Water Exchanges in Eco-industrial Parks through Multiobjective Optimization and Game Theory

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Abstract

The current environmental context makes urgent the development of robust methodologies able to design innovative industries. Industrial ecology, and most particularly the concept of eco-industrial parks, aims at proposing at several companies to gather in a same geographical site to share several fluxes (water, energy, utilities…) in order to decrease environmental impacts of their industrial activities. A recent literature analysis has shown the emergence of new works devoted to the application of optimization methodologies to design greener and more efficient eco-industrial parks. In this work, the method of goal programming is applied for the first time to design optimal exchanges of water in an academic case of park. Goal programming is employed to deal with several conflicting objectives: the cost for each company included in the park. This method is proven to be reliable in this context because it proposes to obtain one solution instead of a set of optimal solutions that takes directly into account the preferences of the decision maker. Although the solution obtained in this study is quite interesting and is a good compromise, the main perspective of this work is to be extended by being coupled with a game theory approach so that an more equilibrate solution can be obtained.

Keywords: Eco-industrial Park, Water Network, Multiobjective Optimization, Goal Programming, Game theory

1. Introduction

Over the past ten years, most industrialized countries have invested heavily in environmental research thanks to a general awareness about natural resources depletion. Especially in the case of fresh water, there is a real need to reduce its consumption by redefining and designing industrial networks with a low environmental impact. In response to these environmental problems, the concept of industrial ecology is born. Frosch and Gallapoulos (1989) initiated the scientific community to look very closely at the gathering of industries with a common goal of sustainable development. During the last twenty years, many terms and concepts have emerged in the broad field of industrial ecology. Eco-industrial parks (EIP) are a particular manifestation of industrial ecology and a definition commonly admitted was given by Lowe (1997) as: "A community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resource issues including energy, water, and materials. By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realize if it optimized its individual performance only." Since these preliminary studies, a lot of concrete examples have emerged through the world including the most famous example of the EIP of Kalundborg in Denmark. Other successful examples even more numerous are built all over the world. Most of them were built in industrialized countries of North America, Europe, or Australia but more recently it is in developing countries that many parks are born (such as China, Brazil and Korea for example).

The approach adopted in this work consists in designing optimal EIP networks (carrying water or energy) before its manufacturing. Optimization methods are then implemented in this context so that optimal networks for EIP can be designed. For a most extended bibliographic review to optimization methods applied to the design of eco industrial parks, the reader can refer to Boix et al. (2015). In this study the increasing interest for this research field during the past few years is highlighted. Figure 1 illustrates the number of studies published and cited during the fifteen past years with "optimization" and "eco industrial parks" keywords in the ISI Web of Science database.

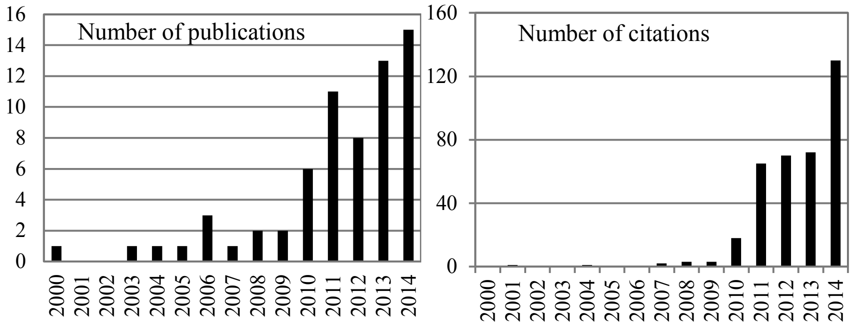

Figure 1. Number of articles referenced in the last 15 years with the keywords: "optimization" and "eco industrial park" (from Boix et al., 2015).

This paper aims at proposing a new methodology to deal with multiobjective optimization of eco-industrial parks. The first part is devoted to the presentation of objective functions, the superstructure and the methodology adopted. Then, a case study illustrates some results applied to the optimal design of a water network in an EIP.

2. Methodology

2.1. Objective functions

The analysis of previous studies has proven the existence of several types of objective functions. The most common is related to the economic cost, one can cite for example: profit of each industry, profit for the local community, transport and logistics or the net present value. However, although the economic cost remains very important for the feasibility of the project, in the context of industrial ecology, many other objectives can also be important. Objective functions in this type of problem are antagonist like for example, the economic cost versus environmental objective. Environmental objectives can be formulated through different ways: minimizing natural resources consumption (water), minimizing greenhouse gases emissions, minimizing water footprint or minimizing health and safety impacts. Another important aspect relative to sustainability development is the social and/or societal criterion. Although most of the time more qualitative than quantitative, social objectives are quite important and include the quality of life of workers, an index of satisfaction for the different participants

(Aviso et al., 2013) or the number of jobs created for example. Finally, topological objectives can also be taken into account as in the work of Boix et al. (2012) so that the network remains feasible.

2.2. Modeling eco-industrial parks

Modeling eco-industrial parks is somewhat a complex problem because of its size (thousands of variables, constraints and hundreds of binary variables) and the number of objectives to take into account. In order to model the network of an EIP, the concept of superstructure is used, it represents all the possible alternatives to connect each process of the network, this systemic approach allows to represent process design. Figure 2 shows the superstructure of an EIP including 3 industries and each industry is composed of process and regeneration units.

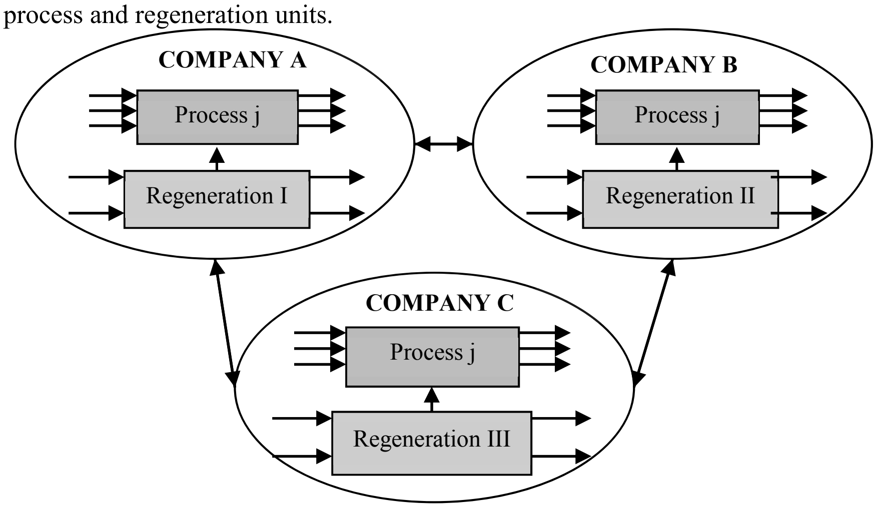

Figure 2.General superstructure of an EIP including 3 industries

After modeling the superstructure, the next step is to model the network with mass balances so that mathematical programming methods can be applied. A "black box" approach is adopted so that each parameter of the different processes are known, for more precision about the modeling stage, the reader can refer to Boix et al. (2012).

2.3. Multi-objective optimization approaches

Resolution methodologies for multiobjective optimization are generally classified depending on the number of generated solutions and on the importance of the decision maker during the resolution. These approaches can be classified into two categories:

- **Generative approaches**: these methods are characterized by the generation of different solutions and the decision maker has to choose one solution among them. These "a posteriori" methods include scalar approaches like weighting method or the epsilon-constraint strategy coupled with mathematical programming and stochastic methods like genetic algorithm. With these methods, a Pareto front is built to propose a set of non-dominated solutions to the decision maker.
- **Preference-based methods**: in this case, decision maker preferences are included along with the resolution and the optimization. These "a priori" approaches like for example, goal programming or interactive methods like NIMBUS directly include the decision maker preferences during the resolution so that one solution is

finally obtained. In this work, we propose to adopt the goal programming approach to solve the case of water allocation in eco industrial parks.

2.4. Characteristics of eco-industrial parks

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 a gain compared to the case where it is individual. Furthermore, each company included in a park has its own objective (for example to minimize its costs) and all of these objectives are always antagonists. In this work, a multiobjective optimization approach is adopted in order to take into account each objective function associated to each company of the EIP. This approach has already been applied to the design of industrial water networks but never with the optimal design of the water network in an EIP which is a different problem.

The optimization of eco-industrial parks includes several bottlenecks: one of the main characteristic of this problem is that the structure (represented by the existence or not of connections between processes and numerically modeled by binary variables) is dominating the solution. The resulting model is large and of MILP (mixed integer linear programming) type which constitute a great challenge and it is relatively new to solve this problem with the help of preference-based approaches. Indeed, previous studies have widely explored generation based approaches but some numerical problems were encountered especially when problems involve many binary variables. In most of the cases, the solver does not succeed to return a feasible solution and when it succeeds to build the Pareto front, it remains a very long and tedious task.

In this work, a goal programming (GP) approach is adopted to obtain one solution that already includes the preferences of the decision maker. This approach is based on a recent study (Ramos et al., 2014) where it has been proven that GP can be a very reliable method to design industrial water networks following multiple antagonist objective functions.

Based on an academic example, this paper explores 3 different scenarios of an EIP in order to point out the difficulties encountered with multiobjective optimization of EIP's.

3. Multiobjective optimization through goal programming

3.1. Presentation of the case study

In this study, an EIP including 3 companies is designed, this academic example has been widely explored in the literature (Olesen and Polley, 1996; Boix et al., 2012). For this reason, it remains a good example to test and to validate a new methodology because solutions are well-known. Each company is composed of 5 process units and the parameters are the same as those defined in Boix et al. (2012).

Three different scenarios are explored (Figure 3), where the position of the regeneration unit differs, so that all the configurations are scanned :

- ***Scenario 1***: the three companies exchange water and each company owns its regeneration unit, chosen among three available types (depending on the outlet concentration);
- ***Scenario 2***: the three companies exchange water and share one regeneration unit;
- ***Scenario 3***: a mixed scenario where each company owns its regeneration unit and an additional unit is shared by the three companies.

It is important to notice that for each above mentioned scenario, three objective functions are minimized: the total cost of each company involved in the EIP.

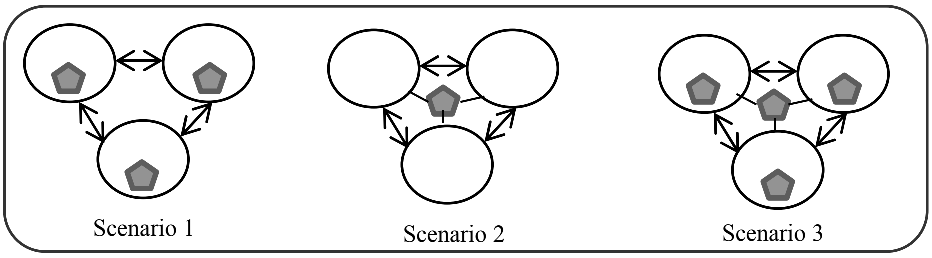

Figure 3. Different configurations of the EIP

In order to show that these objectives are antagonists, table 1 represents the pay-off table that include the values of two objectives while the third is minimized for scenario 2.

Table 1. Pay-off table for scenario 1 (the value in bold is minimized for each line)

Pay-off table	*Cost for ind. A*	*Cost for ind. B*	*Cost for ind.C*
Cost A	**1.143**	4.334	16.985
Cost B	9.349	**1.138**	8.223
Cost C	10.353	9.942	**1.154**

This cost takes into account: fresh water consumption, regenerated water flow rate, cost of external and internal connections between processes and the capital cost of regeneration units.

3.2. Results with the goal programming approach

Results obtained with the goal programming approach are summed up in table 3. Mono-objective optimizations were carried out in a first step in order to obtain minimal (utopia) and maximal (nadir) values of each objective function, that is to say the minimal cost of each company when it is included in the EIP. Then, the goal programming methodology allows to have one solution for each scenario. It is important to note that the optimal solution found by GP leads to an intermediate solutions where all the companies are closed to their personal objective.

Table 2. Results of the multiobjective optimization of the EIP through goal programming, cost are expressed in M$.

	Scenario 1			**Scenario 2**			**Scenario 3**		
	Min	Max	**Solution GP**	Min	Max	**Solution GP**	Min	Max	**Solution GP**
Cost for company A	1.51	6.96	**<u>1.85</u>**	1.14	13.78	**1.98**	1.14	16.09	**2.85**
Cost for company B	1.14	7.05	**1.51**	1.14	6.82	**<u>1.32</u>**	1.14	4.35	**<u>1.34</u>**
Cost for company C	2.81	14.13	**3.52**	1.15	15.36	**2.98**	1.15	12.42	**1.96**

The main interest of this study is to note that for each scenario, one company is favored compared to others. In scenario 1, company A is the closest from its objective whereas in scenarios 2 and 3, it is the company C. Goal programming has been proven to be an efficient approach to design water exchanges in EIP through multiobjective optimization. Furthermore, it proposes a unique solution that satisfies a goal in very low computational times. Although the optimal solutions are intermediate and satisfying in terms of individual costs, it is of great interest to obtain more balanced solutions so that each company is satisfied at the same time.

3.3. A game theory perspective

Game theory could be a promising approach, particularly adapted to the case of the design of exchanges in an EIP. Several methods can be adopted like a non cooperative approach to preserve confidentiality of companies (Figure 4). Furthermore, the main barrier to integrate an EIP for industry is the lack of confidentiality and this approach could be very promising to overcome this problem. This approach could be useful to overcome the difficulties linked to information exchanges between companies in an IEP. However, it is important to deal with an authority that attends to minimize environmental impacts of the EIP. The existence of an optimal solution satisfying Nash equilibrium could insure that none of each company is prejudiced compared to others.

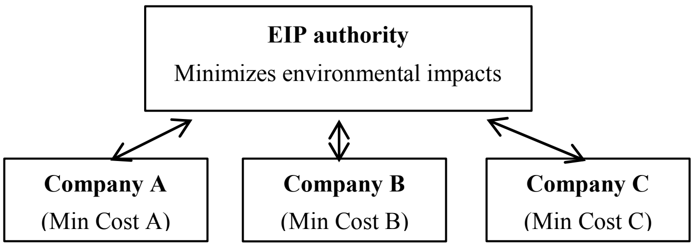

Figure 4. Example of a non cooperative approach to model an EIP through game theory.

4. Conclusions

In this study, water exchanges in an EIP have been optimized by minimizing three objective functions with a goal programming approach. Goal programming is a reliable method of multiobjective optimization and it had been proven to be efficient to find optimal solutions to complex problems. This study dealt with a well-known example to prove the efficiency of the methodology and to make a preliminary study in order to apply further a game theory approach to this work. The development of this method could be coupled with a game theory approach in order to obtain more equilibrate results where no company is favoured to another following the concept of Nash equilibrium.

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