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Water integration in eco-industrial parks using a multi-leader-follower approach

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ABSTRACT

The design and optimization of industrial water networks in eco-industrial parks are studied by formulating and solving multi-leader-follower game problems. The methodology is explained by demonstrating its advantages against multi-objective optimization approaches. Several formulations and solution methods for MLFG are discussed in detail. The approach is validated on a case study of water integration in EIP without and with regeneration units. In the latter, multi-leader-single-follower and single-leader-multi-follower games are studied. Each enterprise's objective is to minimize the total annualized cost, while the EIP authority objective is to minimize the consumption of freshwater within the ecopark. The MLFG is transformed into a MOPEC and solved using GAMS® as an NLP. Obtained results are compared against the MOO approach and between different MLFG formulations. The methodology proposed is proved to be very reliable in multi-criteria scenarios compared to MOO approaches, providing numerical Nash equilibrium solutions and specifically in EIP design and optimization.

1. Introduction

During the last few decades, industrialization has contributed to rapid depletion of natural resources such as water and natural gas. Consequently, there is a real need for industries to ensure minimum natural resources consumption, while maintaining good production levels. In particular, industrial development is often linked to the use of high volumes of freshwater (Boix et al., 2010, 2011). In order to work towards global environmental preservation while increasing business success, the concept of industrial ecology has emerged (Boix et al., 2015). This concept, which is directly linked to sustainable development, aims at engaging separate industries, geographically closed enough, in a collective approach so that exchanges of raw matter, by-products, energy and utilities (Chertow, 2000) are maximized. Indeed, the most widespread manifestations of these kinds of industrial symbiosis are eco-industrial parks (EIP). A definition widely accepted of EIP is "an industrial system of planned materials and energy exchanges that seeks to minimize energy and raw materials use, minimize waste, and build sustainable economic, ecological and social relationships" (Boix et al., 2015; Montastruc et al., 2013; Alexander et al., 2000). As it can be highlighted, a basic condition for an EIP to be economically viable is to demonstrate that benefits of each industry involved in it by working collectively is higher than working as a stand-alone facility.

Boix et al. (2015) highlighted the lack of studies dealing with optimization in order to design optimal configuration of an EIP. However, it is important to develop methodologies able to design an EIP where each industry has an effective gain compared to the case where they operate individually, by also taking into account environmental concerns. Among EIP design studies, water-using network is the most common type of cooperation modelled in literature (Boix et al., 2015). In this kind of studies, the case is often solved as a water-allocation problem through a superstructure-based model where water has to be distributed, treated and discharged in an optimal way between the process units of each enterprise/company involved in the EIP.

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Nomenclature

Latin symbols

nl	number of leaders
L	index set of leaders
x_i	decision variables of leader i
x_{-i}	decision variables of other leaders
w	decision variables of the follower
f	objective function of leader/leaders
g	inequality constraints of leader/leaders
z	objective function of the follower
m	inequality constraints of the follower
np	number of processes per enterprise
P	index set of processes
nep	number of enterprises
EP	index set of enterprises
nr	number of regeneration units
R	index set of regeneration units
M	contaminant load
Cmax^{in}, Cmax^{out}	maximum contaminant concentration allowed in inlet/outlet of processes
C^{out}	outlet concentration of contaminant in regeneration units
$Fpart$	water flow between different processes
Fw	freshwater inlet flow to processes
$Fproreg$	water flow from processes to regeneration units
$Fregpro$	water flow from regeneration units to processes
$Fdis$	water processes to the discharge
$\min f$	minimum flowrate allowed
AWH	annual EIP operating hours

Greek symbols

ν	Lagrange multipliers relative to m
μ	Lagrange multipliers relative to g
ξ	Lagrange multipliers relative to s
$\pi, \nu, \eta, \tau, \varphi$	slacks to inequalities of Prob. 7
α	purchase price of freshwater
β	polluted water discharge cost
δ	polluted water pumping cost
γ	regenerated water cost
ψ	power associated to γ

Modelling EIPs based on water-exchange networks is somewhat a complex problem, since, depending on the number of enterprises and processes, a model with thousands of variables, constraints and disjunctions has to be solved. On the other hand, it is obvious that the design of EIPs through mono-objective optimization it is not trivial, since to choice a single objective function is almost impossible due to the size of the manifold of the possible objective functions. As aforementioned, the main aim of industrial symbiosis is to minimize pollution and resources utilization while maximizing each company's gain. For instance, by using a mono-objective optimization approach and minimizing the EIP total annualized cost do not necessarily agree with environmental objectives. Indeed, it is due to the latter that these kind of problems are better tackled with a multiobjective optimization (MOO) approach (Boix et al., 2015; Montastruc et al., 2013; Boix and Montastruc, 2011).

Recently, Boix et al. (2012) developed a multi-objective optimization strategy based on the ε-constraint method applied to the case of a water network in an EIP under several scenarios. The interest of dealing with multiobjective optimization is to build a Pareto front in which several optimal solutions are available; then, an a posteriori tool of multi-criteria decision making is further applied. In the aforementioned work, three antagonist objective functions were taken into account: freshwater consumption, number of connections and total regenerated water-flowrate. On the other hand, a posterior work of Montastruc et al. (2013) has explored the flexibility of the designed EIPs by changing parameters related to processes. The authors have also analyzed different indicators to test the EIP profitability. Then, a later extension of this work was conducted by Ramos et al. (2015): they employed a multiobjective optimization approach by minimizing each enterprise capital cost by using goal programming (GP). This approach is based on a recent study where GP has been proven to be a very reliable method to design industrial water networks following multiple antagonist objective functions (Ramos et al., 2014).

Indeed, previous studies have widely explored Pareto front generation approaches but some numerical problems were encountered especially when a very large number of binary variables are involved. In most cases, choosing the bounds for generating methods (e.g. ε-constraint method) is a non-trivial task, and the choice of these bounds is important because if they are not well chosen the solver may not succeed into obtaining a feasible solution. Furthermore, if a solution is found it remains a very long and tedious computational task. That is why a GP approach shows more affinity with EIP design. However, Ramos et al. (2015) demonstrated that in different scenarios and by tuning different optimization parameters (e.g. weight factors associated with the objective functions) one company is favoured compared to the others. Although optimal solutions are intermediate and satisfying in terms of individual costs, it is of great interest to