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# Design of robust water exchange networks for eco-industrial symbiosis

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ABSTRACT

The field of industrial ecology promotes the establishment of resource exchange networks in eco-industrial parks (EIPs) as an approach toward resource conservation. Previous studies have shown that full blown resource integration can be encouraged through the exchange of common utilities such as energy and water. Different approaches such as mathematical programming, pinch analysis and game theory have been used to identify the optimal network designs, which can simultaneously reduce the utilization of freshwater resources and the generation of wastewater streams. Since water exchange in an EIP involves multiple independently operating plants, information exchange between the participants is not completely transparent and multiple future scenarios are expected to happen as the fate and plans of other participants are not completely divulged. These future scenarios may bring about changes in the capacity or characteristic of industrial processes and may also involve the entry of additional companies and the closure of previously operating ones. Such aspects have not been fully addressed in previous studies. A robust optimization model is thus developed in this work to determine the optimal network design which can effectively operate in anticipation of multiple probable scenarios. Case studies are solved to demonstrate the capability of the model.



*Keywords:* Water conservation; Industrial ecology; Industrial symbiosis; Robust optimization

## 1. Introduction

Sustainability has been a major concern in the past decade as man's activities continue to threaten his survival in the planet. In fact, Rockstrom et al. (2009) identified some key environmental indicators together with proposed performance limits which are necessary for human sustainability. Among these indicators are greenhouse gas emissions and global freshwater consumption. The proposed limit for greenhouse gas emissions has already been exceeded while global freshwater consumption is rapidly approaching its limit. Furthermore, with the continuing increase in population and the onset of global warming, the problems on freshwater availability and accessibility are expected to worsen. It is thus important to develop strategies for efficiently allocating and utilizing freshwater resources. Industrial ecology (IE) through the concept of industrial symbiosis, presents a framework for minimizing the consumption of resources and the generation of waste based on imitation of cyclic flows in nature (Frosch and Gallopoulos, 1989). Industrial symbiosis (IS) refers to the material and energy exchange between industrial plants such that waste streams from one plant become raw materials for another. These exchanges are encouraged by geographical proximity (Ehrenfeld and Chertow, 2002), which occurs by co-locating firms within the same eco-industrial park (EIP) (Nemerow, 1995; Heeres et al., 2004; Jacobsen, 2006; Park et al., 2008), and through the exchange of common utilities such as water and energy (Chertow, 2007).

Many methodologies and approaches have been developed to identify the design of optimal exchange networks in application to processes within an industrial plant and between plants in an industrial park. Pinch analysis, for example, has been used for identifying the minimum freshwater targets in water networks (Wang and Smith, 1994a; Spriggs et al., 2004; Foo, 2009) including "inter-plant" networks found in EIP's (Foo, 2008) and for designing water networks which integrate effluent water treatment facilities (Wang and Smith, 1994b). Property-based integration (Lovelady et al., 2009; Ng et al.,

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## Nomenclature

*Sets*

| | |
|---|---|
| $I$ | $\{i/i$ is a water source$\}$, $i = 1, 2, 3, \ldots, N_{IK}$ |
| $J$ | $\{j/j$ is a water sink$\}$, $j = 1, 2, 3, \ldots, N_{JK}$ |
| $K$ | $\{k/k$ is a scenario$\}$, $k = 1, 2, 3, \ldots, N_K$ |
| $M$ | $\{m/m$ is a quality parameter$\}$, $m = 1, 2, 3, \ldots, N_M$ |

*Indices*

| | |
|---|---|
| $i$ | index for water source |
| $j$ | index for water sink |
| $k$ | index for scenario |
| $m$ | index for water quality parameter |

*Parameters*

| | |
|---|---|
| $N_{IK}$ | number of water sources in scenario $k$ |
| $N_{JK}$ | number of water sinks in scenario $k$ |
| $N_K$ | number of scenarios considered |
| $N_M$ | number of water quality parameters considered |

*Variables*

| | |
|---|---|
| $F_{jk}$ | freshwater utilized by water sink $j$ in scenario $k$ |
| $r_{ijk}$ | flow rate of recycle stream from water source $i$ to water sink $j$ in scenario $k$ |
| $w_{ik}$ | wastewater generated from water source $i$ in scenario $k$ |
| $x_{ij}$ | binary variable indicating activation of link between source $i$ and sink $j$ |
| $y_{ijk}$ | binary variable which indicates activation of a recycle stream between source $i$ and sink $j$ during scenario $k$ |

*Constants*

| | |
|---|---|
| $C_{ik}$ | impurity concentration in water source $i$ in scenario $k$ |
| $C_{ikm}$ | quality measurement of parameter $m$ in water source $i$ in scenario $k$ |
| $C_{jk}$ | quality limit in water sink $j$ in scenario $k$ |
| $C_{jkm}$ | quality measurement of parameter $m$ in water sink $j$ in scenario $k$ |
| $C_F$ | impurity concentration in the available freshwater |
| $C_{Fm}$ | quality measurement of parameter $m$ in available freshwater |
| $D_{jk}$ | limiting flow rate of water sink $j$ in scenario $k$ |
| $P_k$ | probability of occurrence of scenario $k$ |
| $R^U_{ij}$ | upper limit of recycle flowrate from source $i$ to sink $j$ |
| $R^L_{ij}$ | lower limit of recycle flowrate from source $i$ to sink $j$ |
| $S_{ik}$ | limiting flow rate of water source $i$ in scenario $k$ |
| $z$ | limit on model relaxation |

2009) has been used for systems where the design specifications of the network were dependent on the functionality or property of the material being exchanged. Mathematical programming has also been utilized in identifying the optimal network design for single period (Lovelady et al., 2009; Aviso et al., 2010a, 2010b) and multi-period water exchange (Liao et al., 2007).

IS involves the participation of several independently operating plants which results in uncertain process characteristics, multiple, and often times conflicting objectives, incomplete information exchange and the realization of multiple probable scenarios. The latter arises from independent decisions made by separate companies (e.g., expansion or closure of plants). Liao et al. (2007) proposed a model for flexible multiperiod water exchange taking into consideration changes brought about by uncertainties in process characteristics due to seasonality. However, their work fails to account for the multiple objectives that arise from the individual interests of the participating plants, such that their willingness to join in the exchange network depends on how the collaboration will benefit them individually (Jackson and Clift, 1998; Aviso et al., 2010a, 2010b, 2011). It is necessary to model the system in this way, because as Jackson and Clift (1998) puts it "*every individual actor is essentially a self-interested maximizer of individual profit*." The individual goals may be in the form of reduced operating costs, additional income or improved environmental performance and company image. To address the independent objectives of the plants, Kim and Lee (2007) utilized the concept of benefit sharing among the participants in order to identify the Pareto optimal network. The concept of game theory (Lou et al., 2004; Chew et al., 2009, 2011) has also been used to identify the optimal network using an assessment of the economic and environmental benefits of identified IS strategies. Fuzzy optimization has been used to simultaneously satisfy the goals of multiple stakeholders (Aviso et al., 2010a, 2010b, 2011; Tan et al., 2011).

Information is not completely shared between the participants in an EIP due to confidentiality issues (Aviso et al., 2011) and thus it is unrealistic to model exchange networks as though information exchange between the participants and the EIP developer is completely transparent as depicted in Liao et al. (2007). Industrial plants must thus be modeled as black boxes, such that detailed information about its processes are not readily divulged, and only the input and output stream characteristics are available for common use (Keckler and Allen, 1999; Nobel and Allen, 2000; Singh and Lou, 2006; Aviso et al., 2010a, 2010b, 2011; Tan et al., 2011). Modeling industrial plants using the black box approach has been successfully utilized in designing exchange networks in consideration of regeneration units in the EIP (Keckler and Allen, 1999; Singh and Lou, 2006), topological constraints (Nobel and Allen, 2000) and multi-objective optimization (Aviso et al., 2010a, 2010b, 2011; Tan et al., 2011). Finally, since the plants are operating independently of each other, this leads to the possibility of multiple future scenarios as the fate of other participating plants are not made known completely to partners. Future scenarios may indicate an increase or decrease in the number of participating plants, and may include changes in the networks' process characteristics. This condition will affect the reliability and continuity of exchange networks and becomes a critical decision-making factor for plants who intend to be involved in it. It is thus important that the design of the network will work regardless of which future scenario is realized. Though this problem may seem at first to be similar to the multi-period problem addressed by Liao et al. (2007), flexible water networks are different from robust networks. Flexibility involves deterministic variations resulting from seasonal or daily cycles. Dealing with different future scenarios means that only one of the scenarios will occur, and hence planning the network must consider this risk. The risk is addressed by