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Benefits analysis of optimal design of eco-industrial parks through life cycle indicators

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Abstract

Industrial symbiosis offers to companies the possibility to make economic benefits and to minimize environmental impacts by sharing flows and increasing inter-enterprise exchanges. However, even if some studies have demonstrated the benefits of the development of eco-industrial parks (EIP), there is no consensus to evaluate their benefits in a global point of view and there is a lack of integrated indicators for the assessment of EIPs. The aim of this study is to propose a holistic approach to evaluate the global impacts of an EIP. To reach this goal, the potential eco-industrial park of Mongstad in Norway has been chosen. Several steps are considered: a simulation through Aspen Properties®, then the superstructure optimization problem solved within GAMS® environment by minimizing the total cost of the EIP is done. Finally, an evaluation of the optimal solution through a life cycle approach is carried out. The results show that companies included in the EIP have environmental impacts reduced from 45% to 80% compared to the impacts of stand-alone companies.

Keywords: life cycle assessment, industrial symbiosis, process simulation, optimization, multicriteria decision making.

1. Introduction

Following several famous environmental summits, and more particularly, at a national scale, the French Environmental Conference that occurred in 2013, France defined some guidelines for its ecological transition. The main research axis that has been defined is the development of a circular economy in order to design new ways of producing goods and services that allow decreasing resources consumption (water, energy and raw materials). In this context, the development of industrial and territorial ecology has become one of the big international issues. One of the answer to overcome this issue consists in implementing eco-industrial parks (EIP) (Boix et al., 2015). Indeed, industrial symbiosis offers to companies the possibility to make economic benefits as it is the case in the eco-industrial park of Kalundborg, in Denmark, for example. 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).

As it can be inferred, 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. However, even if some studies have demonstrated

the benefits of some punctual environmental indicators such as water consumption (Alnouri et al., 2016), global warming potential or energy consumption (Valenzuela-Venegas et al., 2016), there is no consensus to evaluate the benefits of eco-industrial parks in a global point of view. Furthermore, there is a lack of integrated indicators for the assessment of EIPs. EIP optimization models are far from being single-objective classical optimization problems. Zhang et al. (2008) provided a general procedure allowing the early planning and design of EIPs. Furthermore Sokka et al. (2011) proposed to compare stand-alone environmental impacts to an industrial symbiosis system by a life cycle assessment. In the present work, the proposed systemic methodology consists in a combination of modern engineering tools, such as process simulation, mathematical modelling and optimization and life cycle approach to evaluate the solution. The aim of this study is to propose a systemic approach for the design of eco-industrial parks that allows taking into account the multi-participant aspect at the beginning of the project; but also that allows evaluating environmental impacts of the proposed solution that minimizes the cost.

2. Methodology

The generic methodology deployed in this work is illustrated in Figure 1 for several modelling scales.

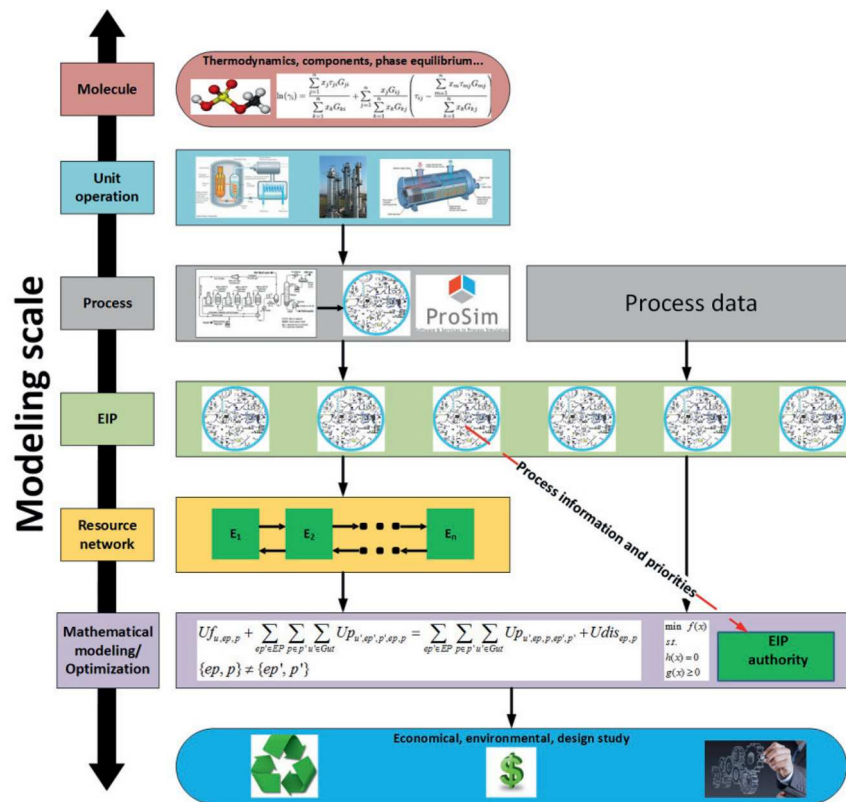


Figure 1. Generic methodology developed

Indeed, whatever the scale of the system it is possible to overcome the data limitations by means of thermodynamics modelling or process simulation to obtain data that allows building the superstructure. For example, specific details from the molecule level are traduced by thermodynamics modelling.

After processing the data, a mathematical modelling is necessary to optimize the whole system regarding an economic criterion. The optimization step is done according to the previous work of Ramos et al. (2016) by using a multi-leader-follower game (MLFG). The game theory approach is proven reliable compared to traditional multi-objective optimization (MOO) methods because it provides a numerical Nash equilibrium solution (Ramos et al., 2016). In this model, the enterprises of the park are considered as Leaders and each one minimizes its own cost while an EIP authority, which is the Follower, is responsible for minimizing resources consumption. In this work, the solution obtained is then environmentally evaluated through a life cycle approach.

3. Application of the methodology to the case study

This holistic method is applied on a case study located at Mongstad, in Norway already studied by Zhang et al. (2008). The system is composed of several companies established in a same geographical area that do not collaborate for the moment (Figure 2). Indeed, Zhang et al. (2008) have already identified this case study as a potential EIP and explored what kind of flows the different companies could share. The main activities were selected to be part of the EIP, the selected ones are those with internal processes, as well as energy exchanges and mass flows relevant for the proper development of the park, such as the refinery or the power plant. Modules as water treatment or aquaculture have been excluded. The selected activities for this study are Coal Gasification, CO₂ Capture, Methanol and Dimethyl Ether (DME) Synthesis, Refinery Plant, Power Plant and Air Separation.

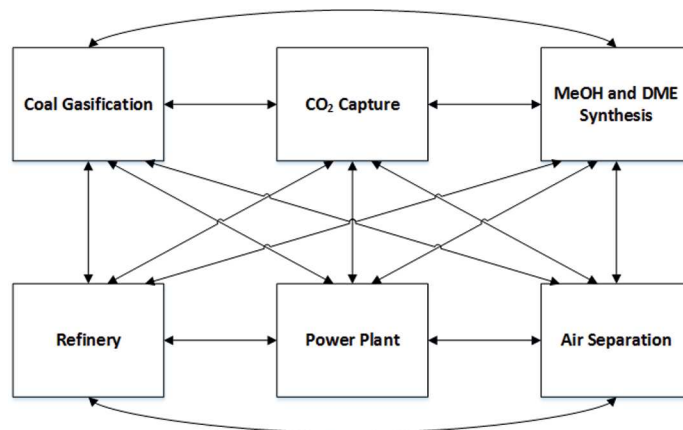


Figure 2. Potential EIP participating plants

In this work, the aim is to propose an optimal configuration for the design of this EIP where every participant is satisfied by its own situation and a good environmental evaluation of this solution. Several steps have been carried out to reach this goal:

- **The first step** consists in the transformation of a real problem with limited data into a mathematical optimization model. Inputs and outputs of each company need to be exactly quantified so that proposal of exchanges can be made. At this step, a process

simulation software (ASPEN Properties®) is used in order to simulate all the flows of water, energies (electricity, utilities) and contaminants of each company.

- **The second step** aims at defining the superstructure according to the flows obtained to formulate the optimization problem, which is solved within GAMS® environment. Thanks to the method developed by Ramos et al. (2016), game theory is implemented and an authority or regulator is created to guarantee the minimization of environmental impacts while each company minimizes its cost. By the way, the issue of confidentiality between plants is solved because all the data are handled by this authority/regulator. The optimal solution constitutes a Nash equilibrium what means that none of the companies are in their interests to change their strategies. The problem includes 2022 variables, 1600 constraints and the CPU time is 7 seconds.
- **The final step** is to evaluate the optimal solution to compare environmental impacts of the integrated EIP to stand-alone companies. This environmental evaluation has been carried out through a life cycle approach where the system boundaries are limited to the whole EIP (Figure 4), thus, it consists in a gate-to-gate analysis. The inventory was conducted according to the norm ISO Standard 14044:2006. The system includes the production of raw materials, wastes and effluents and fuels and electricity used by the different companies. Calculations of impacts were conducted using Simapro 8.0 and IMPACT 2002+ method as well as the EcoInvent database. The functional unit of the study is one-year production of the whole symbiosis.

4. Results and discussion

4.1. Process simulation and optimization of the potential EIP

Each process of the EIP has been defined and simulated with ASPEN Properties®. Given the energy requirements obtained by the simulations, different utilities were considered for the potential EIP: water (at different temperatures) and steam (at low and high pressures).

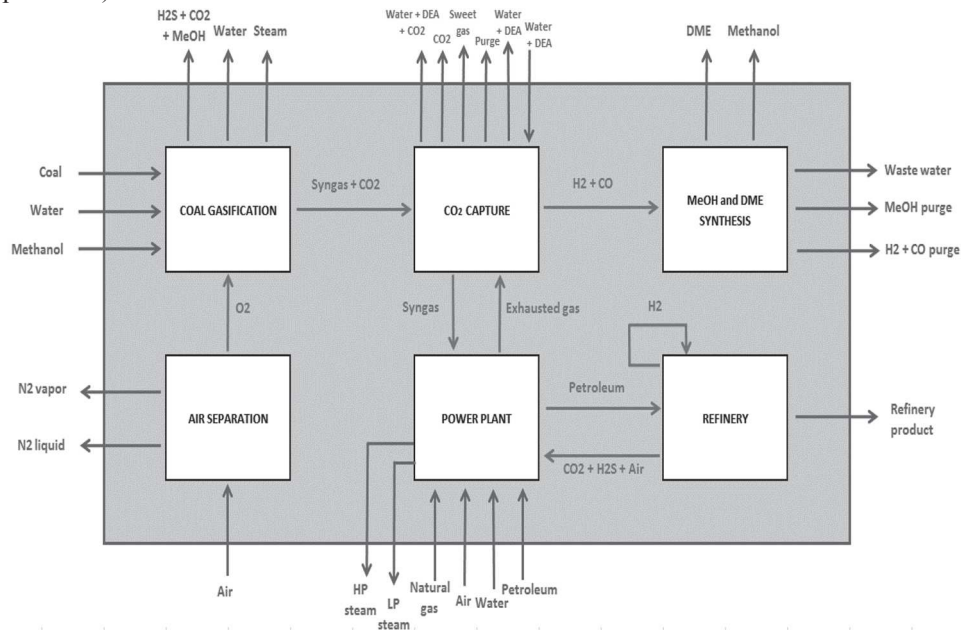


Figure 3. Inputs and outputs for the system studied.

After these simulations, the superstructure of the utility network has been raised in order to implement the game theory approach. The optimal solution is calculated and the different flow exchanges are summarized in Figure 3.

In this solution, some internal exchanges are proposed but it remains a lot of inputs and outputs for the whole system because this solution aims at minimizing the own cost of each company of the EIP. Inter-enterprises flows are represented but they will not affect the environmental impacts. The power plant needs the great majority of the utilities consumed, natural gas, and petroleum that will greatly cause damages on the environment. As expected, utility consumption decrease in the optimal solution and the refinery is the lead CO₂ producing plant. However, in order to fulfil a significant analysis, it is important to quantify the environmental benefits proposed by this solution.

4.2. Environmental impacts of the optimal solution

Environmental impacts of the solution have been calculated and compared to the case where companies work in stand-alone configuration. Mid-point impact categories are reduced from 4.8% for Respiratory organics to 94.5% for Ionizing radiations categories (Figure 4).

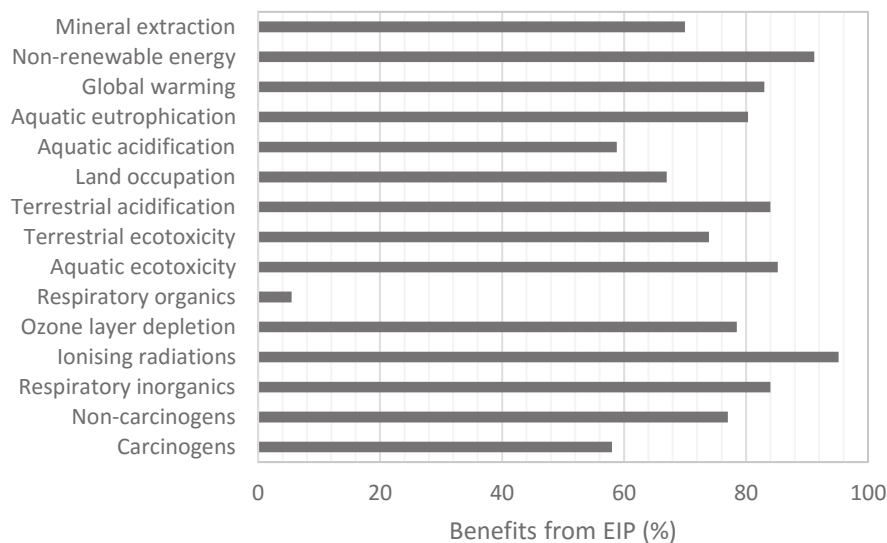


Figure 4. Benefits generated from the EIP configuration compared to stand-alone companies regarding mid-point impact categories (in percentage).

These benefits are mainly due to the fact that 116T/h of CO₂ are recuperated from coal gasification and sent to the CO₂ capture plant within the EIP instead of being released as emissions into the environment. This is the same case for the petroleum of the powerplant partly recycled as an inlet of the refinery. Finally, Figure 5 illustrates the impact points regarding end-point damage categories. The resources consumption remains the principal damage caused because petroleum, natural gas and water are used as inlets of the stand-alone companies. However, in the EIP, although this damage category is drastically reduced (from 480 to 40 points), it could be interesting to design an alternative that proposes the utilization of renewable energies in order to reduce these damages. The climate change damages are also reduced with the EIP option thanks to the recycling of CO₂ at the outlet of the coal gasification plant.

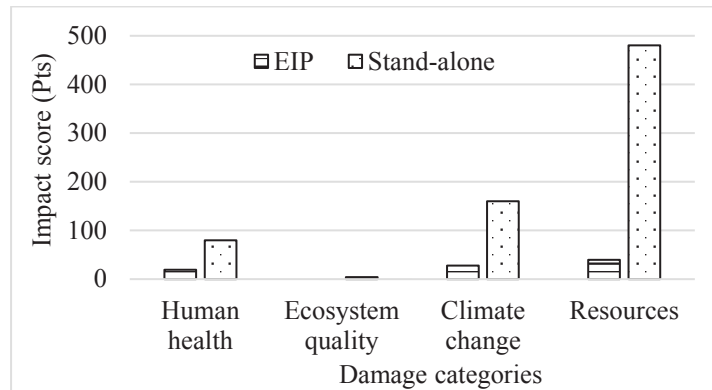


Figure 5. Damage categories generated by the EIP compare to stand-alone companies.

5. Conclusion

In this work, a holistic method has been developed by coupling several tools: process simulation, optimization through game theory and an environmental evaluation of the optimal solution. Usually applied to a product or process, a life cycle approach is here used as a post-optimization evaluation tool applied to the whole EIP system. A comparison of the environmental impacts generated by the companies individually and when included in the park helps to demonstrate concretely the environmental benefits of an EIP. These results show that for each mid-point and end-point categories, the environmental impacts of industrial activities when they are included in the EIP are reduced from 45% to 80% compared to the impacts of stand-alone companies. Furthermore, this integrated approach also permitted to design an EIP solution where significant gains are reached because the total cost is reduced of 25%. In future works it will be interesting to integrate LCA indicators during the optimization step. However, this kind of approach with game theory needs to be formulated as a multi-leader multi-follower game (MLMF) where all the followers aims at minimizing each indicator.

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