Official URL: http://doi.org/10.1016/j.jclepro.2014.09.032

Review

Optimization methods applied to the design of eco-industrial parks: a literature review

Marianne Boix*, Ludovic Montastruc, Catherine Azzaro-Pantel, Serge Domenech

Laboratoire de Génie Chimique, U.M.R. 5503 CNRS/INP/UPS, Université de Toulouse, 4, Allée Emile Monso, 31432 Toulouse Cedex 4, France

Keywords:
Eco-industrial parks (EIP)
Industrial ecology
Optimization
Energy
Water network
Mathematical programming

A B S T R A C T

With the growing environmental concern, there is evidence that increasing symbiotic relationship between plants in the same industrial area, highly contributes to a more sustainable development of industrial activities. The concept of industrial ecology extended to the terms of eco-industrial park (or ecopark) or industrial symbioses is the topic of extensive research since the five last years. More particularly, even if a lot of ecopark examples and realizations already exist throughout the world, a lot of ecopark proposals are in progress but not achieved. Recently, this vision leads the research community to focus on works proposing methods to optimize the exchanges of an ecopark prior to its design and construction. We find it especially interesting for the scientific community to propose a detailed paper review focused on optimization works devoted to the design of eco industrial parks.

This paper is based on a comprehensive literature search in Web of Science database for publications that listed 'industrial symbiosis' (or 'eco industrial park', or 'inter plant integration') and 'optimization'. This study is segmented into different sections with first, a description of the different concepts evoked in the literature. Then, the several types of networking in an eco-industrial park are detailed in association with the optimization methods employed to solve each problem. The following sections reviews the different objective functions that are formulated to optimally design an eco-industrial park. The last part of the paper is devoted to a critical analysis of the state of the art by proposing several routes to improve the methodologies found in the literature. Another aim of this paper review consists in finding the gaps existing in previous studies. These major gaps are found to be: the lack of multiobjective optimization studies, the absence of social/societal objectives formulation also needs to be addressed and the lack of works taking into account flexibility of ecoparks in an operational point of view.

1. Introduction and concepts

Nowadays, it is commonly admitted in the literature that several factors lead to an increasing depletion of natural resources (UNEP, 2000; UNESCO, 2009). One can cite for instance the rising of both worldwide population size (Nielsen, 2005) and urbanization. Facing this disturbing observation, a lot of research projects are now devoted to the global environmental preservation focused on industrial development based on the concept of "sustainable development" (Brundtland et al., 1987). To preserve environment while increasing business success is the main goal of industrial ecology. This concept, directly linked to sustainable development, appeared in the 1970's (Gussow and Meyers, 1970; Hoffman, 1971; Watanabe, 1972). The term of "Industrial Ecology" was then popularized by Frosh and Gallopoulos (1989) by using the analogy between natural ecosystems and industrial systems. Indeed, in natural ecosystems the use of energy and materials are optimized while wastes and pollution need to be minimized. By analogy with natural ecosystems, companies included in an EIP can be viewed as different hierarchical trophic levels in a food chain with metabolic links among them (material and energy) (Hardy and Graedel, 2002; Ashton, 2008, 2009). A more recent definition for industrial ecology has been cited by Allenby (2004, 2006): "a systems-based, multidisciplinary discourse that seeks to understand emergent behavior of complex integrated human/natural systems".

The great challenge is now to successfully perform the design of sustainable industries which are economically competitive. Building a sustainable industry is slightly linked to the term Industrial Symbiosis. According to Chertow (2000), an industrial symbiosis engages "separate industries in a collective approach to

* Corresponding author. Tel.: +33 5 34 32 36 66; fax: +33 5 34 32 37 00.
E-mail address: marianne.boix@ensiacet.fr (M. Boix).

List of abbreviations

BBIS	bioenergy-based industrial symbiosis
CCEIS	coal-chemical eco-industrial system
CHP	cogeneration of heat and power
CWWTP	centralized wastewater treatment plant
Dp	depletion number
EIP	eco-industrial park
EIPWN	eco-industrial park water network
ENC	equivalent number of connections
GAMS	general algebraic modeling system
GEC	global equivalent cost
GHG	green house gases
GIS	geographic information system
HRSG	heat recovery steam generator
LCA	life cycle assessment
LCC	life cycle cost
LCI	life cycle inventory
LP	linear programming
MCDM	multicriteria choice decision making
MILP	mixed integer linear programming
MIND	method for analysis of industrial energy systems
MINLP	mixed integer non linear programming
NLP	non linear programming
NPV	net present value
TAC	total annual cost
WCA	water cascade analysis

competitive advantage involving physical exchange of materials, energy, water and by-products". A primordial feature of an industrial symbiosis is the collaboration offered by the geographic proximity of several companies. Most widespread manifestations of industrial symbioses are Eco-Industrial Parks. Several definitions for the concept of "eco-industrial park" can be found in the literature. However, a definition commonly adopted 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" (PCSD, 1996; Alexander et al., 2000). At last, a basic condition for an EIP to be economically viable is to demonstrate that the sum of benefits achieved by working collectively is higher than working as a stand-alone facility (Boix et al., 2012).

In order to design sustainable stand-alone industries, a lot of tools are available including administrative, prevention or "end-of-pipe" solutions. The administrative tool consists of environmental regulations by political decrees or laws whereas a preventive approach promotes a new organization of a particular industry so as to pollute less. The end-of pipe solution is the more conventional even if it is not the most appropriate. This approach consists in decontaminating outlet streams by using several types of expensive processes (e.g. water treatment plant) so; the main drawback of this method is that environmental protection is changed into an economical cost. These traditional tools are not adequate to compensate the increasing pollution in the world and therefore, new initiatives in the fields of Industrial Ecology or Cleaner Production appeared.

According to Chertow (2004), an activity can be qualified as an industrial symbiosis if cooperating businesses include components of materials, water or energy exchange. An eco-industrial park can be represented by several types of configurations as long as it involves environmentally friendly goals and supports cooperative approaches (Chertow, 2004). In the literature, several types of cooperation have been reported, a summary of them is proposed in Table 1, the check marks are the summary from the review conducted in this study. A check mark means that at least one publication has been found to apply optimization methods to the corresponding type of cooperation.

In this table, a list of cooperative activities is constructed and the second column shows if this collaboration is involved into any optimization approach.

2. Methods and scope

The design of eco-industrial parks is a part of these recent initiatives and, alongside of several years of qualitative studies, a lot of quantitative approaches are involved during the last years. Inherently, an eco-industrial park needs to operate optimally or near its optimal conditions regarding several antagonist objectives. Despite a comprehensive review about the successful development of EIP's written by Tudor et al. (2007), there is a lack of data especially devoted to optimization in this field. This paper presents a literature review of the optimization methods applied to the development of EIP's because we find it meaningful to distinguish what has been done, in order to underscore the directions towards where future researches have to move.

This review is based on literature, and we have used the ISI Web of Science database and searched for the combination of "eco industrial park" or "industrial symbiosis" or "inter plant" and "optimization" as a topic. 44 publications in international peer-review journals were the results of this research. Fig. 1 shows the number of published articles during the last 15 years with these key words and the number of citations of the related articles.

Based on the results of this research, the publications have been identified and analyzed in order to propose a relevant outline to this paper review. The aim of this literature review is to emphasize the different methodologies developed during the last years to optimize the design of industrial symbioses and/or eco-industrial parks. First, we describe the types of symbiotic relationships that can be found in the literature (Section 3). In this part, the different methods of optimization are detailed for each type of cooperation: cooperation through the water network (Section 3.1), via energy (Section 3.2) and finally through exchanges of materials (3.3). As in any optimization problem, the following section details the objective functions considered to improve the design of an EIP in Section 4. A particular focus is made on the mathematical formulation of the different types of criteria: societal, economic, topological and environmental. Finally, a critical analysis allows to bring out the

Table 1
Types of cooperation between companies in an EIP (modified from Tudor et al., 2007).

Type of cooperation at process level	Used in optimization approaches
Exchange of materials, water and/or energy	✓
Share of units: water regeneration units, heat utilities	✓
Transformation of wastes into by-products	×
Exchanges of knowledge, human and technical resources	×
Transport of goods and people	×

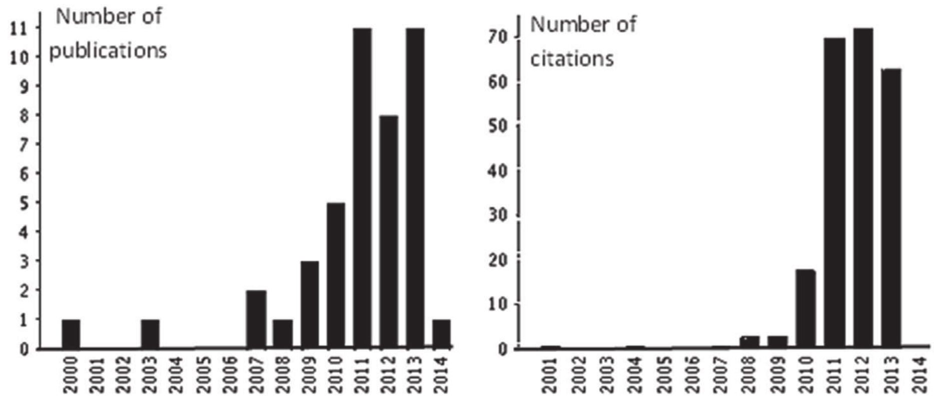

Fig. 1. Number of articles referenced in the last 15 years with the keywords: "optimization" and "eco industrial park" (Source: Web of Science).

main gaps and to propose some strategies to follow for future research works in this field.

3. Exchange of water, energy and/or materials

Exchanges of materials, water and/or energy through a sharing network between companies of an EIP are the main way to design an optimal EIP. The research studies focus most of the time on the optimal design of an EIP network while taking into account separately water, energy and material.

3.1. Water network optimization in an eco-industrial park

Among them, water-using network is the most common type of cooperation in the literature (e.g. Keckler and Allen, 1999; Aviso et al., 2010a,b; Chew et al., 2009; Lovelady and El-Halwagi, 2009; Rubio-Castro et al., 2010; Tan et al., 2011; Taskhiri et al., 2011a,b; Boix et al., 2012). In these studies, the rules and methods applied to optimization for a single-plant integration (Takama et al., 1980; El-Halwagi, 1997; Olesen and Polley, 1996; Karuppiah and Grossmann, 2008; Boix et al., 2011) are used to deal with inter-plant integration (El-Halwagi et al., 2003; Lim and Park, 2010; Rubio-Castro et al., 2012), as long as the approach supports large-scale problems (Rubio-Castro et al., 2011). The case is often solved as a water-allocation problem where water needs to be distributed, treated and discharged in an optimal way between the process units of each company included in the park (Lovelady et al., 2009; Chew and Foo, 2009; Boix et al., 2012).

There are several kinds of approaches to design an integrated inter-plant water network. Chew et al. (2011) defined two types of schemes: direct inter-plant integration and indirect inter-plant network. Furthermore, considering a water network in an EIP can be a difficult approach to adopt because the considered companies often pollute water with different types of contaminants (Rubio-Castro et al., 2011).

Water-using system in an EIP is generally optimized through two main approaches (Yoo et al., 2007): 1. Conceptual graphical design (pinch technology) and 2. Mathematical programming optimization.

Water minimization through the targeting procedure (water grid diagram) has been first developed for simple industrial water networks by Wang and Smith (1994, 1995). This procedure was then extended to the design of one water network divided into three geographical zones, which is now considered as a precursor of EIP optimization (Olesen and Polley, 1996, 1997). In this study, the authors used the graphical concepts of pinch technology with load tables to reach the targeting water flow-rate of the overall site by introducing geographical locations and piping costs of each zone. Later, Spriggs et al. (2004) addressed the problem of inter-plant integration for fixed water flow-rates by using the material recovery pinch diagram. Similarly, Foo (2008) utilized the water cascade analysis (WCA) for targeting plant-wide integration by sending water sources into different geographical zones, this approach allowed to reduce water consumption of about 56%. In the past five years, some authors developed new strategies in order to adapt pinch techniques for interplant resource conservation network. To process such an adaptation, pinch technology needs to be coupled with other optimization strategies; Chew and Foo (2009) used a graphical approach coupled with mathematical programming. In this study, an automated targeting procedure is involved, followed by a linear programming approach to design a detailed water network. Chew et al. (2010a; 2010b) presented a paper series where the target water flow-rate is obtained by a pinch approach and the result is then processed with a genetic algorithm for the synthesis of total resource network.

The main drawbacks of pinch-based methods are the inability to design water network involving several contaminants, to study large-scale problems and to deal with multi-objective optimization which is often the case when an eco-industrial park is involved. Mathematical programming approaches are suitable for these types of large and complex problems and are consequently well studied in the literature with the help of the superstructure concept. Keckler and Allen (1999) considered the case of water reuse in a simple "industrial park" through a linear formulation. They calculated the best configuration for an existing water network. Using the same methodology, Nobel and Allen (2000) proposed a shared water network in an EIP by integrating a geographical analysis. Their model included a linear programming model in a Geographic Information System (GIS) to model the water reuse in an EIP. Almost ten years later, Chew et al. (2008) introduced the concepts of direct versus indirect interplant water integration (Fig. 2) and analyzed them through mathematical programming techniques. In the direct interplant water integration scheme, water from a company can be directly integrated into another company as long as it satisfies all the quantity and quality requirements. In the indirect scheme, water from a company needs to be sent to a utility hub before being introduced into another company. They formulated the problem for the direct integration scheme through a Mixed Integer Linear Programming (MILP) model whereas the indirect scheme was formulated as a Mixed Integer Non Linear Programming (MINLP) while minimizing the fresh water flow-rate.

Lovelady and El-Halwagi (2009) proposed a nonlinear program (NLP) or an MINLP to formulate the problem depending on the

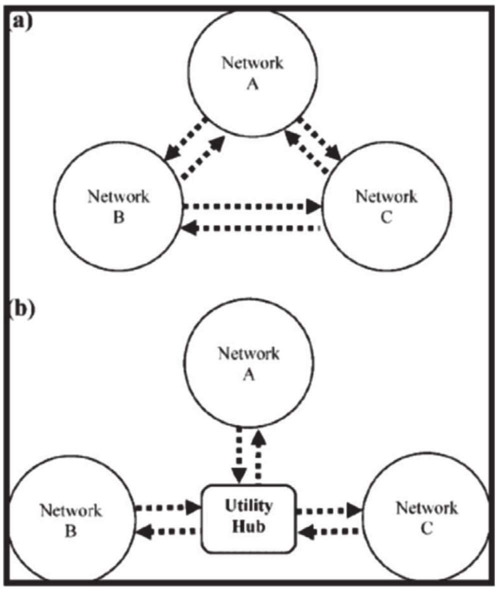

Fig. 2. Interplant water integration schemes (from Chew et al., 2008).

interception modeling (indirect or direct) and cost functions. Their objective function is the total annualized cost which takes into account the interception device, the cost of fresh water and waste treatment. Fig. 3 illustrates the schematic representation of an EIP involving p processes and k interceptors (Lovelady and El-Halwagi, 2009).

Similarly to the works of Chew et al. (2008) and Lovelady and El-Halwagi (2009), Lovelady et al. (2009) developed a systematic procedure for the optimal design of an EIP through a source-interception-sink superstructure (Fig. 3). The nonlinear program (NLP) can be solved to determine the allocation of streams and the design of the EIP. A property-based water minimization case study is also used to illustrate their method and they observed that processes participating in an EIP can obtain significant savings. Based on a similar approach, Lim and Park (2010) proposed an optimization model which minimizes the consumption of industrial water. Their case study is an existing iron and steel industrial park in Korea composed of six processes from three factories. They also carried out a post-optimization analysis of life cycle assessment (LCA) and life cycle cost (LCC) to evaluate the environmental and economic performances of their solution. The water network studied by Lim and Park (2010) involves two contaminants (chemical oxygen demand and suspended solid) and the problem is formulated through a nonlinear model (NLP) without considering the number of pipes in the park. In 2011, Rubio-Castro et al. proposed an approach for water integration in an EIP by taking into account several contaminants through an MINLP formulation. In order to obtain a global optimal solution, they discretized the nonlinear formulation to yield a MILP problem. In their program, environmental regulations are introduced as constraints and the objective function is to minimize the total annual cost (mono-objective optimization) applied to four cases study. The linear formulation of a problem induces to find a global optimal solution if it exists. This is the reason why Taskhiri et al. (2011b) proposed an MILP model for emergy optimization in water networks of an EIP. Emergy was introduced by Odum (1996) by this definition: “the cumulative energy which is used directly and indirectly to produce a product or service”. The utilization of this concept lead to directly quantify the true value of a commodity based on resource flows (Ulgiati and Brown, 2009). In their work, Taskhiri et al. (2011a) used emergy as a basis to design an optimal EIP configuration for water reuse network with a mixed topology in a monocontaminant water network. More recently, Boix et al. (2012) developed a multi-objective optimization strategy based on the ε-constraint approach applied to the case of a water network in an EIP under several scenarios. The interest of dealing with multi-objective optimization is to build a Pareto front in which a lot of optimal solutions are available and a tool of multiple criteria decision making (MCDM) can be further applied. Three objectives were taken into account: the consumption of freshwater, the number of pipes and the regenerated water flow-rate. This work was then extended to a flexibility analysis in Montastruc et al. (2013) where two economic indicators are used for analyzing the EIP performances: the equivalent number of connections (ENC) which reflects the piping and pumping costs in the EIP infrastructure, and the Global Equivalent Cost (GEC) expressed as an equivalent of freshwater flow rate. Another flexibility analysis of multiple plant water networks was done in Liao et al. (2007) where the authors developed a two-stage methodology to take into account uncertainty and multi-period issues. First, an MINLP formulation solved with GAMS (2005) is carried out to provide the connections

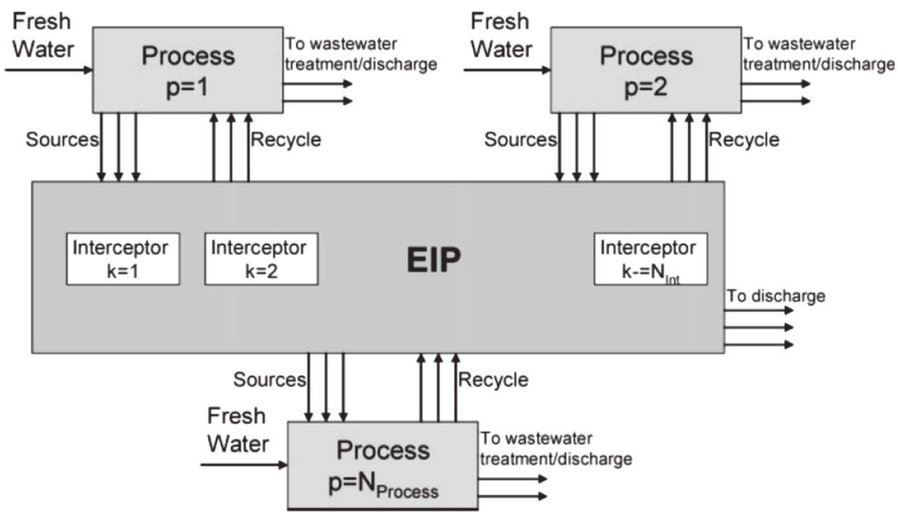

Fig. 3. Representation of the EIP design problem (from Lovelady and El-Halwagi, 2009).

between plants and the target of fresh water usage, this is the "targeting stage". The second step is the "design stage" where an MILP problem is proposed to achieve a flexible water network that meets the freshwater target in all periods.

Some other techniques have also been employed to add more considerations in the problem formulation. Aviso et al. (2010 b) developed a bi-level fuzzy optimization model so that two levels of decision-makers (participating plants and park authority) can have conflicting objectives. This approach consists in solving two objective functions, one for the leader and the other for the followers. If both solutions coincide, the solution is considered as optimal and if not, another objective function is included to maximize levels of satisfaction for the leader and its followers as long as a feasible solution can be found. In the second part of their work (Aviso et al., 2010 b), the authors introduce the role of an external agent (government) to induce cooperation among companies. Lastly, Chew et al. (2009, 2011) adopted the game theory approach for inter-plant water integration. In Chew et al. (2009), the game theory approach assisted the selection of an optimal solution for direct integration schemes whereas in Chew et al. (2011) the indirect integration scheme is more precisely studied. This type of work is divided into two steps: first, a set of schemes are generated using pinch techniques and then, the game theory approach (cooperative versus non-cooperative) is used as a decision-making tool.

3.2. Energy network in an EIP

In contrast to EIP material-flow management (water, wastes) where relatively numerous works exist, there is a little number of publications dealing with interplant energy flow management (Fichtner et al., 2004). However, as it is the case for the optimization of water networks in EIPs, energy savings in an EIP can also be achieved by using pinch analysis or mathematical programming approaches.

Without referring to terms such as "eco-industrial park" or industrial ecology, the study of Bagajewicz and Rodera (2000) developed the notion of energy savings in a "total site" first introduced by Dhole and Linnhoff (1992) and Hui and Ahmad (1994). Based on a pinch analysis, they proposed heat integration through linear models (LP and MILP) for a site consisting of n plants. The study evokes direct heat integration as well as indirect integration solutions by making a suitable redistribution of heat flows between units in the network. They pointed out that by using a pinch approach, the geographical position of each plant is fundamental because the redistribution of flows depends on their pinch temperature and the distances play an important role in operating and capital costs.

More recently, a lot of research studies have investigated total site heat integration by using pinch analysis for both graphical (Karimkashi and Amidpour, 2012; Varbanov et al., 2012) and numerical (Liew et al., 2013, 2014 a, b) methods. Most particularly, Liew et al. (2014a) developed a method based on the cascade analysis methodology in order to target the minimum multiple utility requirements for a total site system by considering the water sensible heat. A complementary study from the same group (Liew et al., 2014b) detailed this whole algorithmic methodology and introduced variable energy supply and demand. The tool developed is named the total site problem table algorithm (TS-PTA) and can also be used in order to estimate the required heat storage capacity.

At this time, none of the works found in the literature deal with multiobjective optimization of an EIP sharing energy flows. As it is shown in this review, there are relatively few studies that deal with energy management in an EIP through mathematical optimization. The main barrier to optimize an EIP by taking into account energy flows is the difficulty to acquire reliable process data from the plants included in the EIP. Furthermore, energy balances require an exact resolution through an MILP or LP which makes mathematical programming the only approach available to solve the problem.

Fig. 4 proposes a summary of the different steps to follow to optimize an EIP by considering energy management. For energy exchanges, the specificity comes from the variety of data to collect to properly model the structure of the EIP. Furthermore, the difficulty to be complete, the model must includes binary variables to represent the presence of a particular flow. This formulation is of MILP type and is often difficult to solve with complex problem, which is the case of EIP's, this is for this reason that the majority of authors need to simplify the problem in order to have an LP formulation, which is easier to solve.

In the literature, energy network between different firms is more often managed and designed but almost never optimized. In this section, we discuss about the possibilities of integrate an inter-firm energy network in the light of previous studies. Fichtner et al. (2004) pointed out that there are fundamental differences between energy and material (e.g. water) flow management due to specifics of energy flows:

- Energy is hard to store such as electricity or process heat, necessitating an electricity production simultaneously to the demand.
- The link of energy flows in an EIP requires an increase of the investment cost due to some specific utilities (heat exchangers, boilers, turbines or steam pipes for example).
- The companies included in the EIP need to be close enough because investments and heat losses increase with the length of the pipeline (Korhonen, 2001).
- Even if the investment cost for a shared-energy network is high, its components get a long technical lifetime that requires taking into account long-term aspects during the optimization step.

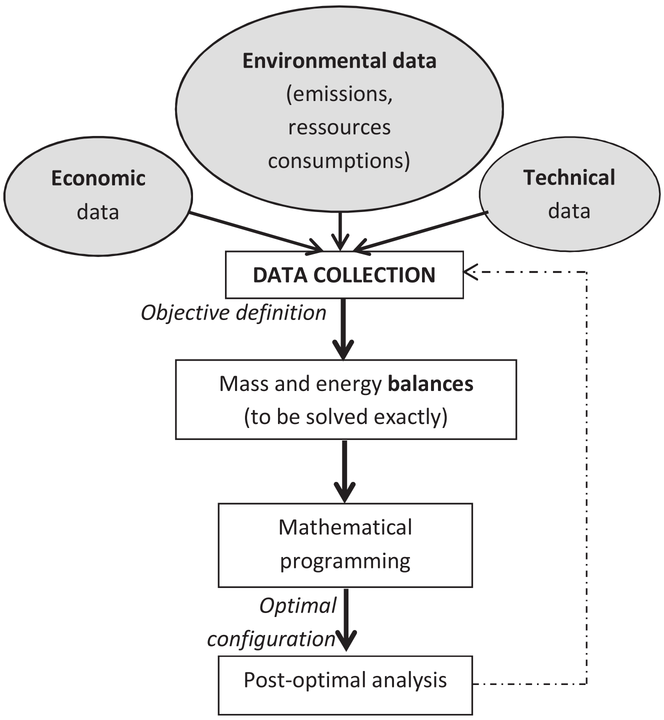

Fig. 4. Illustration of the approach to optimize an EIP.

Inter-firm energy supply concepts were explored later by Fichtner et al. (2004) starting from the statement that there were very little practical experience and only few methods to connect energy flows of different production companies. The authors developed PERSEUS-IFC programmed in GAMS, which is an energy and material flow model to be applied to the energy systems of the firms involved in a park. With this model, they are able to know how a given energy demand maintaining the production in the firms should be fulfilled at minimal cost for specific data. The model is formulated as a multi-periodic MILP which minimizes all decision-relevant costs using the net present value method. Fichtner et al. (2004) covered the technical and economic dimensions but they underscored that social aspects also need to be considered because a lot of barriers can exist such as the share of confidential information and the dependence of partners. Following roughly the same approach, Hirata et al. (2004) developed a multi-period mathematical programming model for solving site-wide optimization problems. They focused on the industrial case study of Mitsubishi Yokkaichi plant site which was one of the largest chemical production plant in Japan. Their final model minimizes the total cost of the production site by taking into account the budget planning, the electricity contract, fuel and water balances and shutdown maintenance scheduling. Another practical case study of energy systems in an eco-industrial park can be found in the study of Starfelt and Yan (2008). These authors examined the feasibility of implementing gas turbine cogeneration technology (with a heat recovery steam generator, HRSG) to replace the engine-based system in an existing EIP in China. The energy requirements in this park (Dongguan city in China) are electricity for production procedure and refrigerators and heat for absorption refrigerators and hot water. After a stage of data collection and a field study, modeling and simulation (ProSim™) steps were carried out to analyze efficiency and economic performance. The main conclusion of this work is that the profitability of the use of the gas turbine technology highly depends on fuel prices at local conditions. A sensitivity analysis on the costs of the system allows the user to investigate the feasibility of such a change in a park. Chae et al. (2010) focused their study on the energy optimization in an EIP using industrial symbiosis of waste heat. The optimal network is found using a MILP model that decides the operating variables of the waste heat recycle. The authors emphasized the specificity of the step of data collection which is particularly important when the energy network is optimized due to seasonal effects, production cycles and emergency situations. The Yeosu National Industrial Complex in South Korea is taken as the case study of this work and three types of waste heat networks are synthesized respectively minimizing three different objectives: the total cost, the extra fuel cost and the last network takes into account the flexibility of the network. In all the cases studied, the results show significant improvements and reduction of regional energy consumption by utilizing industrial waste heat.

The same industrial case (Yeosu Industrial Complex) was also investigated by Kim et al. (2010) using a three step approach:

- Development of process models using thermodynamic principles, mass and energy balances (based on a source/sink modeling).
- Development of a multi-period MILP model for each process system by minimizing the total cost which is the objective function of the problem.
- Analysis of the solution to identify improvements.

Kim et al. (2010) have shown that with a minor increase of the investment cost to add new pipelines between the companies of the EIP, the industrial complex can have a lower total cost and can also decrease its waste load up to 10%.

Karlsson (2011) developed a decision support dedicated to the optimization of industrial energy systems named MIND (Method for analysis of INDustrial energy systems). This tool is a Fortran-based MILP formulation which was later developed as a Java-based interface and renamed reMIND. The energy system is represented as nodes and branches and the objective function is usually the minimization of cost based on net present value calculations. The same research group applied the MIND method to optimize different case studies. Karlsson and Wolf (2008) demonstrated how the MIND method can be used in order to evaluate a symbiosis in the forest industry. The total site is constituted by a chemical pulp mill, a sawmill and a biofuel upgrading plant that can all be possibly connected to a district heating system. In this paper, Karlsson and Wolf (2008) showed that the industrial symbiosis can lead to economic benefits although they did not consider investment costs, process equipments or loss of flexibility. Furthermore, Klugman et al. (2009) also used the MIND method to propose the energy optimization through local heat cooperation in a Swedish integrated pulp and paper mill.

Maes et al. (2011) proposed a review paper to explore different specific strategies to manage energy in eco-industrial parks in Flanders. In this review article, the authors discuss the experimental program of EIP development in Flanders, without referring to optimization they emphasize barriers to link energy flows in an industrial symbiosis. The authors notice that energy clustering is a local optimization problem which is believed to provide strong benefits. More recently, Hiete et al. (2012) adapted the thermal pinch analysis to intercompany process integration. Their exemplary case study involves three different processes:a pulp producer (requiring complex installations and already integrating internal energy), a bio-oil production company and another company that produces fiberboards for upgrading wood waste. The authors optimized cost savings by taking into account the distances between each company. The methodology is composed of several steps:

- The identification of relevant processes for energy integration, that is to say heating and cooling demands and sources.
- The collection of data relative to costs:investment cost for heat exchangers and cost of piping systems.
- The heat integration between processes using an optimization tool
- The analysis of allocation savings using different game theory methods to evaluate the total savings for each company under several scenarios.

With this study, Hiete et al. (2012) employed different methods of cooperative game theory to show that savings compared to individual process integration can be significant (up to 25% of cost savings for some companies compared to individual savings). They also underscored that their model can be improved by taking into account the heat losses during heat transfer between companies, by considering the operational flexibility of process design integration. Also, another limitation is the long-term commitment due to long payback periods that often requires trust between partners. By introducing life cycle concepts into the optimization of an EIP, Kantor et al. (2012) opened a way to evaluate the environmental impacts and benefits of such a symbiosis. In their work, they proposed to evaluate the life-cycle emissions of profitable designs of an ecopark. They have modeled a hydrogen production network composed of several chemical processing plants, namely a gasification, CO_2 capture, a pressure-swing absorption, an ammonia manufacture, an urea manufacture and a combined heat and power. After identifying quantities of energy and material to exchange, the authors have drawn the connections between facilities. A linear modeling (LP) makes the problem relatively easy to solve through GAMS with the CPLEX solver (CPLEX Optimization, 1995). The objective function is a dual function with two weighted factors:emission deviations (based on life cycle concepts) and economic incentives. With this mono-objective optimization, Kantor et al. (2012) have shown that profit remains relatively unaffected compared to the reduction in emissions. Finally, following a similar approach, Zhou et al. (2012) proposed a model to optimize a coal-chemical eco-industrial system (CCEIS) in China. Their objective is to minimize the gap between calculated and optimal results for each of their three indicators: resource use (coal utilization efficiency), CO_2 emissions for the environmental indicator and the economic benefit of the system. The problem is also kept linear (LP) and optimization is carried out under different weight settings for their three indicators gathered in one objective function.

Finally, in this section devoted to energy, it is also important to mention the emergence of numerous recent works related to bioenergy-based industrial symbiosis system (BBIS). For instance, Kasivisvanathan et al. (2012) developed a retrofit methodology to transform an existing palm oil mill into an integrated biorefinery. Among others, more recently, Ng et al. (2014) also studied a palm oil mill to apply their methodology based on a disjunctive fuzzy optimization approach. With this approach, the flexibility of the different choices (the choice for a given company to take part or not within the BBIS system) is taken into account and different scenarios are analyzed by maximizing economic performances of the participants.

3.3. Material sharing in an EIP

Regarding the material exchanges in an EIP, they can be of different types: by-products (Lowe, 1997), wastes or real-value products. In an EIP, the wastes from a company can serve as a feedstock to another company of the park. The main difficulty to optimize the material sharing network of an EIP lies on the multiplicity of the materials produced or used in a park composed of a lot of very different companies. Consequently, very few studies propose a real optimization of these exchanges. In existent EIP's, material exchanges are one of the first links that was put into practice at the beginning of a symbiosis. An example of material sharing can be found in the industrial complex of Kalundborg where the desulfurization process produces industrial gypsum used further in the production of plasterboard at a co-located factory, instead of using natural gypsum (Ehrenfeld and Gertler, 1997; Jacobsen, 2006). Another example of symbiosis with developed material exchanges is the gulf coast project (Boons and Howard-Grenville, 2009; Massard et al., 2012) in USA. In this project, there is a well-developed chlorine exchange network (HCl or Cl_2) between the different plants (Fig. 5).

Although in reality, examples of material sharing in EIP's truly exist, they are not often included in optimization works. Only a few studies evoked material exchanges by really optimizing the network. One of the first in this field was the study published by Connelly and Koshland (2001a,b), which is devoted to an exergy-based definition of resource consumption for industrial ecology. For the authors, exergy defines “the maximum amount of work that may theoretically be performed by bringing a resource into equilibrium with its surroundings through a reversible process”. They developed a thermodynamic-based indicator of resource depletion called the Depletion number (Dp) that measure the extent of which specific resource conservation strategies are implemented. In 2004, Tietze-Stöckinger et al. (2004) developed a model called LINKopt which is an MILP model. This model aims at determining a waste management system on an intercompany-level with minimal decision-relevant costs considering transportation, handling,

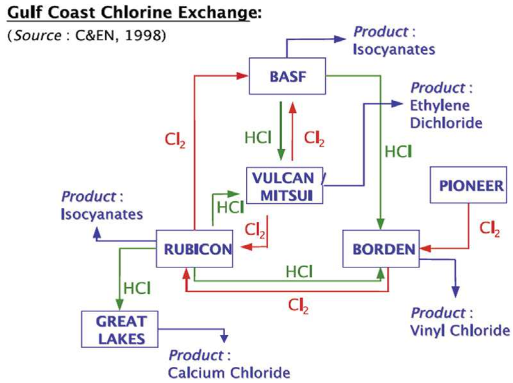

Fig. 5. Gulf Coast chlorine exchanges network (Francis, 2003; Massard et al., 2012).

storage and treatment of waste materials. To solve the optimization problem, CPLEX is used in order to find the best configuration (material flows, available transport modes and investment options) under constraints (transport availability, mass balances and capacity limitations). More recently, Cimren et al. (2012) also used a deterministic approach with Eco-Flow™ based on an MILP. The aim of their study was to present an interactive end-user tool in order to optimize complex networks. They applied their methodology to the case of a material flow network, where they have to determine how to best assign material flows by minimizing costs and environmental impacts (represented by different scenarios). Their application case is the Kansas City by-product synergy network and the results show that a reduction of up to 29% in the total cost can be reached, as well as a decrease of CO_2 emissions up to 30%. More recently, a few research on material exchanges were also related to different applications: palm oil industry or rice mill complexes. In the case of palm oil industry, the challenge is to propose an optimal utilization of by-products (soapstocks, palm fatty-acid distillate for example) generated along with the refining of crude palm oil. To address this problem, Haslenda and Jamaludin (2011) developed a systematic framework formulated as MILP to optimize the supply chain network of the by-products generated from palm oil refining processes. This tool named I2IBEN (industry-to-industry by-products exchange network), provides a decision support in order to determine the optimal distribution of by-products. For the case of rice mill complexes, a few studies have also emerged (Shiun et al., 2011; Lim et al., 2013a,b) these last years. In their recent review article, Lim et al. (2013c) focused on the transformation of conventional rice mills into integrated resource-efficient rice mill complexes (IRE). In these types of mills, integration must be “site-wide” and models need to be developed to take into account trade-offs to optimize the rice supply chain.

Facing the lack of works proposing a material (except water) sharing optimization in an EIP, future investigation and improvements should include this important side of collective symbiosis.

4. Main objectives

Regarding the analysis previously done, an EIP can be viewed and optimized from different ways. One can consider the optimization of energy linkages and reuse, the water and wastewater network or the exchanges of materials (raw material, by-products or wastes). The final aim is to optimize all these components simultaneously in order to obtain an EIP as ecological as possible. Another important issue in the field of optimization lies on the characterization of the objective function(s). Indeed, what is giving cause for concern in numerous research works is to deal with conflicting objectives (Erol and Thöming, 2005). The optimization of this large-scale problem highly depends on several criteria and EIP's have to face two main classes of challenges that can determine their development. The former is the Technical/Economic challenge: if the exchanges among the participants are infeasible, no EIP can be successful. Indeed a real connectivity must exist between the companies within the EIP. The latter related to the organizational/commercial points can represent the biggest hurdle. In order to feed the discussion, Fig. 6 shows the different indicators to evaluate every industrial estate project, chosen by IEAT (Industrial Estate Authority of Thailand (2010)) and translated in english by Panyathanakun et al. (2013).

In the following section, a presentation of the different criteria taken in the literature is exposed. Although more often qualitative as quantitative, the societal/managerial objectives are first described followed by economic, environmental and technical objectives. Finally a short discussion about political regulations is carried out at the end of the section.

4.1. Societal/managerial objectives

Social aspects are fundamental in the development of an EIP project, as the social part is one of the three pillars of sustainable development definition with environmental and economic aspects (Brundtland et al., 1987). Aviso et al. (2011a) underscored that the establishment of a network between different plants requires mutually beneficial cooperation among partners. Even if the technical and economical feasibility will affect the optimal design, the trigger should be the willingness of individual plants to participate (Heeres et al., 2004; Mirata, 2004). Some research has been devoted to develop quantitative indicators to evaluate the satisfaction of each participant of an EIP (Tiejun, 2010; Zhu et al., 2010). Aviso et al. (2010a,b; 2011a) considered the individual interests of the participating plants in a fuzzy optimization model (based on

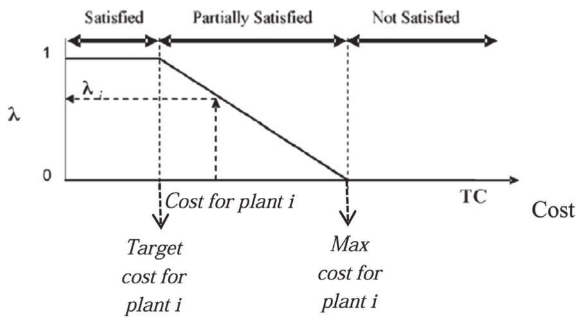

Fig. 7. Fuzzy membership function to evaluate the degree of satisfaction of each participant (modified from Aviso et al., 2011).

Czolaga and Zimmermann, 1986). They realized a mono-objective optimization where their objective is the maximization of the degree of satisfaction λ of the least satisfied participant. Fig. 7 shows the linear membership function attributed to each plant of the EIP (from Aviso et al., 2011a).

Even if the degree of satisfaction can trigger the development of such a project, it is not really an indicator of social effects. Indeed, if one plant is overall satisfied, it will be included in the park but it does not guarantee any local social benefits. The social criterion is the most difficult to mathematically formulate because it involves non quantifiable concepts. Jung et al. (2013) pointed out that the construction of an EIP helps to improve the social image of an area to a great extent, which counts as an important social benefit. The social effect has been evaluated using the MAGIQ method developed by Jung et al. (2013) including the number of networks in the park, the number of participating companies and the number of forums. The authors think that these factors help form a social consensus in local areas and thus reflect the social performance of the park.

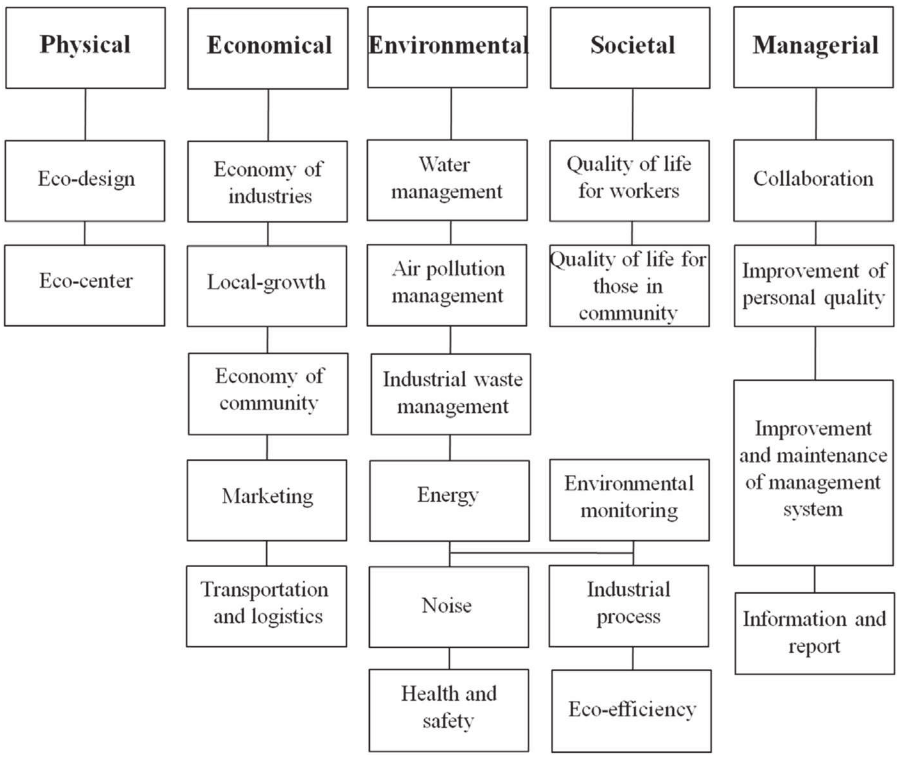

Fig. 6. IEAT initiatives divided in 5 categories and their 22 areas (modified from Panyathanakun et al., 2013).

As already shown in Fig. 6, a social objective should include quantitative indices of quality of life for workers, quality of life for those in community, noise, health and safety for workers and also local employment level. It is also important to underscore that the social aspects can be considered at different levels: plant, site, regional or higher levels. Finally, it can also be relevant to consider the social impacts induced by job creation through remanufacturing if it is necessary. In a study about the design of logistic channels, not directly applied to ecoparks, El-korchi and Millet (2011) developed a social assessment linked to the number of hours of local labor created through remanufacturing. This kind of indicator could be an interesting opportunity to evaluate the social impact during the design of an EIP.

More recently, Hipolito-Valencia et al. (2014) proposed an optimization for the design of interplant trigeneration systems where they evaluate the social impact of their best solution (minimizing cost and greenhouse gas emissions). The social function determines the creation of jobs for the production of the biofuels, fossil fuels, and for the operation of the solar collector to satisfy the energy requirements in the system. To reach this goal, three separate impacts are determined: a direct effect (for example, crews to construct a new plant), indirect effects (takes into account the increase of economic activity that occurs, for example suppliers providing materials) and finally, induced effects (changes in wealth induced by the project).

4.2. Economic objectives

Contrary to social impacts, the most easy to evaluate through a mathematical formulation is the economic objective. It is also probably the most important for the stakeholder's point of view because if the cost is reduced, there is a real short-term interest to be involved in the EIP. In previous studies, there are many and varied ways to formulate an economic indicator and in mono-objective optimization problems, the cost remains the more often used objective to minimize. This formulation can come through:

- the annualization of a global cost, formulated with the net present value (NPV)
- a periodic evaluation of costs,
- a project-based approach where the formulation is done for a well-delimited period (30 years for example).

The great majority of authors use the first category where they define an objective function as the minimization of the annualized cost with several variations between sources. Nobel and Allen (2000) defined their objective function as combination of the cost to purchase, to treat and transport water annually. In 2010, Chae et al. minimized the total energy cost which is the summation of the external energy fuel cost and the waste heat distribution cost to optimize the waste heat utilization network in an eco-industrial park. In the same way, Kim et al. (2010) formulated their objective function as a combination of raw material cost, investment cost and operating cost named total cost to be minimized.

Another approach to evaluate economic performance of EIP's was adopted by Lim and Park (2010). They evaluated the life cycle cost (LCC) to estimate all economic costs incurred from each water system to remodel an industrial park into an EIP. The costs were estimated with the databases consisting of price and information (Korea Price Information, 2006 a,b) and the service life for the LCC was set at 15 years. They found that the most principal contributors to the LCC is first, the consumption of industrial water and then the electricity cost. However, there is still some cost reductions up to 15% in an EIP compared to a conventional industrial park.

The annualized capital cost and operating costs were taken into account by Keirstead et al. (2012) by considering simultaneously the cost of imported fuels, the conversion, the storage and the transportation technologies in one objective function. Finally, Rubio-Castro et al. (2011, 2013) used the total annual cost (TAC) including the freshwater cost, the regeneration cost and the cross-plant pipeline capital cost. It is important to notice that the formulation of the cost objective function highly depends on what kind of network the authors need to optimize. When the water network of an EIP is considered, the cost function will take into account the water cost and the regeneration cost for example (Keckler and Allen, 1999) but it is not representative of the global cost of the EIP.

Another type of formulation takes into account a multi-period evaluation of costs. Hirata et al. (2004) optimized a production site by minimizing the total cost for several planning periods by varying the utility system's operation. Using a similar methodology, Fichtner et al. (2004) evaluated all decision relevant cost based on the net present value method over a time horizon well-defined. This last method consists in evaluating the financial cost generally on a 30 years period which is a project-based approach. Recently, Jung et al. (2013) defined an objective function named cash flow equation, expressed as follows:

$$CF = (NR + CS) - (NI + S + GE) \qquad (1)$$

where CF is the cash flow, NR the net revenue, CS the cost saving, NI the new investment, S the subsidy from government and GE the general expenses. They evaluated the cash flow and the net present value of 18 pilot projects for a 30 year period.

It is important to notice that the cost is evaluated for the total EIP, however, it could also be suitable to introduce an objective or a constraint that forces the several plants to have the same relative gain when they are introduced into the park. Indeed, one key factor is the trust in each partner and the fact that every plant has the same relative gain could contribute to a success in this way. In the study of the literature, no constraint or objective relative to this has been found. Boix et al. (2012) introduced this concept by introducing a constraint so that every plant must have the same gain (in equivalent fresh water).

4.3. Topological objectives

Highly linked to the cost of a network, another objective, often neglected in the literature, is the evaluation of the complexity of the network. The network complexity, that is to say, the number of connections in the total network needs to be considered as it represents an investment cost, and directly traduces the feasibility of a network. By taking into account pipes, binary variables are introduced into the problem formulation, which becomes an MILP (Aviso et al., 2011a; Taskhiri et al., 2011b; Rubio-Castro et al., 2011; Boix et al., 2012). Indeed, each flow in the network is associated to a binary variable equal to zero if the link does not exist, and equal to one otherwise. In previous studies, the number of connections between processes is often formulated as a topological constraint to avoid some impossible links (Rubio-Castro et al., 2011). Some constraints can also be formulated relatively to the topology in order to avoid some nonsensical links as for instance one link constructed for a very small flowrate (Boix et al., 2012). Most of the time, adding these binary variables permits the authors to count the number of linkages in the EIP and thus, to introduce a connection and/or a piping cost to each link. This cost is finally accounted for the total cost of the network (Rubio-Castro et al., 2011).

It is also worth noticing that in an EIP, there is a distinction between internal (in the same plant) and external (inter-plant links) linkages. As noticed by Nobel and Allen (2000) and later by Aviso et al. (2011a), since plants are separated by large distances as compared to distances between processes within a single plant, it is desired that the number of inter-plant link is relatively small to avoid problems of excess network complexity. Despite this assumption, more recently, Tian et al. (2014) proposed a study of the performances of several EIP's in China. In this study, the authors tried to identify the key measures supporting the performance improvement of the EIP's. Among several measures, they underscored that infrastructure sharing is another key aspect for EIP development such as cogeneration of heat and power (CHP) or centralized wastewater treatment plant (CWWTP). Tian et al. (2014) revealed that fifteen out of seventeen Chinese EIPs are equipped with CHPs (using SO_2 scrubbers) that contribute greatly to reduce SO_2 emissions. Integration of CHPs to design industrial symbioses is commonly considered in literature (see e.g. Fernando et al., 2006; Karlsson and Wolf, 2008; Ng et al., 2014). Moreover, the utilization of CWWTP has proved to reduce of 37% the total freshwater consumption of the seventeen Chinese EIPs studied by Tian et al. (2014). Boix et al. (2012) have also shown that in some specific case studies, decentralized or individual waste water treatment units can lead to greater amounts of saved water compared to a CWWTP. In all cases, the installation of different equipments needs a lot of connections between plants and evaluations of EIPs projects encourage to improve symbiotic relations between plants. Boix et al. (2012) considered the number of connections in the EIP as an objective function to minimize. The authors considered the total number of connections in the EIP as their third criteria and showed that this objective function is antagonist to the freshwater consumption. Consequently, it could be wise to minimize the sum of nonsensical inter-plant links and, at the same time, to increase efficient inter-plant exchanges.

4.4. Environmental objectives

Preserving the environment is one of the main motivation of industrial symbioses or development of eco-industrial parks. Optimal design of industrial symbiosis allows to decrease environmental impacts and to promote industrial activities by developing synergies between plants of the EIP. This concept leads to use resources as optimally as possible and consequently, the total environmental impact of economic activities aims to stabilizes and can possibly decreases (Fig. 8).

In the literature, several criteria have been formulated in order to minimize environmental impacts of an eco-industrial park. They can be classified into different categories: objectives formulated to minimize natural resources consumption, impacts formulated through a life cycle assessment approach or objective functions based on the water footprint approach. In the second approach, it is usual to evaluate environmental impacts of the optimal solution found after minimizing the cost.

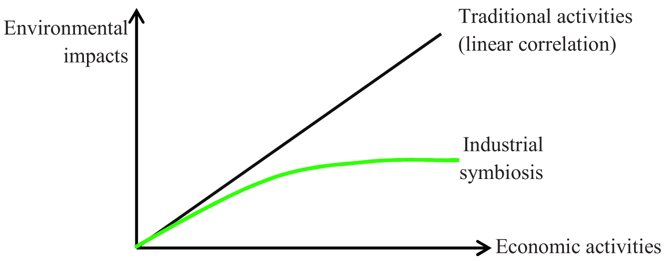

Fig. 8. Decoupling environmental impacts from economic activities through industrial symbiosis (from UVED, 2012).

4.4.1. Resources conservation criteria

In the majority of previous studies, the objective to minimize is the natural resources consumption, mainly freshwater or energy. When the water network of an EIP is designed, the total fresh water flowrate feeding the network is minimized:

$$\mathrm{Min}\sum_{n}\sum_{j}Fw_{j,n} \tag{2}$$

with n the number of companies included in the EIP, j the number of processes in each company and Fw the fresh water consumption. With this approach, Nobel and Allen (2000) minimized the quantity of water used in the network and compared their results obtained under various scenarios (with or without water reuse for example). The same objective was also used by Yoo et al. (2007), Chew et al. (2011), Rubio-Castro et al. (2011) and Boix et al. (2012). More recently, Aviso (2014) also minimized the total freshwater consumption within the EIP under the presence of multiple possible scenarios. For this purpose, the author adapted equation (2) to this case by minimizing the weighted sum of the freshwater consumed (Fw_{jk}) in each scenario k. In this case, the weights are defined by the probability of occurrence of a scenario. Zhu et al. (2010) pointed out that because of growing water-saving awareness, industrialists also need to increase the proportion of recycling water into the network. However, this last criteria can be either maximized if it is considered for environmental concerns (Zhu et al., 2010), or it can also be minimized if the cost of recycling water is taken into account (Boix et al., 2012). In the latter configuration, it becomes an economic indicator.

Following the same approach, for the design of energy sharing network, the total energy consumption needs to be minimized. Hiete et al. (2012) pointed out that energy consumption is reduced through cooperation leading to reduced total cost, despite increased investment related cost. The energy utilities to minimize can be electricity, heat or fuel gases for instance. Kim et al. (2010) also underscored that in addition to economic pressures, environmental concerns must be considered during the design of an EIP to satisfy environmental regulation regimes, such as the Kyoto Protocol. For this reason, optimization of the utility network within an EIP is an essential aspect. As it is also the case for freshwater consumption, the part of total energy consumption often accounted for the total economic cost of the network.

Zhou et al. (2012) focused on the resource conservation criteria by minimizing the coal utilization in a CCEIS in China. They proposed an indicator to evaluate the coal utilization efficiency of the system and attributed weights to each indicator (gross product for economy and CO_2 emissions for environment).

4.4.2. Environmental impact evaluation

In addition to the preservation of natural resources, these last years, the scientific community devoted a great interest in the evaluation of the environmental impacts of an inter-company symbiosis. The most famous tool to evaluate the performance of industrial facilities is the concept of Life Cycle Assessment (LCA).The LCA method is dictated by standards (ISO 14040, ISO 14044) and guidelines (ILCD, 2010) and aims at analyzing the environmental impacts associated to a product. This notion is further extended to evaluate the environmental impacts of a process, company, city or country (Mattila et al., 2012) and consequently, to an EIP. Even if this concept is generally well accepted by the scientific community, it essentially serves to evaluate the impacts of a solution in a post-optimization step. Indeed, there is no work that includes environmental impacts (in the LCA sense) as objective functions of an optimization model. In this section, we will focus on the evaluation of impacts of the optimal configuration of an EIP. Fichtner et al. (2004) is one of the first authors that deal with an analyze of ecological effects of an inter-firm network. In this study, the authors used GaBi 3.0 (1998), which is a life cycle engineering software to complement their optimization of the energy network. Compared to the case where the industries do not cooperate to link energy flows, one of their best economic solutions proposes a decrease of the contribution in global warming of 21% and to acidification of 58%. The other ecological impacts are not commented in the study. Later, Lim and Park (2010) used the same software GaBi 4.0 (2004) and Ecoinvent database (v. 1.2., 2005) databases for the life cycle inventory analysis for the design of a water network system in an EIP (EIPWNS). They compared their results to a conventional water system in a traditional industrial park. The case study is an iron and steel industrial park solved as an NLP with the solver MINOS in GAMS environment. They focused on the necessity of reducing the total carbon footprint of participant's water supply systems what gives meaning to their ecological analysis after the optimization stage. Their results show that the transformation of an industrial park into an EIP leads to environmental impact reduction between 7.5% and 16% depending on the impact category. Finally, they also showed that the environmental impacts are greatly attributed to the operation and maintenance stage (for 98%–100%) compared to all other stages: design and supervision, maintenance and repairs or disposal stage. By using a life cycle inventory (LCI) approach, Sokka et al. (2011) analyzed the 2005 fuel use and greenhouse gases (GHG) emissions of an existing industrial symbiosis centered around pulp and paper manufacturing (Kymi EIP in Finland). Even if there is no optimization step in this study, the authors compared their results to a stand-alone system in which the actors of the system would work individually. They conducted their calculations using the KCL-ECO v4.0 LCA software (2004), after a great step of collecting data from the companies, and from LCA databases (Ecoinvent, 2007) and VAHTI (2008) concerning the production of raw materials, recycling and treatment of wastes. These authors showed that compared to a stand-alone system, CO_2 emissions are drastically reduced up to 75%, which is totally due to a reduction of CO_2 emissions of the key plant of the EIP: the pulp and paper plant. Finally, the authors also focused on the fact that it is important to study an EIP by taking into account upstream processes because they have a large impact on total GHG emissions; an EIP highly depends on its surrounding environment. More recently, Kantor et al. (2012) applied LCA metrics methods to optimize the production of hydrogen in an existing EIP. The authors formulated an objective function constructed by two functions in order to produce a new index for the analysis of an EIP. After a brief review of several methods, they concluded that a new index is required so that it takes into account both environmental management and economic profitability. The part of the objective function regarding environment consists is assessing the reduction in waste and emissions. For each particular emission (CO_2, SO_x, NO_x or Solid Wastes), the difference between the stand-alone facility and the integrated scheme is weighted by the environmental cost of each emissions. This study doesn't mention any LCA software because the authors defined their own objective function which is based on life-cycle concepts without really conducting the LCA methodology. The main improvement to this study would be to model the problem through an MILP instead of an LP to consider the different connections and the whole superstructure of the EIP. Applying LCA to industrial symbioses has been recently further developed by Mattila et al. (2012). In this study, the methodological issues encountered in the application of industrial symbioses are analyzed. The authors pointed out that very few studies applied LCA to the design of industrial symbioses and that is a tool mainly devoted to quantify environmental impacts of existing systems. To conclude with the LCA aspects, the literature review of Boons et al. (2011) evoked the RECIPE (2008) integrative method that combines LCI results with midpoint and endpoint impact categories of LCA. The authors emphasized that LCA encounters some important problems when they are applied to a symbiosis because it is very difficult to move towards a low level of uncertainty (left side of Fig. 9). Indeed, when aggregation of impact categories occurs (endpoint), the level of uncertainty on real environmental impacts drastically increases.

Finally, some recent studies have also evaluated environmental impacts of existing EIP with indicators not taken from LCA concepts and without any optimization stage. For instance, Block et al. (2011) evaluated the feasibility of an industrial park to reach CO_2 neutrality. Jung et al. (2013) evaluated EIP pilot projects in South Korea to determine several performances such as the environmental one. These authors used the MAGIQ method (Multi-Attribute Global Inference of Quality) to evaluate environmental performances. For the calculation of this index, some weights are attributed to the different categories: energy and pollutants and several sublevels into these categories are considered (acid and alkali, waste oil, wastewater, SO_x, etc …). At last, Liu et al. (2014) evaluated the GHG of the Beijing economic technological development area, considered as an industrial park not really eco-efficient.

4.4.3. *Water footprint approach*

Following the same concepts than LCA, the water footprint (Chapagain and Hoekstra, 2004) aims at assessing the water intensity utilization of a product (Velazquez, 2007) a process or more recently to the product brand level (Ridoutt and Pfister, 2010). To a more comprehensive review of differences between LCA and water footprint, the reader can refers to De Benedetto and Klemes (2009). A commonly admitted definition for the total water footprint is written by Chapagain and Hoekstra (2007): the water footprint of a nation can be quantified as the total volume of freshwater that is used to produce the goods and services consumed by the inhabitants of the nation. Aviso et al. (2011b) applied this concept to the optimization of an eco-industrial supply chain. In this fuzzy optimization model, the water footprint of a region k is introduced and constrained between a minimal and a maximal value, the amount of water required to produce goods for local consumption is the total water footprint. In this study, the authors developed a multi-regional fuzzy input–output model to optimize under water footprint constraints. This approach is relevant as it allows considering the environmental impacts relative to water of the whole supply chain and also considers the surrounding

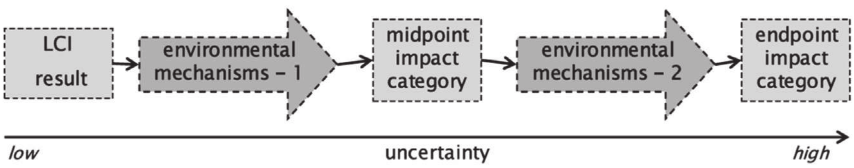

Fig. 9. RECIPE 2008, modified from Boons et al. (2011).

environment where the EIP is located. One of the main aspect of this work is to provide a link between LCA methodology (usually applied to a product) and industrial symbiosis concepts. The authors show that the design of an EIP implying improvements to the design of individual industries influences the LCA performance of the system.

5. Analyses and perspectives

As specified by Chertow (2004), “an eco-industrial park may include many ecologically desirable goals, including mechanisms to reduce overall environmental impact, conserve materials and energy, and foster cooperative approaches to resource efficiency and environmental management”. This definition directly refers to the concept of a circular economy within an industrial area, where a goal of zero waste needs to be reached. Indeed, by minimizing environmental impacts, symbiotic relations have to be increased to maximize the resources recycling within the EIP. To attain this aim, the implementation of different methodologies are primordial; these methodologies can be heuristic, more easy to solve but limited to small problems, or, in the case of EIP (large-scale problems), optimization methods can be applied to solve more complex problems. Regarding the literature review done in this study, it is obvious that EIP are promising solutions to reduce environmental impacts and improve economic profitability as well as societal aspects of industrial development. On the first hand, numerous examples of EIP's are present all over the world and are the subject, after their realization, to evaluations through several indices (see Section 3.4). On the other hand, optimization helps to design better systems that can satisfy one or several objective functions while following constraints. This literature review about optimization of EIPs permits to give rise to some gaps in these research fields.

One of the major issues is the lack of multiobjective optimization studies applied to the design of EIP. Indeed, even if most of the studies evoked in this work, deal with optimization, only a few consider several objective functions simultaneously. This field is a great challenge because the design of an EIP implies, by definition, the satisfaction of three essential pillars: environmental, economic and social. The problem of EIP design is typically a multiobjective problem.

Some improvements have to be done in this way regarding the mathematical formulation of objective functions. Most of the previous studies focused on minimizing the total or global cost of the network which is relatively easy to traduce mathematically. However, what gives concern is to formulate one or several environmental objective functions that can be take into account in the optimization problem resolution. The evaluation of environmental impacts (through LCA approach for instance) after being optimized can only notice but cannot improve a solution. The formulation of environmental objective function is a key development to reach environmental optimal solutions. A promising development in this way could be the water footprint approach (Aviso et al., 2011b), that can also be extended to carbon footprint. This indicator could be formulated as an objective function to minimize in the model formulation.

A relevant perspective for future works will be to formulate a social-related objective function. Some attempts have been reported to quantify social impact of an EIP, like the index based on the creation of jobs (Hipolito-Valencia et al., 2014), but these formulations needs to be improved. These improvements will come through cooperation with socio-economic research communities.

At the present state, the optimization of EIP lies on the decoupling of networks. In the literature review, it is emphasized that authors optimized either the water network, or the energy links or waste disposal facilities but never the whole networking. However, it is important to optimize simultaneously the water and the energy network because these networks have to interact (through exchange of steam for instance) to increase the symbiotic relations among industries in an EIP. This issue also raises the specific barrier to collect a lot of data relative to each plant of the potential EIP. Facing this issue, a lot of fictive problems have been created to validate methodologies (Boix et al., 2012).

In the field of EIPs, another important issue is to consider uncertainties over energy supplies, and more particularly for renewable energy sources. Indeed, more realistic model would include a discretization over the time in several periods, so that it can considers variability of energy supplies. According to Nemet et al. (2012) daily cycles and/or variability of renewable energy supplies can be accounted following two approaches: dynamic formulation or multiperiod model. However, the authors underlined that dynamic models are unsuitable for design or long-horizon operational optimization. The model developed by Nemet et al. (2012) and further automated and improved by Liew et al. (2014b) is a graphical methodology based on the time slices (TSL) method (Varbanov and Klemes, 2010). Although this method is a very helpful tool to consider short-term variability, other important variations like seasonality and long-term variations in energy availability are not yet considered in the design of a total site or an EIP.

The notion of flexibility and parameters uncertainty that have been recently explored by Montastruc et al. (2013) are also fundamental for the design of an EIP. In this study, the authors studied the feasibility of a particular design by applying some changes in the parameters of one of the plants included in the EIP. Indeed, it is important to explore the consequences of a change in the production of one particular plant included in the EIP. It has been shown that the optimal solution remains highly rigid in this case and the same optimal design cannot be adopted. An interesting perspective, particularly adapted to the optimization of EIP, could be the game theory approach. Game theory is defined by Myerson (1991) as “the study of mathematical models of conflict and cooperation between intelligent rational decision-makers.” The author adds that game theory provides general mathematical techniques for analyzing situations in which two or more individuals make decisions that will influence one another's welfare. Another game theory based work applied on industrial ecosystem, is the work of Lou et al. (2004). These authors studied the possible conflicts of the profit and sustainability objectives of the member entities with the Nash Equilibrium identification. They applied the methodology to a very simple industrial system with two plants involved and they also took into account uncertainties. They obtained conflicting results when they evaluated the system with the Nash Equilibrium and with the environmental evaluation. In this way, Chew et al. (2009) developed the game theory approach in analyzing decision making for water integration in an EIP. Even if the authors provided a tool to analyze the action of each participating companies, it is necessary to develop the model by diversifying the rules of the game. For example, it is important to explore the option where power relationships between plants are not perfectly equal.

Our future researches will focus on the development of robust optimization methods that can allow to deal with complex problems (which is the case with EIP), with multiobjective optimization and that will take into account several periods formulation. The flexibility of the optimal solution could be studied in a post-optimization step. At last, another important development will also consider the surrounding environment of an EIP. The natural resources available, as well as social and economic situation of the region, which is fundamental to evaluate total impacts of EIPs. To reach this aim it is expected to use for instance geographical information system software to link geographic and demographic data to the optimization model so that the optimal EIP will reach symbiotic relation with its environment.

References

Alexander, B., Barton, G., Petrie, J., Romagnoli, J., 2000. Process synthesis and optimization tools for environmental design: methodology and structure. Comput. Chem. Eng. 24, 1195–1200.
Allenby, B., 2004. Clean production in context: an information infrastructure perspective. J. Clean. Prod. 12, 833–839.
Allenby, B., 2006. The ontologies on industrial ecology? Progress in industrial ecology. Annu. Int. J. 3 (1–2), 28–40.
Ashton, W., 2008. Understanding the organization of industrial ecosystems: a social network approach. J. Ind. Ecol. 12, 34–51.
Ashton, W., 2009. The structure, function, and evolution of a regional industrial ecosystem. J. Ind. Ecol. 13, 228–246.
Aviso, K.B., Tan, R.R., Culaba, A.B., 2010a. Designing eco-industrial water exchange networks using fuzzy mathematical programming. Clean. Technol. Environ. Policy 12, 353–363.
Aviso, K.B., Tan, R.R., Culaba, A.B., Cruz Jr., J.B., 2010b. Bi-level fuzzy optimization approach for water exchange in eco-industrial parks. Process Saf. Environ. Prot. 88, 31–40.
Aviso, K.B., Tan, R.R., Culaba, A.B., Foo, D.C.Y., Hallale, N., 2011a. Fuzzy optimization of topologically constrained eco-industrial resource conservation networks with incomplete information. Eng. Optim. 43, 257–279.
Aviso, K.B., Tan, R.R., Culaba, A.B., Cruz Jr., J.B., 2011b. Fuzzy input-output model for optimizaing eco-industrial supply chains under water footprint constraints. J. Clean. Prod. 19, 187–196.
Aviso, K.B., 2014. Design of robust water exchange networks for eco-industrial symbiosis. Process Saf. 92, 160–170.
Bagajewicz, M.J., Rodera, H., 2000. Energy savings in the total site. Heat integration across many plants. Comput. Chem. Eng. 24, 1237.
Block, C., Van Praet, B., Windels, T., Vermeulen, I., Dangreau, G., Overmeire, A., D'Hooge, E., Maes, T., Van Eetvelde, G., Vandecasteele, C., 2011. Toward a carbon dioxide neutral industrial park – a case study. J. Ind. Ecol. 15, 584–596.
Boix, M., Montastruc, L., Pibouleau, L., Azzaro-Pantel, C., Domenech, S., 2011. Eco industrial Parks for water and heat management. In: Pistikopoulos, E.N., Georgiadis, M.C., Kokossis, A.C. (Eds.), 21st European Symposium on Computer Aided Process Engineering. Elsevier Science Bv, Amsterdam, pp. 1175–1179.
Boix, M., Montastruc, L., Pibouleau, L., Azzaro-Pantel, C., Domenech, S., 2012. Industrial water management by multiobjective optimization: from individual to collective solution through eco-industrial parks. J. Clean. Prod. 22, 85–97.
Boons, F.A., Howard-Grenville, J.A., 2009. The Social Embeddedness of Industrial Ecology. Edward Elgar Publishing Ltd, Cheltenham.
Boons, F., Spekkink, W., Mouzakitis, Y., 2011. The dynamics of industrial symbiosis: a proposal for a conceptual framework based upon a comprehensive literature review. J. Clean. Prod. 19, 905–911.
Brundtland, G., Khalid, M., Agnelli, S., Al-Athel, S.A., Chidzero, B., Fadika, L.M., et al., 1987. Our Common Future: the World Commission on Environment and Development. Oxford University Press, Oxford, 1987.
Chae, S.H., Kim, S.H., Yoon, S.-G., Park, S., 2010. Optimization of a waste heat utilization network in an eco-industrial park. Appl. Energy 87, 1978–1988.
Chapagain, A.K., Hoekstra, A.Y., 2004. Water footprints of nations. In: Value of Water Research Report Series, vol. 16. UNESCO-IHE, Delft, the Netherlands.
Chapagain, A.K., Hoekstra, A.Y., 2007. The water footprint of coffee and tea consumption in the Netherlands. Ecol. Econ. 64, 109–118.
Chew, I.M.L., Foo, D.C.Y., 2009. Automated targeting for inter-plant water integration. Chem. Eng. J. 153, 23–36.
Chew, I.M.L., Tan, R., Ng, D.K.S., Foo, D.C.Y., Majozi, T., Gouws, J., 2008. Synthesis of direct and indirect interplant water network. Ind. Eng. Chem. Res. 47, 9485–9496.
Chew, I.M.L., Tan, R.R., Foo, D.C.Y., Chiu, A.S.F., 2009. Game theory approach to the analysis of inter-plant water integration in an eco-industrial park. J. Clean. Prod. 17, 1611–1619.
Chew, I.M.L., Foo, D.C.Y., Ng, D.K.S., Tan, R.R., 2010a. Flowrate targeting algorithm for interplant resource conservation network. Part 1: unassisted integration scheme. Ind. Eng. Chem. Res. 49, 6439–6455.
Chew, I.M.L., Foo, D.C.Y., Tan, R.R., 2010b. Flowrate targeting algorithm for interplant resource conservation network. Part 2: assisted integration scheme. Ind. Eng. Chem. Res. 49, 6456–6468.
Chew, I.M.L., Thillaivarrna, S.L., Tan, R.R., Foo, D.C.Y., 2011. Analysis of inter-plant water integration with indirect integration schemes through game theory approach: pareto optimal solution with interventions. Clean. Technol. Environ. Policy 13, 49–62.
Chertow, M., 2000. Industrial symbiosis: literature and taxonomy. Annu. Rev. energy Environ. 25, 313–337.
Chertow, M., 2004. Industrial symbiosis. Encycl. Energy 3, 407–415.
Cimren, E., Fiksel, J., Posner, M.E., Sikdar, K., 2012. Material flow optimization in by-product synergy networks. J. Ind. Ecol. 15, 315–332.
Connelly, L., Koshland, C.P., 2001a. Exergy and industrial ecology - Part 1: an exergy-based definition of consumption and a thermodynamic interpretation of ecosystem evolution. Exergy Int. J. 1, 146–165.
Connelly, L., Koshland, C.P., 2001b. Exergy and industrial ecology. Part 2: a non-dimensional analysis of means to reduce resource depletion. Exergy Int. J. 1, 234–255.
CPLEX Optimization, Inc, 1995. Using the CPLEX Callable Library. CPLEX Optimization, Inc, Incline Village, NV.
Czogala, E., Zimmermann, H.-J., 1986. Decision making in uncertain environments. Eur. J. Oper. Res. 23, 202–212.
De Benedetto, L., Klemes, J., 2009. The environmental performance strategy map: an integrated LCA approach to support the strategic decision-making process. J. Of Clean. Prod. 17, 900–906.
Dhole, V.R., Linnhoff, B., 1992. Total site targets for fuel, cogeneration, emissions, and cooling. Comput. Chem. Eng. 17, S101.
Ecoinvent database, v.1.2, 2005. Swiss Center for Life Cycle Inventories. Ecoinvent data version 1.2.
Ecoinvent database, v.2.01, 2007. Swiss Center for Life Cycle Inventories. Ecoinvent data version 2.01.
Ehrenfeld, J., Gertler, N., 1997. Industrial ecology in practice: the evolution of interdependence at kalundborg. J. Ind. Ecol. 1, 67–79.
El-Halwagi, M.M., 1997. Pollution Prevention Through Process Integration – Systematic Design Tools. Academic Press, CA, USA, ISBN 978-0-12-236845-5.
El-Halwagi, M.M., Gabriel, F., Harell, D., 2003. Rigorous graphical targeting for resource conservation via material recycle/reuse networks. Ind. Eng. Chem. Res. 42, 4319–4328.
El-korchi, A., Millet, D., 2011. Designing a sustainable reverse logictics channel : the 18 generic structures framework. J. Clean. Prod. 19, 588–597.
Erol, P., Thöming, J., 2005. Eco-design of reuse and recycling networks by multi-objective optimisation. J. Clean. Prod. 13, 1449–1460.
Fernando, S., Adhikari, S., Chandrapal, C., Murali, N., 2006. Biorefineries: current status, challenges, and future direction. Energy Fuels 20, 1727–1737.
Fichtner, W., Frank, M., Rentz, O., 2004. Inter-firm energy supply concepts: an option for cleaner energy production. J. Clean. Prod. 12, 891–899.
Foo, D.C.Y., 2008. Flowrate targeting for threshold problems and plant-wide integration for water network synthesis. J. Environ. Manag. 88, 253–274.
Francis, C.G., 2003. The chemical industry from an industrial ecology perspective. In: Bourg, D., Erkman, S. (Eds.), Perspectives on Industrial Ecology. Greenleaf Publishing Limited, Sheffield, UK, pp. 120–134.
Frosh, R.A., Gallopoulos, N.E., 1989. Strategies for manufacturing. Sci. Am. 261, 144–152.
Gabi 4.0 Software, 2004. IKP, PE Europe GMBH.
GAMS, 2005. A User Guide. GAMS Development Corporation, Washington DC.
Gussow, D., Meyers, J., 1970. Industrial Ecology, vol. 1.
Hardy, C., Graedel, T.E., 2002. On the concept of industrial ecology. J. Ind. Ecol. 6, 29–38.
Haslenda, H., Jamaludin, M.Z., 2011. Industry-to-industry by-products exchange network towards the zero waste in palm oil refining processes. Resour. Conserv. Recycl. 55, 713–718.
Heeres, R.R., Vermeulen, W.J.V., de Walle, F.B., 2004. Eco-industrial park initiatives in the USA and the Netherlands: first lessons. J. Clean. Prod. 12, 985–995.
Hiete, M., Ludwig, J., Schultmann, F., 2012. Intercompany Energy integration adaptation of Thermal pinch analysis and allocation of savings. J. Ind. Ecol. 16, 689–698.
Hipolito-Valencia, B.J., Lira-Barragan, L.F., Ponce-Ortega, J.M., Serna-Gonzalez, M., El-Halwagi, M.M., 2014. Multiobjective design of interplant trigeneration systems. AIChE J. 60, 213–236.
Hirata, K., Sakamoto, H., O'Young, L., Cheung, K.Y., Hui, C.W., 2004. Multi-site utility integration – an industrial case study. Comput. Chem. Eng. 28, 139–148.
Hoffman, C., 1971. The Industrial Ecology of Small and Intermediate-sized Technical Companies: Implications for Regional Economic Development. Report Prepared for the Economic Development Administration COM-74-10680. Texas University, USA.
Hui, C.W., Ahmad, S., 1994. Total site heat integration using the utility system. Comput. Chem. Eng. 18, 729.
IEAT, Industrial Estate Authority of Thailand, 2010. Annual Report of 2009, p. 43. Available from: URL: http://www.ieat.go.th.
ILCD, International Reference Life Cycle Data System, 2010. General Guide for Life Cycle Assessment (LCA) – Detailed Guidance. Joint Research Centre, Institute for Environment and Sustainability, Ispra, italy.
ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization, Geneva, Switzerland.
ISO 14044: Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization, Geneva, Switzerland.
Jacobsen, N.B., 2006. Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects. J. Ind. Ecol. 10, 239–255.
Jung, S., Dodbiba, G., Chae, S.H., Fujita, T., 2013. A novel approach for evaluating the performance of eco-industrial park pilot projects. J. Clean. Prod. 39, 50–59.
Kantor, I., Fowler, M., Elkamel, A., 2012. Optimized production of hydrogen in an eco-park network accounting for life-cycle emissions and profit. Int. J. Hydrog. Energy 37, 5347–5359.
Karimkashi, S., Amidpour, M., 2012. Total site energy improvement using air-curve concept. Energy 40, 329–340.
Karlsson, M., 2011. The MIND method: a decision support for optimization of industrial energy systems – principles and case studies. Appl. Energy 88, 577–589.

Karlsson, M., Wolf, A., 2008. Using an optimization model to evaluate the economic benefits of industrial symbiosis in the forest industry. J. Clean. Prod. 16, 1536–1544.
Karuppiah, R., Grossmann, I.E., 2008. Global optimization of multiscenario mixed integer nonlinear programming models arising in the synthesis of integrated water networks under uncertainty. Comput. Chem. Eng. 32, 145–160.
Kasivisvanathan, H., Ng, R.T.L., Tay, D.H.S., Ng, D.K.S., Foo, D.C.Y., Kamal, M., Hallaler, N., Klemes, J.J., 2012. An algebraic approach to identifying bottlenecks in linear process models of multifunctional energy systems. Theor. Found. Chem. Eng. 46, 642–650.
KCL-ECOinvent database, V1.2, 2005. Swiss Center for Life Cycle Inventories. Ecoinvent data version 1.2.
Keckler, S.E., Allen, D.T., 1999. Material reuse modeling: a case study of water reuse in an industrial park. J. Ind. Ecol. 2, 79–92.
Keirstead, J., Samsatli, N., Pantaleo, A.M., Shah, N., 2012. Evaluating biomass energy strategies for a UK eco-town with an MILP optimization model. Biomass Bioenergy 39, 306–316.
Kim, S.H., Yoon, S.-G., Chae, S.H., Park, S., 2010. Economic and environmental optimization of a multi-site utility network for an industrial complex. J. Environ. Manag. 91, 690–705.
Klugman, S., Karlsson, M., Moshfegh, B., 2009. A Swedish integrated pulp and paper mill – Energy optimisation and local heat cooperation. Energy Policy 37, 2514–2524.
Korea Price Information, vol. 422, 2006. The Price Information, Corp., Seoul, South Korea.
Korea Price Information, 2006. The Cost Estimation, Corp., Seoul, South Korea.
Korhonen, J., 2001. Four ecosystem principles for an industrial ecosystem. J. Clean. Prod. 9, 253–259.
Liao, Z.W., Wu, J.T., Jiang, B.B., Wang, J.D., Yang, Y.R., 2007. Design methodology for flexible multiple plant water networks. Ind. Eng. Chem. Res. 46, 4954–4963.
Liew, P.Y., Wan Alwi, S.R., Varbanov, P.S., Manan, Z.A., Klemes, J.J., 2013. Centralised utility system planning for a total site heat integration network. Comput. Chem. Eng. 57, 104–111.
Liew, P.Y., Wan Alwi, S.R., Lim, J.S., Varbanov, P.S., Klemes, J.J., Manan, Z.A., 2014a. Total site heat integration incorporating the water sensible heat. J. Clean. Prod. 77, 94–104.
Liew, P.Y., Wan Alwi, S.R., Varbanov, P.S., Klemes, J.J., Manan, Z.A., 2014b. Algorithmic targeting for total site heat integration with variable energy supply/demand. Appl. Therm. Eng. 70, 1073–1083.
Lim, S.-R., Park, J.M., 2010. Interfactory and intrafactory water network system to remodel a conventional industrial park to a Green eco-industrial park. Ind. Eng. Chem. Res. 49, 1351–1358.
Lim, J.S., Manan, Z.A., Wan Alwi, S.R., Hashim, H., 2013a. A multiperiod model for optimal planning of an integrated, resource-efficient rice mill. Comput. Chem. Eng. 52, 77–89.
Lim, J.S., Manan, Z.A., Hashim, H., Wan Alwi, S.R., 2013b. Optimal multi-site resource allocation and utility planning for integrated rice mill complex. Ind. Eng. Chem. Res. 52, 3816–3831.
Lim, J.S., Manan, Z.A., Hashim, H., Wan Alwi, S.R., 2013c. Towards an integrated, resource-efficient rice mill complex. Resources. Conserv. Recycl. 75, 41–51.
Liu, W., Tian, J., Chen, L., 2014. Greenhouse gas emissions in China's eco-industrial parks: a case study of the Beijing economic technological development area. J. Clean. Prod. 66, 384–391.
Lou, H., Kulkarni, M., Singh, A., Huang, Y., 2004. A game theory based approach for emergy analysis of industrial ecosystem under uncertainty. Clean Technol. Environ. Policy 6, 156–161.
Lovelady, E.M., El-Halwagi, M.M., 2009. Design and integration of eco-industrial parks for managing water resources. Environ. Prog. Sustain. Energy 28, 265–272.
Lovelady, E.M., El-Halwagi, M.M., Chew, I.M.L., Ng, D.K.S., Foo, D.C.Y., Tan, R.R., 2009. A property-integration approach to the design and integration of eco-industrial parks. In: 7th International Conference on Foundations of Computer-aided Process Design (FOCAPD), Colorado, USA, 2009.
Lowe, E.A., 1997. Creating by-product resource exchanges: strategies for eco-industrial parks. J. Clean. Prod. 5, 57–65.
Maes, T., Van Eetvelde, G., De Ras, E., Block, C., Pisman, A., Verhofstede, B., Vandendriessche, F., Vandevelde, L., 2011. Energy management on industrial parks in Flanders. Renew. Sustain. Energy Rev. 15, 1988–2005.
Massard, G., Jacquat, O., Wagner, L., Zürcher, D., 2012. International Survey on Eco-innovation Parks – Learning's from Experiences on the Spatial Dimension of Eco-innovation. Bundesamt für Umwelt BAFU, Swiss Confederation, p. 295.
Mattila, T., Lehtoranta, S., Sokka, L., Melanen, M., Nissinen, A., 2012. Methodological aspects of applying life cycle assessment to industrial symbioses. J. Ind. Ecol. 16, 51–60.
Mirata, M., 2004. Experiences from early stages of a national industrial symbiosis programme in the UK: determinants and coordination challenges. J. Clean. Prod. 12, 967–983.
Montastruc, L., Boix, M., Pibouleau, L., Azzaro-Pantel, C., Domenech, S., 2013. On the flexibility of an eco-industrial park (EIP) for managing industrial water. J. Clean. Prod. 43, 1–11.
Myerson, R.B., 1991. Game Theory: Analysis of Conflict. Harvard University Press, London.
Nemet, A., Klemes, J.J., Varbanov, P.S., Kravanja, Z., 2012. Methodology for maximising the use of renewables with variable availability. Energy 44, 29–37.
Ng, R., Ng, D., Tan, R., El-Halwagi, M., 2014. Disjunctive fuzzy optimization for planning and synthesis of bioenergy based industrial symbiosis systems. J. Environ. Chem. Eng. 2, 652–664.
Nielsen, R., 2005. The Little Green Handbook. Picador, New-York.
Nobel, C.E., Allen, D.T., 2000. Using Geographic Information Systems (GIS) in industrial water reuse modelling. Process Saf. Environ. Prot. 78, 295–303.
Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. Wiley, New-York.
Olesen, S.G., Polley, G.T., 1996. Dealing with plant geography and piping constraints in water network design. Process Saf. Environ. Prot. 74, 273–276.
Olesen, S.G., Polley, G.T., 1997. A simple methodology for the design of water networks handling single contaminants. Chem. Eng. Res. Des. 75, 420–426.
Panyathanakun, V., Tantayanon, S., Tingsabhat, C., Charmondusit, K., 2013. Development of eco-industrial estates in Thailand: initiatives in the northern region community-based eco-industrial estate. J. Clean. Prod. 51, 71–79.
PCSD, President's Council on Sustainable Development, 1996. In: Eco-industrial Park Workshop Proceedings. Washington (DC), 1996.
RECIPE, 2008. Based on a report published in January 2009. http://www.lcia-recipe.net/.
Ridoutt, B.G., Pfister, S., 2010. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. Glob. Environ. Change 20, 113–120.
Rubio-Castro, E., Ponce-Ortega, J.M., Serna-González, M., Jimenez Gutierrez, A., El-Halwagi, M.M., 2010. Water integration of eco-industrial parks using a global optimization approach. Ind. Eng. Chem. Res. 49, 9945–9960.
Rubio-Castro, E., Ponce-Ortega, J.M., Serna-González, M., Jimenez Gutierrez, A., El-Halwagi, M.M., 2011. A global optimal formulation for the water integration in eco-industrial parks considering multiple pollutants. Comput. Chem. Eng. 35, 1558–1574.
Rubio-Castro, E., Ponce-Ortega, J.M., Serna-González, M., El-Halwagi, M.M., 2012. Optimal reconfiguration of multi-plant water networks into an eco-industrial park. Comput. Chem. Eng. 44, 58–83.
Rubio-Castro, E., Ponce-Ortega, J.M., Serna-González, M., El-Halwagi, M.M., Pham, V., 2013. Global optimization in property-based interplant water integration. AIChE J. 59, 813–833.
Shiun, L.J., Hachim, H., Manan, Z.A., Wan Alwi, S.R., 2011. Optimal design of a rice mill utility system with rice husk logistic network. Ind. Eng. Chem. Res. 51, 362–373.
Sokka, L., Pakarinen, S., Melanen, M., 2011. Industrial symbiosis contributing to more sustainable energy use – an example from the forest industry in Kymenlaakso, Finland. J. Clean. Prod. 19, 285–293.
Spriggs, D., Lowe, E., Watz, J., El-Halwagi, M.-M., Lovelady, E.M., 2004. Design and development of eco-industrial parks. In: AIChE Spring Meeting 2004, New Orleans.
Starfelt, F., Yan, J., 2008. Case study of energy systems with gas turbine technology for an Eco-industrial Park. Int. J. Energy Res. 32, 1128–1135.
Takama, N., Kuriyama, T., Shiroko, K., Umeda, T., 1980. Optimal water allocation in a petroleum refinery. Comput. Chem. Eng. 4, 251–258.
Tan, R.R., Aviso, K.B., Cruz Jr., J.B., Culaba, A.B., 2011. A note on an extended fuzzy bi-level optimization approach for water exchange in eco-industrial parks with hub topology. Process Saf. Environ. Prot. 89, 106–111.
Taskhiri, M.S., Tan, R.R., Chiu, A.S.F., 2011a. Emergy-based fuzzy optimization approach for water reuse in an eco-industrial park. Resour. Conserv. Recycl. 55, 730–737.
Taskhiri, M.S., Tan, R.R., Chiu, A.S.F., 2011b. MILP model for emergy optimization in EIP water networks. Clean. Technol. Environ. Policy 13, 703–712.
Tian, J., Lie, W., Lai, B., Li, X., Chen, L., 2014. Study on the performance of eco-industrial park development in China. J. Clean. Prod. 64, 486–494.
Tiejun, D., 2010. Two quantitative indices for the planning and evaluation of eco-industrial parks. Resour. Conserv. Recycl. 54, 442–448.
Tietze-Stöckinger, I., Fichtner, W., Rentz, O., 2004. A model to minimise joint total costs for industrial waste producers and waste management companies. Waste Manag. Res. 22, 466–476.
Tudor, T., Adam, E., Bates, M., 2007. Drivers and limitations for the successful development and functioning of EIPs (eco-industrial parks): a literature review. Ecol. Econ. 61, 199–207.
Ulgiati, S., Brown, M., 2009. Emergy and ecosystem complexity. Commun. Nonlinear Sci. Numr. Simul. 14, 310–321.
UNEP, United Nations Environmental Programme, 2000. Global Environmental Outlook 2000. Earthscan, London.
UNESCO, United Nations Educational Scientific and Cultural Organization, 2009. Water in a Changing World. The United Nations World Water Development. Report 3.
UVED, 2012. Université Virtuelle Environnement et Développement durable. In french. Last access online in 2014. www.uved.fr.
VAHTI Database, 2008. Finnish Environmental Administration, Finland.
Varbanov, P., Klemes, J.J., 2010. Total sites integrating renewables with extended heat transfer and recovery. Heat. Transf. Eng. 31, 733–741.
Varbanov, P.S., Fodor, Z., Klemes, J.J., 2012. Total site targeting with process specific minimum temperature difference (dt_{min}). Energy 44, 20–28.
Velazquez, E., 2007. Water trade in Andalusia. Virtual water: an alternative way to manage water use. Ecol. Econ. 63, 201–208.
Wang, Y.P., Smith, R., 1994. Wastewater minimization. Chem. Eng. Sci. 49, 981–1006.
Wang, Y.P., Smith, R., 1995. Time pinch analysis. Trans. Inst. Chem. Eng. 73a, 905–914.

Watanabe, C., 1972. Industrial-ecology: Introduction of Ecology into Industrial Policy. Ministry of International Trade and Industry (MITI), Tokyo.
Yoo, C.-K., Lee, T.-Y., Kim, J., Moon, I., Jung, J.-H., Han, C., Oh, J.-M., Lee, I.-B., 2007. Integrated water resource management through water reuse network design for clean production technology: state of the art. Korean J. Chem. Eng. 24, 567–576.
Zhou, L., Hu, S.-Y., Li, Y., Jin, Y., Zhang, X., 2012. Modeling and optimization of a coal-chemical eco-industrial system in China. J. Ind. Ecol. 16, 105–118.
Zhu, L., Zhou, J., Cui, Z., Liu, L., 2010. A method for controlling enterprises access to an eco-industrial park. Sci. Total Environ. 408, 4817–4825.