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Laura Garcia de Dios, Marianne Boix, Sabine Simeoni-Sauvage, Iréa Touche, Roxelane Cakir, et al.. Multiobjective optimization of eco-industrial parks: evaluation of environmental impacts at the watershed scale. *Computer Aided Chemical Engineering*, 2018, 43, pp.67-72. 10.1016/B978-0-444-64235-6.50014-0 . hal-02135637

HAL Id: hal-02135637

<https://hal.science/hal-02135637>

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To cite this version:

de Dios, Laura Garcia and Boix, Marianne and Simeoni-Sauvage, Sabine and Touche, Iréa and Cakir, Roxelane and Montastruc, Ludovic and Sánchez-Pérez, José Miguel Multiobjective optimization of eco-industrial parks: evaluation of environmental impacts at the watershed scale. (2018) *Computer Aided Chemical Engineering*, 43. 67-72. ISSN 1570-7946

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Multiobjective optimization of eco-industrial parks: evaluation of environmental impacts at the watershed scale

Laura Garcia de Dios^a, Marianne Boix^a, Sabine Sauvage^b, Iréa Touche^a,
Roxelane Cakir^b, Ludovic Montastruc^a, Jose Miguel Sanchez Perez^b

^a*Laboratoire de Génie Chimique (LGC), UMR 5503 INPT-CNRS-UPS, 4, Allée Emile Monso, 31432 Toulouse, France*

^b*Laboratoire d'Ecologie Fonctionnelle (ECOLAB), UMR 5245 CNRS-UPS-INPT, Avenue de l'Agrobiopole, 31326 Castanet-Tolosan, France*

Abstract

Water, as everybody knows, is a limited and fragile resource. In fact, water faces several challenges in the future due to the increase of population, pollution, climate change, etc. To overcome these problems, some concepts linked to sustainable development such as “Industrial Ecology” have emerged. The concept of industrial ecology is defined as a group of companies, close in proximity to each other, who cooperate with the objective of sharing resources such as energy, water or services in order to act in a more efficient way and more respectfully to the environment. However, environmental impacts of such organizations are still difficult to identify and the impacts on the local environment could be very different from a larger surrounding ecosystem such as a watershed. The aim of this work consists in defining the optimal configuration of EIP in the watershed so that impacts of industrial activities are minimized considering a large-scale system. This study develops a multiobjective optimization based approach by combining two models. The first one consists of the optimisation of the water networks of clusters of companies to make them work as eco-industrial parks where a multi-objective optimisation approach is used. Secondly, the impact of this ecological strategy/policy is studied at a bigger scale: the Garonne watershed, in France modelled through a Material Flow Analysis (MFA). This model helps to track and measure the quality of the water, before and after the implementation of the eco industrial parks. In each scenario studied, there is a significant reduction of the pollutant concentration, proving the benefits of the implementation of an industrial ecology policy at a larger scale. Depending on which industrial area is transformed into an EIP, one can observe a diminution of the pollutant concentration up to 70% at the estuary.

Keywords: eco-industrial parks, multi-objective optimization, watershed scale, Material Flow Analysis

1. Introduction

Water is a fragile, precious and limited resource and is not only important for domestic or sanitary purposes, but every human economic activity relies on the existence of this element. In addition, leaving the human scope, every marine and terrestrial ecosystem depends on water somehow. This fact underlines the huge importance of this resource. Nevertheless, many recent reports have demonstrated that water is in danger. Indeed,

there is a clear evidence that in many rivers and aquifers there has been a reduction in its water quantity and quality. Water scarcity is a problem in many countries and many ecosystems have been modified until a point of no return. One of the most prominent problem is the pollution caused by agriculture and industry. This situation can cause significant damages, not only to ecosystems, but also to humans.

In conclusion, most of the problems evoked have a human origin and as a result, governments and society in general must act to reverse this situation. Efficiency in water use must be increased, technology must be developed and in this situation, research has an important role, because there are still many questions to answer and strategies to establish.

All this concern about resources in general, not only water, led to the birth of a great deal of new concepts such as sustainable development or industrial ecology. Industrial ecology consists of understanding human industrial activities as a natural ecosystem (Frosh and Gallopoulos, 1989). Indeed, a natural ecosystem represents equilibrium, sustainability and the use of every resource in the most efficient way as possible, reducing consumption and waste. One of the most important ideas in implementing Industrial Ecology is to establish eco-industrial parks. An eco-industrial park can be understood as a group of facilities in the same geographic region that try to optimise the use of energy, water and raw material flows, looking for economic benefits for all of them and for a better environmental performance (Lowe, 1997). Nevertheless, among all the eco-industrial parks that have been built, most of them are working in sub-optimal conditions because they have been built somehow, spontaneously. In other words, gradually some improvements were introduced, but a complete industrial park reconfiguration was never established.

The objective of this research is to introduce the conception of robust mathematical methods to design eco-industrial parks while taking into account the effects of such a policy at a bigger scale: the watershed scale. In order to convince the industries owners to be a part of these changes and to obtain real profits from them through a multiobjective optimization.

2. Objectives and methodology

During this research, several EIPs are going to be established within a region, from existing facilities or existing industrial areas. The reconfiguration of these facilities into eco-industrial parks is going to be limited to their water networks. The idea is to investigate deeply the impact of this politic at a bigger scale, the scale of the whole watershed. The objectives of this work are summarized below:

- To model a watershed. A Material Flow Analysis (MFA) to track and measure the quality of the river water is developed based on Lopez-Diaz et al. (2015).
- To develop a multi-objective optimization model for the water networks reconfiguration.
- To study the impacts of these changes on the watershed.
- To look for data to apply, specifically, this model to the Adour-Garonne watershed in France.

According to Figure 1, the two models interact with firstly the run of the MFA model to obtain the parameters of the watershed without the eco-industrial park's effects. Then, in the optimization model (MILP), the data related to water network of the industries are changed to make the industries work as eco-industrial parks. Finally, the results of the EIPs reconfiguration are loaded again into the MFA model to obtain the effects of these

modifications in the watershed, following the methodology developed by Lopez-Diaz et al. (2015).

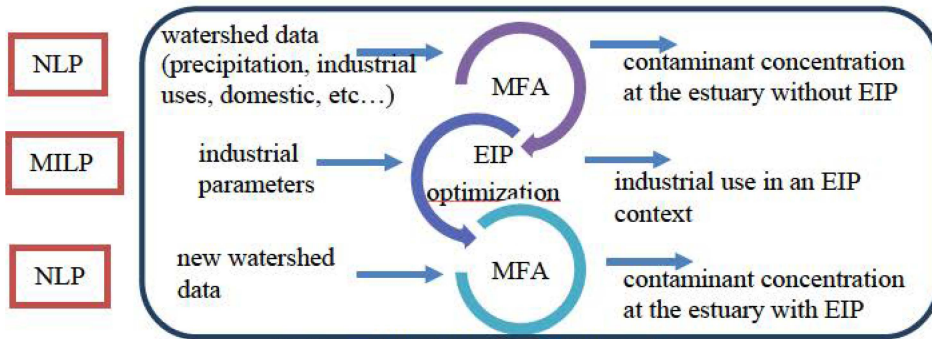


Figure 1. Methodology used in this study

3. Material Flow Analysis

The river flow along the watershed is modeled through a Material Flow Analysis (MFA), so its quality can be studied before and after the reconfigurations of the eco-industrial parks. To start with, the river is divided into several parts (Figure 2). The main parts are going to be called reaches and the secondary sections will be the tributaries. In general, this model is going to consist of some mass balances per reach and tributary, this allows to solve several consecutive small problems rather than a big non-linear one, more difficult to solve. This problem is formulated as a Non-Linear Problem (NLP) that has been solved within GAMS environment with DICOPT solver. Its most important variable is the pollutant concentration at the final disposal. With the changes on this variable before and after the establishment of the eco-industrial park their effects on the environment will be evaluated.



Figure 2: Decomposition of the river basin in reaches and tributaries (from Lopez-Diaz, 2015)

4. Multi-objective optimization of eco-industrial parks

As it has been showed in the previous figure, within a single watershed there can be several industrial parks or clusters of companies. Moreover, these industrial complexes are constituted by individual plants modelled as a group of process sources (i) and process sinks (j) to be reconfigured as EIP. Besides, a regeneration to clean the water

that has been used is added. This unit can be called an interception unit as well. The interception unit consists of several interceptors (int).

The superstructure defines the whole set of available solutions in a network so that all the possible links between units can be seen. For instance, the water used by a process unit leaves the sources to be used again in a process sink if some conditions, in relation to quality, are achieved. This water can also be sent to the regeneration unit. Furthermore, the flow leaving the sources can be sent directly to the environment without any previous treatment if the concentration constraints are respected. The process sinks can receive water from the sources, the interception unit or from fresh water sources directly. Finally, the interception unit is constituted by several interceptors, as it has been mentioned before. Each interceptor receives used water from process sources, it cleans the water and it can send it, either to the environment or to other process sinks so the water can be used again.

The companies that constitute the industrial parks are going to be working on their own at the beginning. With this methodology, all the plants characterized by their sources, sinks and interceptors are going to start working together, by sharing their water networks. For example, the water of one source of one specific plant can feed any sink of any plant; it can go to any interceptor of the industrial complex, etc. This way, the industrial plants will integrate an eco-industrial park. This optimization step will give a new optimal topological configuration of the water network as a solution by minimizing the total cost and environmental impact (fresh water consumption).

The problem is formulated as an MILP and solved within GAMS environment with CPLEX solver. The main equations are mass balances for each sink, source and interceptors, the total cost and environmental functions and more constraints that complete the model (Boix et al., 2012).

5. Case study: the Garonne watershed in France

5.1. Description of the case study

In this study, four possible eco-industrial parks are considered to be placed in the Garonne watershed. To model the Garonne watershed firstly, it is necessary to divide the watershed into different sub-watersheds, as the MFA model requires. Secondly, some information about the watershed was needed for each partition that had been done, for example the precipitations rate, industrial, residential and agricultural discharges, losses, usages, initial flows, etc.

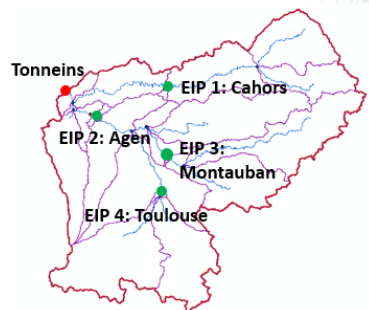


Figure 3: Garonne watershed

To reach this purpose, a model is developed in ArcSWAT (Arnold et al., 2012) for the watershed of Garonne. The watershed has been divided into 22 sub-basins and the final disposal has been placed in Tonneins. Also, it has been decided to place the possible eco-industrial parks in Toulouse, Montauban, Cahors and Agen (Figure 3). Firstly, with all this information, the MFA model for the Garonne watershed with normal industrial parks (without any collaboration) was developed and the concentration of pollutant at the final disposal is obtained: 2.03 ppm. Then, the multi-objective optimization of all the four industrial parks is carried out and the information obtained in relation to the pollutant concentration and the wastewater is introduced again into the MFA model to evaluate the changes in the pollutant concentration.

5.2. Reconfiguration of industrial parks into EIP by multi-objective optimization

In this study, four possible eco-industrial parks are considered to be placed in the Garonne watershed. For each of them a multi-objective optimisation process has been carried out. The optimisation variables were fresh water, regenerated water, number of connections, total cost and the pollutant concentration expelled to the environment. To solve this problem, for each eco-industrial park a Pareto front has been drawn and, from this set of optimal solutions, the optimal TOPSIS solution has been chosen. In order to illustrate this step, Figure 4 represents one of the four EIP Pareto fronts that have been built; the figure is related to EIP n°1 and represents the fresh water consumption (environmental objective) with the regenerated water (economic objective) for several number of connexions.

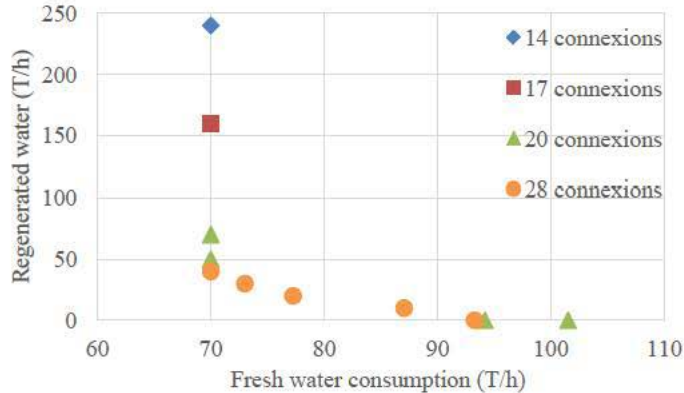


Figure 4: Pareto Front of the EIP 1

5.3. Environmental impacts of EIP policy at the watershed scale

Several strategies were studied: first, only one of the four EIP is working while the others stay as classical industrial parks, then some combinations of them and finally all of them are working at the same time. All these configurations were then compared to the pollutant concentration at the final disposal, without any eco-industrial park in the watershed. Figure 5 summarizes the results obtained during this study where the pollutant concentration at the final disposal is reported for the different strategies explored.

Some important results must be underlined:

- A global diminution of the pollutant concentration at the estuary is observed for every strategy of EIP development

- Each EIP does not have the same effect on the overall watershed, for example, EIP 3 leads to a greater reduction than EIP 4. This is mainly because EIPs have different sizes and are located at different places in the watershed what causes different environmental impacts.

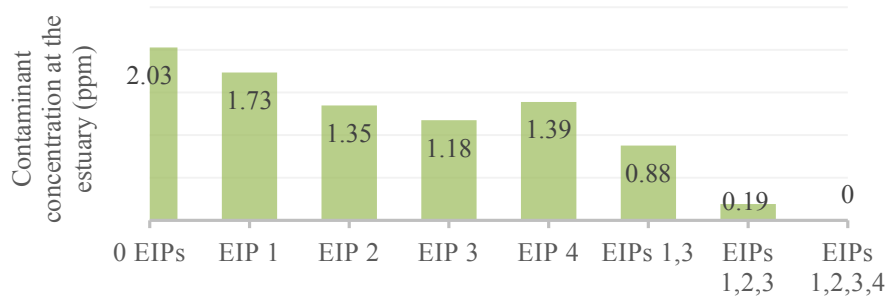


Figure 5: Pollutant concentration at the final disposal under several strategies of EIP development

6. Conclusions

As a general conclusion, it must be highlighted that the implementation of industrial ecology strategies is always interesting. The development of eco-industrial parks reduces pollution and studying the eco-industrial parks effects on a bigger perspective or scale, such as the scale of a whole watershed. This study helps us to understand their influence or beneficial impacts in a better way and the strategy developed aims at implementing this strategy with a higher performance. The optimal location for these eco-industrial parks in the watershed has a major influence in their final environmental impact. Nevertheless, this task is not completely finished. Some improvements can be added to both models, the EIP's model and the MFA model. Starting with the first one, this model can be enhanced by making the code multi-pollutant, the cost equations can be improved, other ways of introducing the ecological effects into the code or more ecological parameters could be studied. Moreover, the eco-industrial park concept can be extended by sharing not only water but also more resources such as energy or other materials.

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