of wastewater. This study proposes a model that simultaneously minimizes the economic and the environmental objective functions of an EIP through goal programming. The economic costs considered integrates the necessary piping and operating costs together with the freshwater, wastewater, and treatment costs, while the environmental impact considered the volume and the quality of the water used and released by the EIP. Results showed that the considering water volume and quality in minimizing the environmental impact gave better results than considering water volume only. Economic costs and environmental impacts were also found to be dependent on the priorities given to each goal, as well as the treatment quality of the processes.

1. Introduction

Approximately 70% of the planet is covered with water, but only 2.5% of the total global water resource is freshwater. Out of this 2.5%, only 0.4% is available and readily accessible to humans in the form of lakes and rivers. Unlike oil or other resources that have multiple energy forms, there is no suitable substitute for water (Shiklomanov, 1993).

The unprecedented increase of human activities throughout the past few decades has had a severe impact in the depletion of the earth's freshwater resources. If this were to continually increase, man's survival in this planet may be seriously jeopardized. Because of the growing environmental concerns, the need for the development and implementation of sustainable solutions has been called for. When defined formally, the term "sustainable development" is the developmental ability to meet the present generation's needs without comprising the future generations' ability of meeting their own needs (Gu et al., 2013). In order to establish sustainable development, the most recent trends are now geared towards limiting pollution at the source (Aviso et al., 2010). Such approaches promote cleaner production more efficiently than end-of-the-pipe approaches.

Approaches that have sparked significant research interest among researchers are the concepts of Circular Economy and Industrial Ecology. Circular Economy is done by addressing economic growth while considering the shortage of raw materials, energy, and the emergence of new business models that can fit Circular Economy (Murray et al., 2015). Through Circular Economy, procurers and suppliers can collaborate in order to achieve lower raw material utilization and waste generation, while still promoting the development of more sustainable business models (Witjes and Lozano, 2016). On the other hand, Industrial Ecology is devoted to global environmental preservation based on sustainable development in an industrial setting. The main goal of Industrial Ecology is to preserve the environment while increasing business success. The term Industrial Ecology was first coined by Frosch and Gallopoulos (1989) by using the analogy between natural systems and industrial systems. In natural ecosystems, the consumption of energy and materials are optimized through the interaction of different animals in food chains and food webs. Wastes are also minimized since these are consumed by decomposers in the ecosystem. In the same way, companies included in an Eco-Industrial Park (EIP) can be viewed as different organisms in a food chain engaging in exchanges of material and energy. More recently, Allenby (2006) has defined Industrial Ecology as "a systems-based multidisci-

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http://dx.doi.org/10.1016/j.resconrec.2016.06.005
0921-3449/

Nomenclature

Subscripts

i	Index for source plant i
j	Index for sink plant j
k	Index for treatment process k

Parameters

s_i	Available water flowrate in plant i (in tons/day)
d_j	Required water flowrate in plant j (in tons/day)
$cout_i$	Contaminant concentration of water exiting from plant i (in mg/L)
cin_j	Maximum contaminant concentration of water entering plant j (in mg)
$ctreat_k$	Contaminant concentration of water treated by process k (in mg/L)
$cfresh$	Contaminant concentration of freshwater (in mg/L)
pd_{ij}	Distance between plant i and plant j (in m)
sd_j	Distance between freshwater source and plant j (in m)
dd_i	Distance between disposal site and plant i (in m)
pc	Cost of pipes expressed as a per day cost (in $/m)
oc	Cost of operating water transfer in pipes (in $/ton)
tc_k	Cost of treatment using process k in ($/ton)
fc	Cost of using freshwater (in $/ton)
wc	Cost of disposing wastewater (in $/ton)
$xmin$	Minimum economic cost value for goal programming model
$xmax$	Maximum economic cost value for goal programming model
$ymin$	Minimum environmental impact for goal programming model
$ymax$	Maximum environmental impact for goal programming model
$cweight$	Weight given to economic goal deviation
$eweight$	Weight given to environmental goal deviation

Variables

p_{ij}	Binary variable (1 if plant i is connected to plant j)
q_j	Binary variable (1 if source is connected to plant j)
r_i	Binary variable (1 if plant i is connected to disposal site)
t_{ik}	Binary variable (1 if plant i uses treatment process k)
f_j	Freshwater flowrate entering plant j (in tons/day)
w_i	Wastewater flowrate generated from plant i (in tons/day)
a_{ij}	Treated water flowrate from plant i to plant j (in tons/day)
e_{ij}	Untreated water flowrate from plant i to plant j (in tons/day)
b_{ijk}	Linearization variable representing $A_{ij} \times T_{ik}$
u	Deviation from economic goal
v	Deviation from environmental goal

plinary discourse that seeks to understand the emergent behavior of complex integrated human/natural systems."

Under the Industrial Ecology framework, one of the more common concepts closely associated with building a sustainable industry is the concept of Industrial Symbiosis. There are numerous ways that Industrial Symbiosis is defined in literature. It is the consideration of material and energy exchanges between industrial plants such that waste streams from one plant become raw materials for another (Aviso, 2014). Gu et al. (2013) explains Industrial Symbiosis as the sharing of services, utility, and by-product resources among diverse industrial actors in order to add value, reduce costs, and improve the environment. Finally, Chertow (2000) defines Industrial Symbiosis engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products.

In most cases, industrial symbiosis involves the participation of independently operating companies which results in multiple conflicting objectives and incomplete information exchange. To date, the most widespread manifestations of Industrial Symbiosis are EIPs. An EIP can be defined as "an industrial system of planned material and energy exchanges that seeks to minimize waste, and build sustainable economic, ecological, and social relationships" (Alexander et al., 2000). This concept of Industrial Symbiosis and EIPs have been seen to be implemented in many countries around the world (Ehrenfield and Gertler, 1997; Chiu and Geng, 2004; Gibbs and Deutz, 2005; Park et al., 2008; Geng et al., 2010; Zhang et al., 2010).

Most of the EIP optimization studies focused on optimizing one of three main categories: (1) Water, (2) Energy and Heat, and (3) materials (Boix et al., 2015; Kastner et al., 2015). Among these three main categories, water exchange networks have been the most studied type of cooperation in literature. According to Yoo et al. (2007), water exchange EIP systems are generally optimized through two main approaches: (1) Pinch Technology and (2) Mathematical Programming. While pinch technology offers easy-to-understand solutions because of its graphical concepts, it is unable to perform two important functions: (1) design optimal water networks involving several contaminants, and (2) study large-scale problems that deal with multiobjective optimization (which is often the case in an EIP). There have been numerous studies that presented the water exchange EIP systems as mathematical programming problems.

The main objectives included in optimization models for water exchanges in EIPs may be subdivided into two: (1) Economic Objectives and (2) Environmental Objectives (Boix et al., 2015). Between the two indicators, the economic indicators in an EIP have been the most developed and studied among EIP optimization studies (Kurup, 2007). Majority of models developed in literature considered costs of purchasing, treating, and transporting water between plants (Nobel and Allen, 2000; Aviso et al., 2010; Boix et al., 2012). Other studies developed models which focused on minimizing the quantity of water consumed by the EIP which was then converted into financial savings (Nobel and Allen, 2000; Geng et al., 2007; Lovelady et al., 2007; Chew et al., 2008; Lovelady and El-Halwagi, 2009; Aviso et al., 2010; Boix et al., 2012; Aviso, 2014). In another study, Rubio-Castro et al. (2012) developed a model which considered the minimization of the capital and operating costs needed in constructing piping connections and treatment facilities. Economic cost indicators in an EIP may have been well developed, however, there has been no model that integrates all these economic indicators together.

The environmental indicators in an EIP may not be as well developed as the economic indicators, but there have been numerous studies that considered environmental indicators as the objective functions to their models. Majority of models developed in literature considered the minimization of the volume of freshwater consumed by the EIP (Yoo et al., 2007; Chew et al., 2008; Rubio-Castro et al., 2011; Boix et al., 2012). In an attempt to account for both the freshwater consumption and wastewater disposal, Aviso et al. (2011) developed a model that minimized an EIP's water footprint, which was a concept introduced by Hoekstra et al. (2009). While the environmental impact in terms of the volume of the freshwater consumed and the wastewater disposed have already been well accounted for, the volume of water alone is not enough to measure the environmental impact due to water activ-