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Industrial By-Product Reuse and Synergy Optimization

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Abstract. By-products synergy is a growing practice worldwide. It consists in the maximization of resources utilization with the replacement of raw materials by by-products as inputs for industrial processes. In order to support decision-making in such strategic projects, appropriate tools must be developed. This article presents the results of a research project, which includes the development of a multi-objective mathematical programming model for the optimization of by-products flows, synergy configurations and investment decisions in eco-industrial networks. This model is evaluated using data related to the Kalundborg industrial symbiosis in order to illustrate its utilization, as well as to assess, in a retrospective manner, the behaviour of the companies involved with respect to both economic and environmental benefits of synergies. The experiments also illustrate the influence of the municipality on synergy implementation, and how a scenario-based approach can be used to anticipate raw materials price increase. The results are generally coherent with the actual timing of synergy initializations. Furthermore, the considerable effect of water price on the length of investments' payback period illustrates the impact of policies and regulations on industrial symbiosis.

Keywords: Eco-industrial park, industrial symbiosis, multi-objective optimization, decision support system, by-product synergies.

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Introduction

Industrial symbiosis is part of the recent field of industrial ecology that aims to promote effluents, energy flows and solid waste exchanges. To put this idea in practice, by-product synergy networks are today growing all around the world, either in defined regions or within industrial parks. Industrial synergies are business relationships between two or more companies, which aims to optimize resources utilization through industrial waste utilization or other forms of resources sharing. As observed by Sakr *et al*. (2011), even if a high degree of collaboration is needed between the participants in a symbiosis, it is not always sufficient. Lessons from past projects also demonstrate that industrial ecosystems developed in a network perspective are more efficient than industrial ecosystems developed from an isolated-enterprise point of view (Haskins, 2006). Therefore, independent network facilitators can often play a critical role in the success of these initiatives (Kincaid and Overcash, 2001).

In this context, this article presents a multi-period and multi-objective mathematical optimization model, which can be used in different contexts. First, this model aims to support the development of industrial symbiosis by identifying optimal industrial by-product and waste reuse in a network of potential partnerships. Second, this model also optimizes synergy configuration with respect to inventory location, as well as waste transformation and treatment technology choice. Consequently, this mathematical optimization model can be use either by a network facilitator to develop an efficient industrial symbiosis, or by a single company to plan the strategic development of its symbiotic relationship.

The multi-period nature of this model allows for the modeling of the decision-making context over several time periods, in order to capture the potential trends of some parameters. Similarly, thanks to its multi-objective structure, this optimization model can also be used to analyze the trade-off between environmental and economic benefits of by-products synergies. Indeed, studies have shown that even if the first motivation behind eco-industrial projects seems to be the preservation of natural resources and the improvement of waste management strategies, economic feasibility is essential to obtain companies' involvement (Lehtoranta *et al*., 2011). In the literature, several systems designed to identify and assess symbiotic opportunities have been proposed. However, logistic and operational feasibility, as well as the dynamic nature of eco-industrial decision contexts and relations are often neglected. Therefore, since supply chain designers must also such challenges, the use of tools generally used in supply chain design seems adapted to the context of industrial symbiosis design.

Literature review

Industrial ecology is defined by Chertow (2004) as "the study of flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory and social factors on the flow, use, and transformation of resources". Its global objective is to reduce the environmental and economic impacts related to intensive natural resources use (Adoue, 2007). Industrial symbiosis is a subset of this field focusing on exchanges of materials, energy, water and by-products through businesses networks. As suggested by the term, the idea, on which this concept is based, is to reproduce the behavior of natural ecosystems, in which the waste of a species becomes a resource for another, in industrial networks (Frosch & Gallopoulos, 1989). The eco-park of Kalundborg, Denmark is the most documented in the literature. Therefore, it was chosen in order to illustrate a context of use of the proposed mathematical optimization model. Many other eco-industrial networks have been investigated to identify the key success factors of industrial symbiosis (Haskins, 2006). Among others, synergies identification and assessment steps have to be assisted with relevant tools, such as the one introduced in this paper.

Many tools have been developed in the last few years in order to help managers and network facilitators find by-product exchanges opportunities. Grant *et al*. (2010) have surveyed seventeen of them, including Presteo, which proposes its own terminology to describe flows, and FaST (Facility Synergy Tool), developed by the Environmental Protection Agency (EPA). The authors compared their functionalities, strengths and weaknesses and evaluated opportunities for improvement. Chertow (2000) classifies these tools under three categories: input-output matching, stakeholder processes and materials budgeting. Many of these tools aim to support the process of matching companies with respect to their input-output compatibility.

In order to do this, information about the flows and availability of materials must be collected and analyzed. Eckelman & Chertow (2009) and Hsiao *et al*. (2002) show how Material Flow Analysis (i.e., MFA) can be used to identify resources reuse, by presenting case studies in Oahu Island, Hawaii and Taiwan. Once found, potential synergies must be analyzed and selected based on their benefits. The Eco-flow software uses mathematical programming to design such networks by minimizing weighted sum of costs and environmental impacts of material flows. Revenues from the sale of by-product material are treated as negative cost, which makes this model equivalent to a profit maximization model. Cimren *et al*. (2011) present an application of this tool to analyze potential synergies in an industrial symbiosis project in North America. Although this software is useful to analyze network configuration alternatives and minimize cost, it gives a static view of the eco-industrial network. Furthermore, synergy costs and benefits are analytically compared within a single time period, which may exclude relatively costly synergy setup when the length of this time period is too short (i.e., not enough revenue generated). Along the same line, Li *et al*. (2011) evaluate sorting strategies and their impact on scrap materials consumption. Similarly, in the context of water reuse, Keckler & Allen (1998) propose an optimization model, which aims to minimize distribution and treatment cost by evaluating different network configurations. Karlsson & Wolf (2008) also introduce an optimization method to support the organization and the planning of industrial synergies in the forest industry, which compares network design scenarios based on their economic implication.

In supply chain design, location-allocation optimization models are used to, on the one hand, allocate the production and distribution of goods to factories and distribution centers, and, on the other hand, optimize the location of production facilities or distribution centers, as well as technology selection with respect to equipment conversion and acquisition (Ulstein *et al.*, 2006). These issues are similar whether flows involve finished goods, virgin raw materials or by-products. However, green supply chain design and management take into account environmental factors, which affects operations planning. Beamon (1999) describes other aspects to consider, such as the risk associated with end-of-life product recovery and reverse logistics, and proposes key performance indicators in order to evaluate the efficiency of these processes. Hervani *et al*. (2005) also propose a methodology to measure the performance of green supply chains with a focus on inter-organizational issues. Jayaraman *et al*. (1999) propose a mixed-integer programming model that aims to minimize the cost of closed-loop logistics by optimizing the location of remanufacturing facilities. Similarly, Bouzembrak *et al*. (2011) propose a multi-objective mathematical model to balance the economic and environmental benefits. Finally, Gu *et al.* (2013) introduce a bi-objective optimization model in order to maximize the total economic benefit of an industrial park and the quantity of exchanged flows.

Objectives and methodology

As mentioned earlier, the main objective of the mixed-integer programming model introduced in this article is threefold. First, it aims at optimizing the selection and configuration of by-product synergies in an eco-industrial network in a multi-period decision environment. Second, this model aims at evaluating the economic and environmental sustainability of potential synergies in order to better understand their cost/saving trade-off. Finally, as an extension of the first objective, this model can be used by a single company in order to support strategic decision-making related to synergy configuration, including inventory location and technology investment.

In the context of an eco-industrial park, it is not sufficient to compare the price of waste with the price of raw materials. Logistics activities, including maintaining inventories, residues treatment, processing and transportation must also be taken into account. Similarly, it is also necessary to consider the joint and internal investments required to initialize a synergy. Indeed, the analysis of recent industrial symbiosis projects led in the province of Quebec by the CTTÉI[1] reveals that synergies involving the purchase of sorting or processing equipment are more complex to implement.

Another frequent concern about seller-buyer relationship in an industrial ecology context is the degree of dependency with the partner. One way to deal with this issue, at least partially, is to analyze the profitability of investment decisions over several time periods. Typically in a mathematical optimization model, this leads to a multi-period structure.

In order to address the problem described above, this paper first introduces a mixed-integer mathematical programming model. Next, in order to illustrate how this model can be used to evaluate the cost/saving trade-off and environmental benefits of potential synergies, this paper presents a case study based on the water synergies from the Kalundborg eco-industrial park. In particular, this case study is used to analyze the trade-off between the economic benefit and the volume of water preserved. In this case study, we also assess the level of control that a collectivity, such as the city of Kalundborg, can have in order to promote the development of industrial synergies. In other words, this mathematical optimization model can be used to analyze the impact of resource cost (i.e., water) and end-of-life (i.e., sewage treatment) cost on

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consumption. Similarly, individual companies can use such a model in order to compare synergy opportunities and configurations and plan technology and synergy investments.

The main asset of such optimization tools is their ability to consider an important number of alternative decisions simultaneously. Consequently, this model can be used to optimize, under different contexts and conditions, decisions concerning by-product exchange initiations, synergy configuration, technology selection, as well as by-products inventory location.

Optimization model

The proposed mixed-integer linear programming (MILP) model proposes two objective functions. The first objective function is purely economical, and aims basically at minimizing the costs related to the procurement and storage of material and the disposal of industrial wastes. The second objective function aims at minimizing resource consumption. This model is designed so the user can set the relative importance of each objective in order to represent his willingness to find a compromise between the economic and environmental factors. This model also allows the user to create scenarios to evaluate the impacts of different parameters, as well as the length of the planning horizon. For example, a by-product supplier can evaluate and compare the option of developing a sorting center with the creation of a partnership with a third-party recycler. The profitability of acquiring a resource for an enterprise, alone or with partners, can also be measured. The influence of each parameter can be analyzed using sensitivity analysis. This model can finally be used in order to evaluate material flows in a network when by-products availability and demand evolve over time.

General waste and material flow model

In the model, waste represents by-products produced by the sellers' processes, and material represents treated waste that can be directly used by buyers as inputs for their own processes. The term raw material is dedicated to feedstock supplied directly from the environment. The structure of the model is based on four types of stocks: sellers' waste, sellers' material, buyers' waste, and buyers' material. A generalized view of potential waste and material flows, and their transformation, are presented in Figure 1.

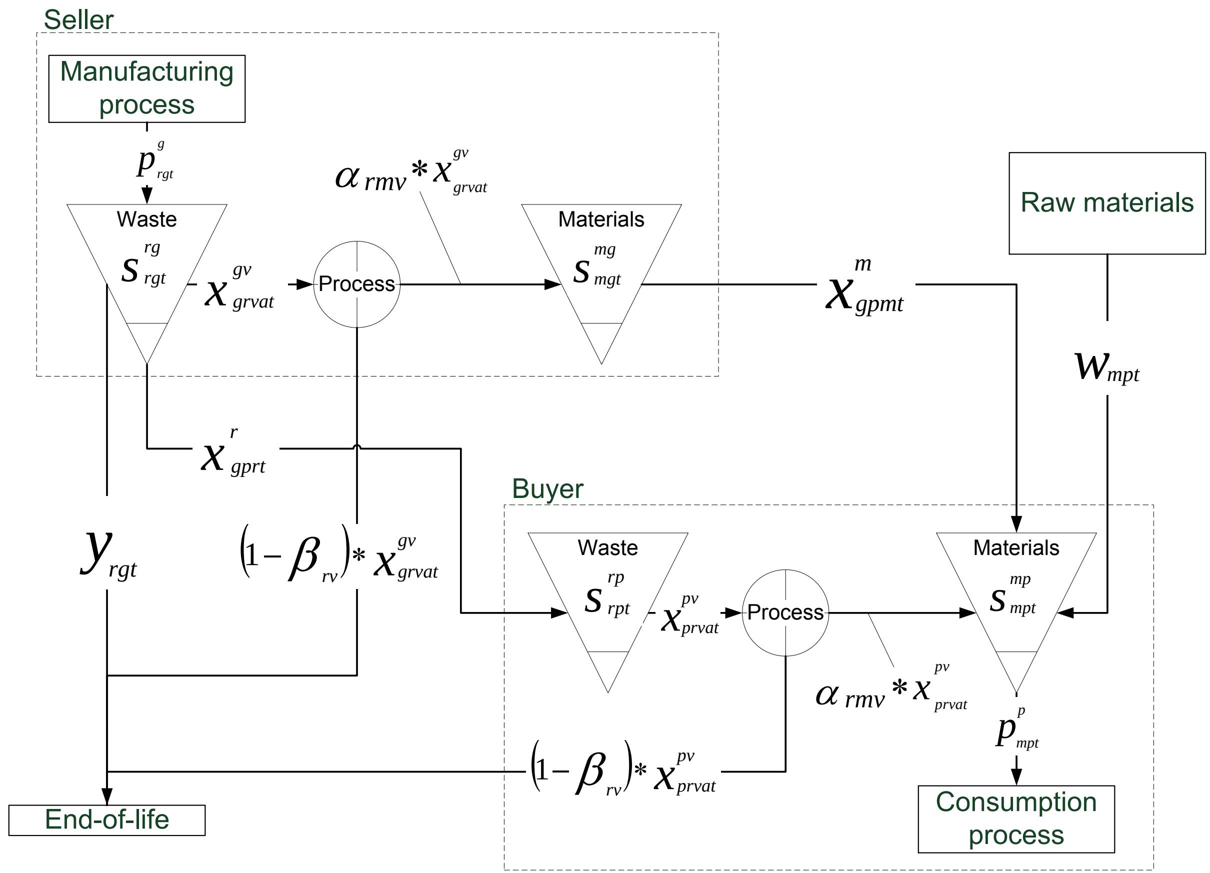

Figure 1: Flows circulation and stock types

In order to obtain meaningful environmental savings and analyze them in a decision-making context, the model's parameters and variables units must be consistent with one another. Therefore, the model introduces the notion of characteristic unit, for which, examples are presented in Table 1. This unit is one of the attributes of each flow. In particular, it is used in all by-product transformation coefficients (i.e., parameter α related to each triplet (waste, material, process)). This parameter ensures that supply and demand are analyzed with coherent units. Along the same line, this model can include simultaneously any type of solid, liquid or energy flows. However, in the case of multiple material flows, the analysis of resources savings (i.e., the second objective to optimize) is based on a subjective rating of the importance of each material.

Table 1: Characteristic units of different flows

Flows	Units
Cooling water, Wastewater, Surface water, Boiler water, Salty cooling water, organic fertilizer, yeast slurry	m^3
gypsum, fly ash, sludge, nitrogen, phosphorus, soy pills, clay	tons
Steam, heat	GJ

Similarly, in order to take into account potential investments that may be necessary to initialize synergies, such as sorting or treatment equipment, this model considers different process and resource (i.e., equipment) alternatives. Each resource is modeled as a finite capacity facility that can only process a certain amount of by-product per time period. Finally, the model also considers the following hypothesis:

- solid by-products can be treated either by a buyer or by a seller;
- third-party recyclers, whose main function is to consolidate by-product flows, are considered as buyers or sellers, depending of their role in the synergy;
- landfilling capacity and available quantity of raw materials are considered sufficient (i.e., infinite);
- buyers cannot acquire by-products and directly send them to landfill;
- the environmental aspects related to waste landfilling include transportation from the enterprise to a landfill site;
- the environmental aspects related to raw material purchase include all activities from cradle to the buyer's process (e.g., extraction, transport from the extraction site to the buyer);
- inventory capacity for by-products and raw materials are independent;
- end product inventories are not considered here;
- investment cost are equally split over the time periods of a horizon of a specific length.

Sets

R = Types of by-product/waste available

M = Raw materials

$F = R \cup M$ = material flows in the network

G = By-products/waste sellers

P = Potential buyers

$E = G \cup P$ = Enterprises involved in the eco-industrial network

T = Time periods considered ($|T|$ is the number of period in T)

V = Treatment processes

A = Transformation/treatment resources

$V_a \in V$ = Processes that resource $a \in A$ can perform

Parameters

p_{rgt}^{g}: Volume of type r waste of seller g available at period t

p_{mpt}^{p}: Volume of material m required by buyer p at period t

ω_{rv}: Volume of waste produced by the treatment with process v of one unit of type r waste

γ_{rva}: Consumption of resource a related to the treatment with process v of one unit of type r waste

α_{rmv}: Volume of material m obtained by the treatment with process v of one unit of type r waste

d_{gp}: Distance in kilometers between seller g and buyer p

ct_{rv}: Treatment cost of one unit of type r waste with process v

tr_f: Transportation cost of one unit of flow f on one kilometer

ce_{rgt}^{r}: Landfill cost of one unit of type r waste of seller g at period t

ce_{vret}^{v}: Landfill cost of one unit of waste produced by the treatment with process v of type r waste of enterprise e at period t

cm_{mt}: Price of one unit of raw material m at period t

k_{gprt}^{r}: Price of one unit of type r waste sold by seller p to buyer g

k_{gpmt}^{m}: Price of one unit of material m sold by seller p to buyer g

st_f: Inventory cost of one unit of flow f during one period

i_{gprt}: Initialization cost of a synergy between seller g and buyer p for type r waste at period t

ni_{gprt}: Costs avoided with the initialization of a synergy between seller g and buyer p for type r waste at period t

cs_{g}^{gr}: Inventory capacity of seller g for waste in m^3

cs_{g}^{gm}: Inventory capacity of seller g for materials in m^3

cs_p^{pr}: Inventory capacity of buyer p for waste in m^3

cs_p^{pm}: Inventory capacity of buyer p for materials in m^3

v_f: Volume in m^3 necessary to hold one unit of flow f in inventory

cap_a: Treatment capacity of resource a per period and per unit of waste

c_{ae}: Purchase price of resource a for the enterprise e

$$g_{ae} = \begin{cases} 1, \text{if enterprise e owns resource a;} \\ 0, \text{otherwise.} \end{cases}$$

f_m: Relative importance of the preservation of one unit of material m

∂: trade-off parameter expressed as a percentage of additional cost the decision-maker is ready to accept for environmental considerations

θ_{gpr}: Number of amortization years of the initialization of a synergy between g and p for by-product/waste r

θ_a: Number of amortization years for the purchase of resource a

Decision variables

In this model, decision variables represent either investment decisions (primary variables), or by-products/waste and material flows (secondary variables). The following list explains all variables used in the model, as illustrated in Figure 1.

x_{grvat}^{gv}: Volume of type r waste of seller g transformed with process v on resource a at period t

x_{prvat}^{pv}: Volume of type r waste of buyer p transformed with process v on resource a at period t

x_{gpmt}^{m}: Volume of material m of seller g transfered to the buyer p at period t

x_{gprt}^{r}: Volume of type r waste of seller g transfered to buyer p at period t

y_{rgt}: Volume of type r waste of seller g landfilled at period t

s_{rgt}^{rg}: Inventory of type r waste held by seller g at period t

s_{rpt}^{rp}: Inventory of type r waste held by buyer p at period t

s_{mgt}^{mg}: Inventory of material m held by seller g at period t

s_{mpt}^{mp}: Inventory of material m held by buyer p at period t

w_{mpt}: Volume of raw material m acquired by buyer p at period t

$$q_{aet} = \begin{cases} 1, \text{ if enterprise e purchases resource a at period t;} \\ 0, \text{ otherwise.} \end{cases}$$

$$z_{gprt} = \begin{cases} 1, \text{ if a synergy is initiated between seller g and buyer p for type r waste at period t;} \\ \quad 0, \text{ otherwise.} \end{cases}$$

$$ze_{gprt} = \begin{cases} 1, \text{ if a synergy exists between seller g and buyer p for type r waste at period t;} \\ \quad 0, \text{ otherwise.} \end{cases}$$

ac_{gprt}: Amortization of the cost at period t of the initialization of a synergy between seller g and buyer p for type r waste

aq_{aet}: Cost of the amortization at period t of the purchase of resource a by enterprise e

Decision objectives and trade-off analysis

As mentioned earlier, this model proposes to optimize two objective functions. In order to optimize both objectives, we use the lexicographic method, as explained in Marler and Arora (2004). In this approach, the total cost of investment and operations are first minimized. This provides the minimum cost reference, referred as $F_1(x^*)$. Next, we switch the objective function in order to minimize resource consumption with a maximum deviation δ% from $F_1(x^*)$. This objective function is referred to as $F_2(x)$. In the context of the case study described in the next section, the specific objective is to minimize water consumption. However, this function could be adjusted in order to minimize GHG emissions, although it would require a large preliminary LCA analysis of the possible options.

$$\boldsymbol{F_1}(\boldsymbol{x}) = \sum_m \sum_p \sum_t cm_{mt} * w_{mpt} + \sum_m \sum_p \sum_g \sum_t st_m * \left(s_{mg(t-1)}^{mg} + s_{mp(t-1)}^{mp}\right) + \sum_g \sum_{p|p\neq g} \sum_t \big(d_{gp} * \left(\sum_r tr_r * x_{gprt}^r + \sum_m tr_m * x_{gpmt}^m\right) + \sum_r k_{gprt}^r * x_{gprt}^r + \sum_m k_{gpmt}^m * x_{gpmt}^m\big) + \sum_r \sum_v \sum_a \sum_t \big(\sum_g \left(\omega_{rv} * ce_{vrgt}^v + ct_{rv}\right) * x_{grvat}^{gv} + \sum_{p|p\neq g} \left(\omega_{rv} * ce_{vrpt}^v + ct_{rv}\right) * x_{prvat}^{pv}\big) + \sum_a \sum_e \sum_t aq_{aet} + \sum_g \sum_{p|p\neq g} \sum_r \sum_t \left(ac_{gprt} + ni_{gprt} * (1 - z_{gprt})\right) + \sum_g \sum_{p|p\neq g} \sum_r \sum_t st_r * \left(s_{rgt}^{rg} + s_{rpt}^{rp}\right) + \sum_r \sum_e \sum_t ce_{re}^r * y_{ret} \tag{1}$$

$$\boldsymbol{F_2}(\boldsymbol{x}) = \sum_m \sum_p \sum_t \left(w_{mpt} * f_m\right) \tag{2}$$

$$Min\ F_i(x) \qquad i = \{1,2\}$$

Constraints

The deviation from the optimal solution is restricted by parameter δ in equation (3).

$$F_1(x) \leq \left(1 + \frac{\partial}{100}\right) F_1(x_1^*) \tag{3}$$

The flow balance of each type of stock for each enterprise is:

$$p_{rgt}^{g} + s_{rg(t-1)}^{rg} - y_{rgt} - \sum_v \sum_a x_{grvat}^{gv} - \sum_p x_{gprt}^{r} = s_{rgt}^{rg} \quad \forall\, r \in R, g \in G, t \in T \tag{4}$$

$$\sum_v \sum_r \sum_a \left(\alpha_{rmv} * x_{grvat}^{gv}\right) + s_{mg(t-1)}^{mg} - \sum_p x_{gpmt}^{m} = s_{mgt}^{mg} \quad \forall\, m \in M, g \in G, t \in T \tag{5}$$

$$\sum_v \sum_r \sum_a \left(\alpha_{rmv} * x_{prvat}^{pv}\right) + \sum_g x_{gpmt}^{m} + w_{mpt} + s_{mp(t-1)}^{mp} - p_{mpt}^{p} = s_{mpt}^{mp} \quad \forall\, m \in M, p \in P, t \in T \tag{6}$$

$$\sum_g x_{gprt}^{r} + s_{rp(t-1)}^{rp} - \sum_v \sum_a x_{prvat}^{pv} = s_{rpt}^{rp} \quad \forall\, r \in R, p \in P, t \in T \tag{7}$$

Equations (8) through (11) ensure that all companies' storage capacity is respected.

$$\sum_r \left(s_{rgt}^{rg} * v_r\right) \leq cs_g^{gr} \quad \forall\, g \in G, t \in T \tag{8}$$

$$\sum_m \left(s_{mgt}^{mg} * v_m\right) \leq cs_g^{gm} \quad \forall\, g \in G, t \in T \tag{9}$$

$$\sum_r \left(s_{rpt}^{rp} * v_r\right) \leq cs_p^{pr} \quad \forall\, p \in P, t \in T \tag{10}$$

$$\sum_m \left(s_{mpt}^{mp} * v_m\right) \leq cs_p^{pm} \quad \forall\, p \in P, t \in T \tag{11}$$

Treatment or sorting resources have a maximum capacity, as shown in equations (12) and (13).

$$\sum_r \sum_{v \in V_a} \left(\gamma_{rva} * x_{grvat}^{gv}\right) \leq cap_a * \left(q_{agi} + g_{ag}\right) \quad \forall\, g \in G, a \in A, t \in T, i \in [1, t] \tag{12}$$

$$\sum_r \sum_{v \in V_a} \left(\gamma_{rva} * x_{prvat}^{pv}\right) \leq cap_a * \left(q_{api} + g_{ap}\right) \quad \forall\, p \in P, a \in A, t \in T, i \in [1, t] \tag{13}$$

Only one purchase of a resource of type a per company can be made. Furthermore, if the company already has the resource, it cannot purchase it again. However, a simple modification of this constraint would allow the model to also consider capacity adjustment.

$$\sum_t q_{aet} \leq 1 \quad \forall\, e \in E, a \in A \tag{14}$$

As explained in equations (15), a synergy can only be initiated once. Next, equations (15) to (17) make sure that once a synergy is initiated, it exists over the rest of the planning horizon. Finally, equation (18) makes sure that a synergy exists between two enterprises before a by-product can be transferred between them.

$$\sum_t z_{gprt} \leq 1 \quad \forall\, g \in G, p \in P, r \in R \tag{15}$$

$$ze_{gprt} \leq z_{gprt} \quad \forall\, g \in G, p \in P, r \in R, t = 1 \tag{16}$$

$$z_{gprt} + ze_{gpr(t-1)} \leq ze_{gprt} \quad \forall\, g \in G, p \in P, r \in R, t \in [2, |T|] \tag{17}$$

$$M * ze_{gprt} \geq \sum_{m}\left(\alpha_{rmv} * x^{m}_{gpmt}\right) + x^{r}_{gprt} \quad \forall\, g \in G, p \in P, r \in R, t \in T \tag{18}$$

Finally, equations (19) and (20) make sure that, if a synergy is initiated, the corresponding amortized costs (i.e., synergy initiation plus equipment investment) are included in the objective function for the amortization horizon.

$$ac_{gpri} \geq \frac{z_{gprt} * i_{gprt}}{\theta_{gpr}} \quad \forall\, g \in G, p \in P, r \in R, a \in A, t \in T, i \in \left[t, \min[(t + \theta_{gpr} - 1), |T|]\right] \tag{19}$$

$$aq_{aei} \geq \frac{q_{aet} * c_{ae}}{\theta_{a}} \quad \forall\, e \in E, a \in A, t \in T, i \in [t, \min[(t + \theta_{a} - 1), |T|]] \tag{20}$$

$$x^{gv}_{grvat}, x^{pv}_{prvat}, x^{m}_{gpmt}, x^{r}_{gprt}, y_{rgt}, ac_{gprt}, s^{rg}_{rgt}, s^{rp}_{rpt}, s^{mg}_{mgt}, s^{mp}_{mpt}, w_{mpt} \geq 0 \tag{21}$$

$$z_{gprt}, q_{aet} \in \{0,1\} \tag{22}$$

As mentioned earlier, with a simple configuration of the parameters, this strategic planning model can either consider the total cost of the entire network, or only the total cost for a single company. Furthermore, the use of specific amortization horizon for each investment required to create synergies only aims at balancing the cost of investment and the benefit of the synergy. In practice, industrial synergies are created because they are profitable. Therefore, in order for synergies that require large investments to be created, such as a pipeline to provide several facilities with water, their cost must be compared with the benefits they procure over a certain horizon. Larger investments must consequently be amortized over a longer horizon. Without this balancing mechanism, the model only proposed large investments in the first time period, when the benefits of a synergy could be gained throughout the entire planning horizon. With it, because the cost of investments is spread over several time periods, according to the nature of the investment, the model can propose investment, whenever it is appropriate. Therefore, no discount rate is used, although a simple adjustment of equation (19) and (20) could introduce it.

Case Study

In order to illustrate the relevance of the use of this optimization model, this paper presents a case study carried out using publically available data from the eco-industrial park located in Kalundborg, Denmark. More specifically, this case study focuses on water exchanges, as depicted in Figure 2. Water is considered both as a process input (synergies A through E) and as an energy source (synergy F). This choice was made because it is the most documented, including several resource investments and operating costs, collected from publicly available papers, studies, and official websites. Several assumptions were also made to obtain the parameters required by the mathematical model.

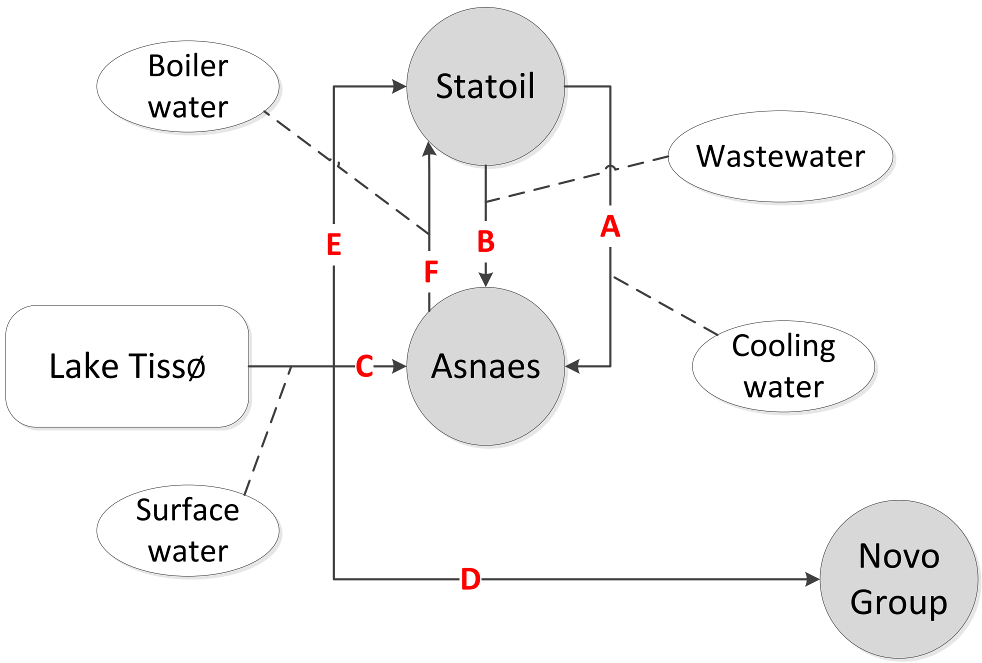

Figure 2: Exchanges considered, *Inspired from Jacobsen (2006)*

First, the reuse of wastewater from the Statoil refinery by the Asnaes power plant has started in 1992. In this win-win partnership wastewater is given away and discharge fees are avoided. The replacement of groundwater with surface water from Lake Tisso located a few kilometers away from the city started in the 1960's and has been evolving ever since. However, in 1997, a large investment was required to extend the pipeline capacity. Another important investment was also required for a water pre-treatment facility at the power station. Although exchanges C, D and E are linked to the joint pipeline investment decision, we intentionally split the joint investment into individual investments according to local pipeline uses. In other words, we considered these exchanges as independent pairwise synergies. This reflects a limitation of the model that cannot yet take into account collective investment, with more than two enterprises. Consequently, the 72 M DKK investment required in 1997 to continue using surface water from the Lake was divided according to the volumes needed by each participant, as shown in Table 2.

Table 2: Pipeline and pre-treatment facility investment per company

Company	**Initial investment required**
Asnaes power plant	17 786 100,11 DKK
Novo Group	12 730 284,48 DKK
Statoil refinery	41 483 615,41 DKK

For the purpose of the study, it is also assumed that from 1997, the three organisations cannot continue using surface water to fulfill their groundwater needs without these investments. The key economical factors in synergies C, D and E were, on the one hand, the pipeline capacity expansion and the pre-treatment facility costs, and, on the other hand, the difference between the price of groundwater and the price of surface water, which is set by the Kalundborg municipality. This highlights the influential role of the municipality that can act as a driving force in the development of by-product exchanges (see second experiment). Lake Tisso, which is considered as a "waste seller" in the decision support process, has an annual capacity of 5 millions m^3.

Since the refinery was occasionally missing boiler water in order to feed its steam facility, its managers could either make an important investment to expand the capacity of their water pre-treatment facility, or develop, for a much smaller investment, a by-product exchange (synergy F) with the Asnaes power plant, which overproduces boiler water. Consequently, this synergy was straightforward for both partners. In order to have a relevant price for boiler water, electricity prices for industrial consumers from the European Commission[2] was used. The thermal efficiency of 80°C boiler water (i.e., 36 MJ/m^3) produced by Asnaes leads to a conversion factor of 10 kWh/m^3 of boiler water (Jacobsen, 2006).

In order to obtain the road distances between companies (Table 1 in annexe), the Google Distance Matrix Application Programming Interface was used, using the address of each company. The symbolic enterprise “Others” is used to represent minor actors of the network for which there is few public information. They are small enterprises, such as local farmers, which do not produce waste or reject energy or water flows in relevant quantities. However, they are still collectively able to participate in the symbiosis by using materials or effluents from actors

[2] http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/main_tables

forming the core of the eco-industrial project. The location of this symbolic company has been set to the city center of Kalundborg.

Case study methodology

In order to evaluate the capacity of the model to provide relevant input to decision makers, it was tested in two distinct series of strategic planning process. To make sure these planning processes (for any specific year) are realistic, we only used the data available at that time. Therefore, parameters, such as water prices, were estimated using data from past years (see next section). In other words, we did not use actual prices and parameters, as they were unknown at that time.

In the first series of strategic planning process, these processes were simulated over a total period of nine years, from 1992, to 2000. At the beginning of each year, the optimization model was used in order to propose investment decisions over a five-year horizon. Then, we compare these investment decisions with the actual decisions made at that time. Because this process is repeated every year, it is referred to as a rolling horizon planning process, and each planning process is referred to as a planning cycle.

Along the same line, because large investments required being amortized over several years, we assumed that the amortization of each investment project is three years, as suggested by Baas (2011). As mentioned earlier, this assumption is important as it allows the total cost of investment to not be allocated just to the first year of its implementation. Therefore, this model allows the cost and benefit of an investment to be balanced over several time periods. In other words, this allows the model to propose a synergy implementation during the few last years of a planning horizon, if specific economic conditions are only met at this period.

Next, in order to follow the actual evolution of the Kalundborg symbiosis, whatever the decision solutions proposed by the model at a given planning cycle, the next planning cycle is always configured using the actual investment decision for the previous year (and only this year). This allowed us, for each planning cycle, to analyze the specific trade-off between cost and water savings using the lexicographic multi-objective approach. In particular, the relevant information for decision-makers is the cost threshold of synergy creation (i.e., the total deviation from the optimal cost solution that leads to the creation of a synergy), which is different for each decision context.

Finally, as explained earlier, although for each planning cycle, actual data was available for the entire planning horizon, we only consider the actual data of previous periods, while data for period one through five were estimated using two different methods. Similarly, because investment decisions could be proposed earlier or later by the model, investments cost were updated with the historic Danish inflation rate.

Because of missing information concerning the Kalundborg eco-industrial park, specific aspects of the optimization model could not be tested. Indeed, since water had to be transferred from the lake to the city by pipeline, transportation and storage options were limited compared to a case with solid wastes. For similar reasons, agreements with third-party recyclers were not studied, even though the general structure of the model would allow such synergy configuration. Some potential revenues, such as government subsidies, were also not taken into account due to missing information in the context of the Kalundborg symbiosis. These aspects would definitely need to be considered in actual strategic planning processes and future case studies.

In order to illustrate the use of the optimization model, two experiments were conducted with the AMPL programming language, and the Cplex solver, as presented in Table 3, and detailed in the next sections.

Table 3: Experiments conducted in the case study

	First experiment			Second experiment
Studied perspective	Involved enterprises			Municipality of Kalundborg
Planning cycles	'92-'96	'93-'97 to '97-'01	'98-'02 to '00-'04	'93-'97 to '97-'01
Synergies considered	B	C, D, E	F	C, D, E
Volumes and prices forecast	Regression analysis based on past values			-Fixed rate -Regression analysis
Optimization	Multi-objective (lexicographic method)			Single-objective

First experiment

In this experiment, we analyze the economic concessions companies must make in order to use synergistic water over the most economical water procurement source. As mentioned before, it is assumed that companies forecast water prices considering only past prices. Therefore, for each planning cycle, the average yearly variation of water prices since 1990 is used to predict the prices for the next five years, using regression analysis. Figure 1 in the annexe shows for each year and each type of water, the average values obtained against the actual prices set by the Kalundborg municipality, which are publicly available. The differences observed are in general minor. These differences arise mainly in the context of disruptive policies set by the municipality to change companies' behaviour, which are difficult to accurately forecast.

In order to assess the value of the concession companies must make to save water, we used the lexicographic method described earlier, by incrementally increasing the ∂ factor until all synergies appeared in the solution. This allowed us, on the one hand, to consider by-product exchanges in a classic sourcing strategy planning exercise (based on a cost-benefit analysis) and, on the other hand, to compare the total cost impacts of saving different quantities of water. This was systematically done for each planning cycle.

Results and discussion

Table 2 in the annexe shows the water and economic savings for all planning cycle. In order to have a reference solution to compute water and economic savings, the values on the first line of each planning cycle (from 1 to 9) are obtained with the calculation of the total network cost with no new synergies. Table 2 in the annexe also shows that, as the willingness of companies to concede a deviation from the minimum cost solution increases (larger δ), more synergies are proposed. Although these results appear obvious, it is interesting to compare threshold cost throughout different planning cycles in order to identify optimal investment period. Indeed, the optimization model does not only compare the prices of by-products with the inputs they replace. It also considers, for both sourcing options, different network configurations and analyzes their environmental and economic impacts. Consequently, the results are not linear, as a slight change of parameters from one planning cycle to the next, can render a synergy profitable, affecting potentially the entire network because of flow conservation constraints.

In the first planning cycle, the model proposes the same synergy that was actually implemented. In the next planning cycles (2 to 6), although nothing was actually implemented until 1997, the optimization model proposes, in certain situations, the initialization of synergies C, D and E as soon as in 1995. In the second planning cycle, synergy D is only proposed in 1997 with a large economic concession (corresponding to a 13.4% increase of total cost). This only enables the Novo Group to acquire 491 000 m^3 of surface water in replacement of groundwater. This corresponds to a cost of 4,63 DKK/m^3 of water preserved.

In planning cycle 3, synergy C is proposed to be implemented in 1998 for a reduction of the total network cost of 1,5%. Also, with an effort of 0,35 DKK/m^3 of water preserved (or a total cost increase of 1,9%), this synergy, along with the synergy D, is proposed for 1997. For a much larger concession of 1,55 DKK/m^3 of water preserved, synergies C, D and E are even proposed in 1998, which corresponds to a total cost increase of 12.2%. Such information is relevant for planning subsidies, in the case of government agencies or a municipality.

For planning cycle 4 and 5, the inclusion of both synergies C and D lead directly to a total cost reduction of 3,5% in 1995 and 2% in 1996, whereas synergy E is included in the plan for respectively 1,7% and 5,7% cost increases. Concerning planning cycle 4, we can see that, even if the number of synergies proposed stays the same for δ=10 and δ=20, water savings still increase quite significantly. This is due to the fact that synergy E is proposed for an implementation in 1999 for δ=10, and for an implementation in 1995 for δ=20 (i.e., a larger concession allows for an earlier setup). It is also interesting to see that in planning cycle 6, the optimal economic plan does not include any synergy, and synergies C, D and E are only included simultaneously in the plan for a total cost increase of more than 10%, which corresponds to a cost of 1,23 DKK/m^3 of water preserved. Within the context of this study, and the limitation of the data available, this result indicates that the Statoil refinery joined the pipeline project although it was not necessarily profitable, at least during the first year of operation in 1997. Therefore, other unknown factors not included in this study might have contributed to this investment, such as government subsidies. Similarly, the amortization period might have been extended over 3 years due to the large capital investment required. Finally, the important economic savings due to avoided discharge fees for the power plant, as well as reduced energy procurement costs for the refinery, explain the inclusion of synergy F in the last three planning cycles (7 to 9), which include 2002, the year the synergy was actually implemented.

Overall, as shown in Figure 2 in the annexe, a 5% concession on total cost leads to one or two synergies. These results highlight planning difficulties due to the lack of visibility with respect to water prices. In particular, the simple forecast method used to compute water prices lead to a significant forecast error. Therefore, strategic planning with this type of synergies should include all actors, including the city, in order to limit the negative effect of externalities.

Furthermore, Figure 3 presents the effect of concessions on total cost with respect to resources savings. From a general standpoint, and within the limitation of the data used to carry out this study, the cost of savings water can be quite high. This highlights the need for subsidies from government agencies for large synergy projects. Similarly, except for planning cycle 2, resources savings generally increase almost linearly with the level of concession made. Beyond this almost linear relationship between concession and saving, it is interesting to notice that each strategic planning cycle has specific cost/savings trade-off. For instance, planning cycle 6 (i.e., horizon 6), water savings can be achieved for much lower concession, than planning cycle 2 (i.e., horizon 2). Therefore, part of the usefulness of this optimization model resides in its ability to compute such trade-offs, as they vary greatly from one decision context to the next.

Finally, Figure 4 shows the economic savings per m^3 of water exchanged for the considered synergies. Using the weighted average volumes of water saved, the only synergies not leading directly to economic savings are synergies D and E, while synergies B and F are clearly profitable in all horizons considered, bringing procurement savings of more than 7 DKK for each m^3 of synergistic water. Similarly, synergy C is, in many cases, proposed at with no concession. Consequently, this optimization model can also be used to identify synergies, which profitability requires subsidies.

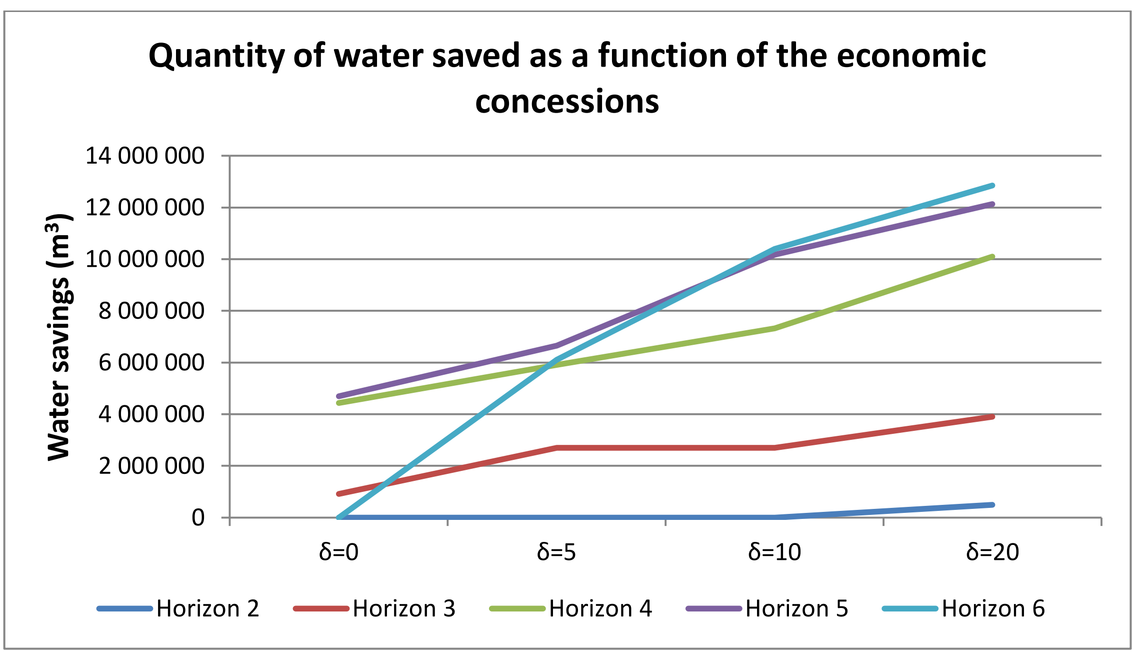

Figure 3: Effect of the δ parameter on the quantity of water preserved

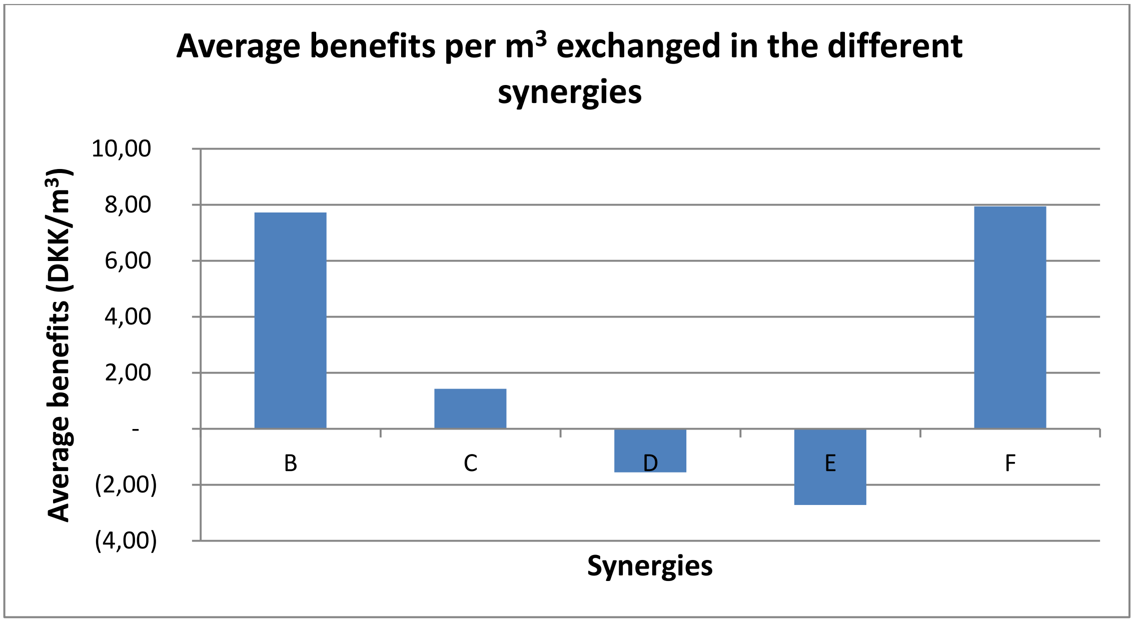

Figure 4: Procurement savings per m^3 exchanged

To conclude experiment 1, it seems that water preservation in the Kalundborg symbiosis was mainly driven by economic factors, with an average payback period of between three and four years. However, although the long-term profitability of a cheaper sourcing strategy is straightforward, the impacts of both internal and external factors, such as price variability, on the payback period of synergy projects make them complex to analyze, especially when synergies can be configured with alternative technology, storage, and location options. This optimization model is consequently useful to provide a means of analyzing this complexity.

Second experiment

As mentioned earlier, the city actually played a key role in setting up the symbiosis by making critical decisions related to the price of acquisition and discharge of water. This second experiment specifically studies the capacity of the municipality to impact the profitability level and the payback period of by-product synergies. The optimization problem no longer considers two objective functions. Only the economic aspect of synergies is considered (i.e., $F_1(x)$). Therefore, the objective is to find the lowest cost solutions that propose synergies by adjusting either water prices or discharge cost.

In order to do this, we carried out a sensitivity analysis to identify the price or cost threshold that leads to the creation of a synergy. For each synergy studied, a specific type of water was selected based on its impact on profitability, as shown in Table 3 in the annexe. Next, for each sensitivity analysis, the studied parameters were set as linearly increasing at a specific rate throughout the entire planning horizon, while the other prices and fees, as well as volumes, were still predicted based on previous years using regression analysis. We also considered for these parameters, an initial price p_0 set as the last year price. For each synergy and each planning horizon, the rate is first set at 0%, and then increased by one percent at the time, until the model proposed new synergies. The publicly available prices (see Table 4 in the annexe (Jacobsen (2006)) was used as reference values p_0 for the calculation of forecasted prices of water over planning horizons.

In this study, any price evolution pattern could have been used. As explained above, we chose arbitrarily a constant annual rate (i.e., linear increase from p_0). This experiment aims to study the capacity of the model to identify the price increase rate that leads to the creation of new synergies. Finally, synergies C, D, E and F were studied in depth because the first experiment showed that they require an economic trade-off for some planning horizons. Therefore, the price of groundwater is the parameter at the center of this second experimentation.

Results and discussion

Table 5 in the annexe shows the results of the second experiment. For each cycle studied, the initial and final (i.e., fifth year of the planning horizon) prices of groundwater are shown, as well as the corresponding annual rates leading to new synergies. The price of saved water is then calculated as the cost variation between the total network cost and the price of water at 0% rate, over the quantity of water saved.

Except for planning cycle 2, annual rates under 10% are generally sufficient to lead to new by-product synergies. It is also possible to observe that in these cycles, synergy C is always the first one to appear, synergy D the second one and synergy E the last one, which is consistent with the results shown in Figure 4. Planning horizons 3 and 4 show that the implementation year proposed by the model can also be affected by the annual rate. The difference between the results for planning cycles 2 and the other planning cycles is attributable to two main factors. First, in 1993, water requirement forecasts for year 1997 and after are quite different, especially concerning synergy C. Next, in reality, the price of groundwater was increased more in 1993 and 1994 than in 1991. Finally, note that, thanks to higher savings, the unit price of water saved drops as the yearly rate increases.

Finally, Figure 5 shows the influence of the annual rate on the volume of water preserved for the different planning cycle. Except for the planning cycle 2, the necessary rate to save the maximum volume of water is 25% or below. This number may appear quite high, but as shown in Table 4 in the annexe, the Kalundborg municipality increased the price of groundwater between 1999 and 2000 by more than 50%. Overall, the volume of synergistic water shown in Figure 5 is not a linear function of the annual increase rate of the price of groundwater. Again, the impact of ground water price is specific the context of each strategic planning cycle. Therefore, another aspect of the usefulness of this optimization model resides in its ability to identify specific price thresholds (e.g., 17% for horizon 5) that lead to the creation of new synergies.

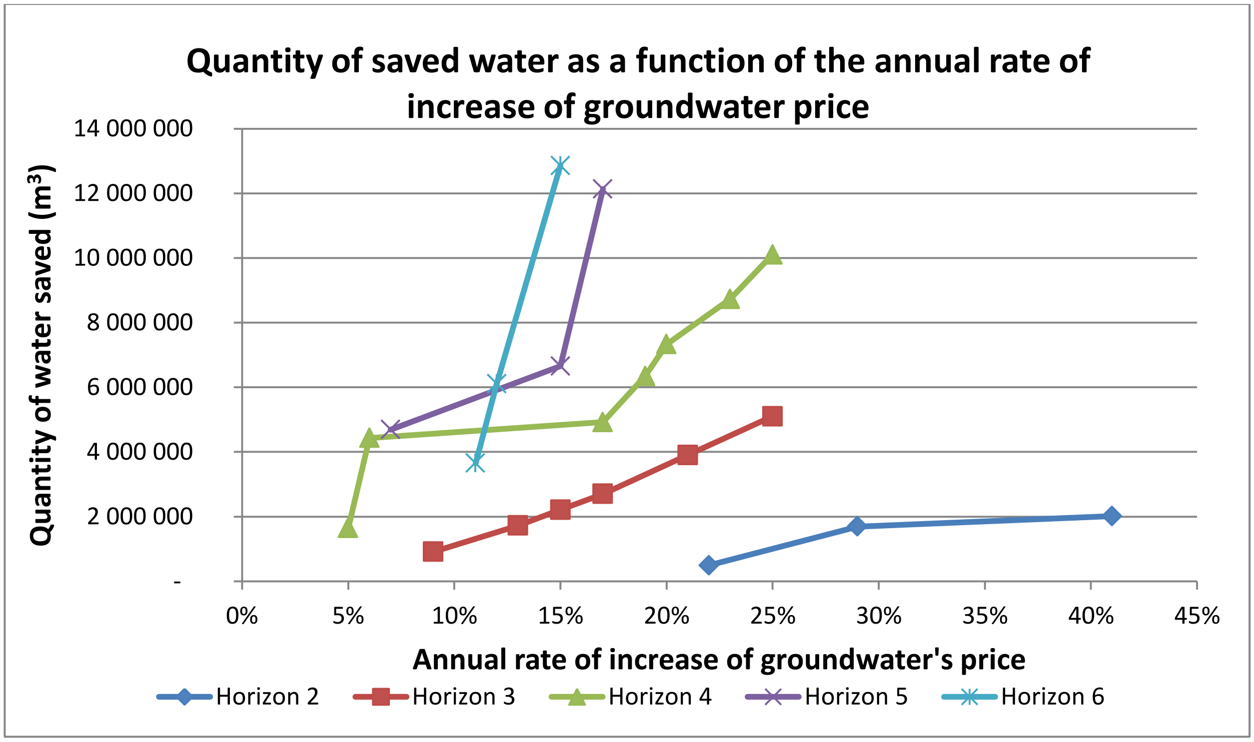

Figure 5: Water savings in different planning horizons

Case study conclusion

Considering the data that was publicly available concerning the Kalundborg industrial symbiosis and the different assumptions we made, the results obtained in the first experiment show that the investments necessary to put in place by-product synergies have payback periods of more than three years. On the one hand, the distribution of the expenses between the three participants in the case of synergies C, D and E was certainly more complex than the simple calculation rule we used in this case study. However, the use of a network perspective is adapted to these cases, where the perspective of an enterprise cannot be considered in an isolated manner. On the other hand, as water management was an important concern for the municipality, it is possible that the enterprises had access to other form of revenues, such as government subsidies, in order to balance part of their investments necessary to initialize synergies. Government subsidies can therefore be an efficient means of supporting the creation of targeted synergy. Another means of promoting industrial synergies, as shown in experiment 2, consists in adjusting resource prices, although this approach does not necessarily target specific synergies.

Conclusion and Future Works

Recently, mathematical optimization models have been developed in order to optimize by-product synergy design. At the same time, methods and tools are developed in order to evaluate the environmental performance of industrial symbiosis. The proposed multi-criteria optimization model aims at supporting companies and network facilitators to integrate and analyse altogether economic and environmental issues. This model also enables decision makers to analyse, through sensitivity analysis, the selling price of a waste, or the minimal processing capacity of a piece of equipment to acquire.

Data from the eco-industrial park of Kalundborg was used to illustrate the potential savings of industrial synergies, as well as when they should be initialized. The results show that, with date available publicly, some synergies could have been initialised earlier. Results also show that, in general, the companies' behaviour is based on a payback period of around three years. This also confirms the fact that economic considerations are often the main driver of by-products synergy networks. However, the last part of the case study also highlights the fact that, with little financial trade-off, some companies could be involved more actively in resources preservation. Along the same line, the municipality of Kalundborg, by controlling the price of water, can significantly affect the profitability of some synergies. Finally, the case study also illustrates the sensitivity of the model with respect to forecasted prices and volumes, as well as the complexity involved in collective investments.

Therefore, future work and improvement of the model include collective investment where at least three companies are involved in the creation of a synergy. Also, the model must be improved in order to integrate life-cycle analysis results in the optimization process in order to obtain accurate GHG emissions savings. Other tests made on solid waste synergies in the Kalundborg eco-industrial network (not discussed in this paper) showed that with the parameters considered, some exchanges did not seem profitable, even if they were initialized. Government subsidies should therefore be included to represent more accurately actual decision-making context. These results also underline the fact that other economic benefits should be taken into account, as the ones associated with the respect of regulations and other elements relative to the field of environmental accounting.

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Annexes

Tables and figures

Table 4: Distance between sellers and buyers of the Kalundborg industrial symbiosis

Enterprises	Novo Group	Statoil	Asnaes	Soilrem	Gyproc	Kalundborg municipality	Others
Novo Group	0 km	3 km	3 km	4 km	1 km	1 km	3 km
Statoil	3 km	0 km	1 km	0 km	3 km	3 km	6 km
Asnaes	3 km	1 km	0 km	1 km	2 km	3 km	6 km
Lake Tissø	16 km	16 km	18 km	17 km	16 km	16 km	20 km
Kalundborg municipality	1 km	3 km	2 km	3 km	0 km	0 km	3 km

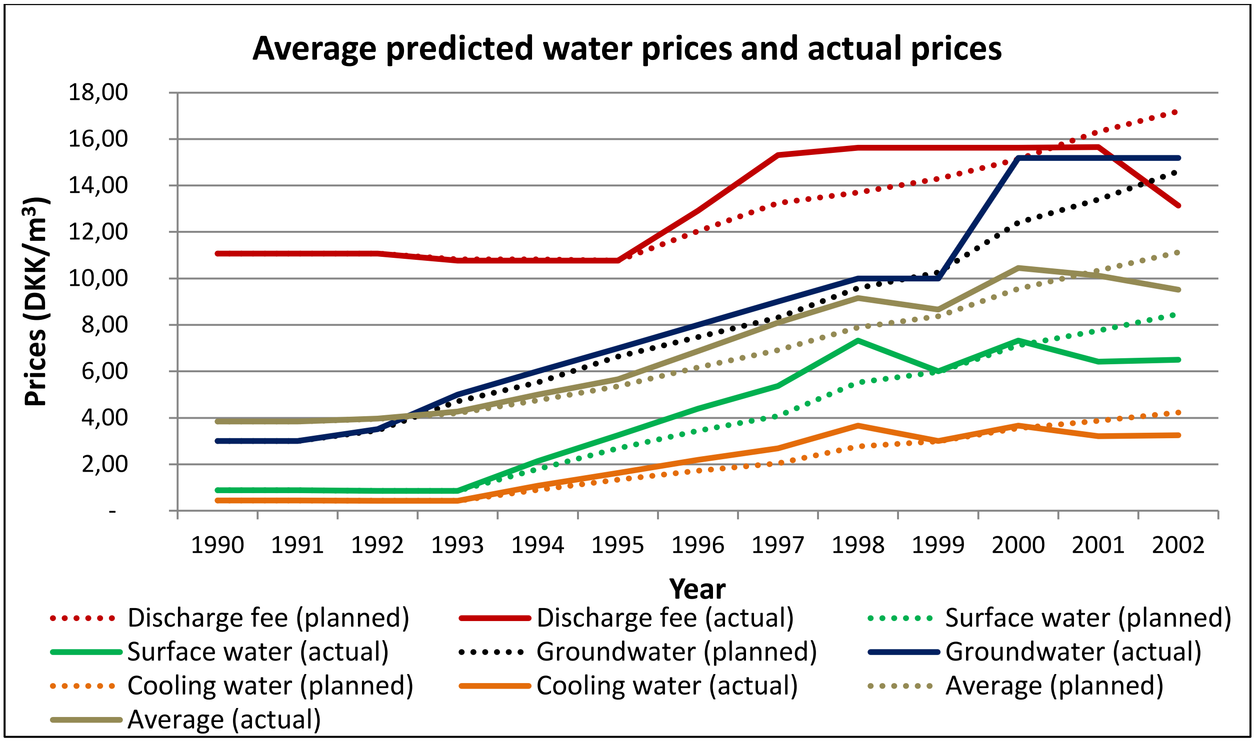

Figure 3: Predicted and actual water price

Table 5: Economic and environmental benefits of different planning horizons computed in the first experiment

Planning cycle	Time Frame	Test	Non-synergistic water (m^3)	Water saved (m^3)	Total network cost (DKK)	Cost variation (DKK)	Price of water saved (DKK/m^3)	Synergies proposed	Init. year
1	1992-1996	**No new synergy**	17 617 783		20 638 844,35				
		δ=0	17 143 783	474 000	16 974 544,35	(3 664 300,00)	(7,73)	B	1992
2	1993-1997	**No new synergy**	17 067 681		18 551 987,43				
		δ=0	17 067 681		18 551 987,43				
		δ=5	17 067 681		18 551 987,43				
		δ=10	17 067 681		18 551 987,43				
		δ=20	16 576 681	491 000	20 826 505,59	2 274 518,16	4,63	D	1997
3	1994-1998	**No new synergy**	20 995 855		50 388 470,89				
		δ=0	20 085 522	910 333	49 614 033,43	(774 437,45)	(0,85)	C	1998
		δ=5	18 293 855	2 702 000	51 325 496,17	937 025,28	0,35	D	1997
								C	1997
		δ=10	18 293 855	2 702 000	51 325 496,17	937 025,28	0,35	D	1997
								C	1997
		δ=20	17 093 855	3 902 000	56 449 581,15	6 061 110,26	1,55	D	1997
								C	1997
								E	1998

Table 2: Economic and environmental benefits of different planning horizons computed in the first experiment (continued)

Planning cycle	Time Frame	Test	Non-synergistic water (m^3)	Water saved (m^3)	Total network cost (DKK)	Cost variation (DKK)	Price of water saved (DKK/m^3)	Synergies proposed	Init. year
4	1995-1999	**No new synergy**	24 913 659		119 284 394,76				
		δ=0	20 482 659	4 431 000	111 383 562,68	(7 900 832,08)	(1,78)	C	1995
		δ=5	19 009 659	5 904 000	115 346 757,87	(3 937 636,89)	(0,67)	D	1995
								C	1995
		δ=10	17 584 659	7 329 000	121 133 345,39	1 848 950,62	0,25	D	1995
								C	1995
								E	1999
		δ=20	14 809 659	10 104 000	131 599 696,89	12 315 302,12	1,22	D	1995
								C	1995
								E	1995
5	1996-2000	**No new synergy**	23 536 551		148 743 991,76				
		δ=0	18 846 151	4 690 400	143 018 791,71	(5 725 200,05)	(1,22)	C	1996
		δ=5	16 882 151	6 654 400	145 881 314,80	(2 862 676,96)	(0,43)	D	1996
								C	1996
		δ=10	13 366 151	10 170 400	156 813 889,19	8 069 897,43	0,79	C	1996
								E	1996
		δ=20	11 402 151	12 134 400	159 676 412,30	10 932 420,52	0,90	D	1996
								C	1996
								E	1996

Table 2: Economic and environmental benefits of different planning horizons computed in the first experiment (continued)

Planning cycle	Time Frame	Test	Non-synergistic water (m^3)	Water saved (m^3)	Total network cost (DKK)	Cost variation (DKK)	Price of water saved (DKK/m^3)	Synergies proposed	Init. year
6	1997-2001	**No new synergy**	20 156 033		155 663 057,73				
		δ=0	20 156 033		155 663 057,73				
		δ=5	14 048 533	6 107 500	159 408 688,15	3 745 630,42	0,61	D	1997
								C	1997
		δ=10	9 753 533	10 402 500	169 415 905,19	13 752 847,46	1,32	C	1997
								E	1997
		δ=20	7 298 533	12 857 500	171 454 664,67	15 791 606,94	1,23	D	1997
								C	1997
								E	1997
7	1998-2002	**No new synergy**	17 932 489		109 349 432,11				
		δ=0	17 882 489	50 000	108 932 503,53	(416 928,57)	(8,34)	F	2002
8	1999-2003	**No new synergy**	20 321 739		173 577 013,65				
		δ=0	20 221 739	100 000	172 757 513,65	(819 500,00)	(8,20)	F	2002
9	2000-2004	**No new synergy**	19 878 164		135 760 607,50				
		δ=0	19 728 164	150 000	134 612 107,50	(1 148 500,00)	(7,66)	F	2002

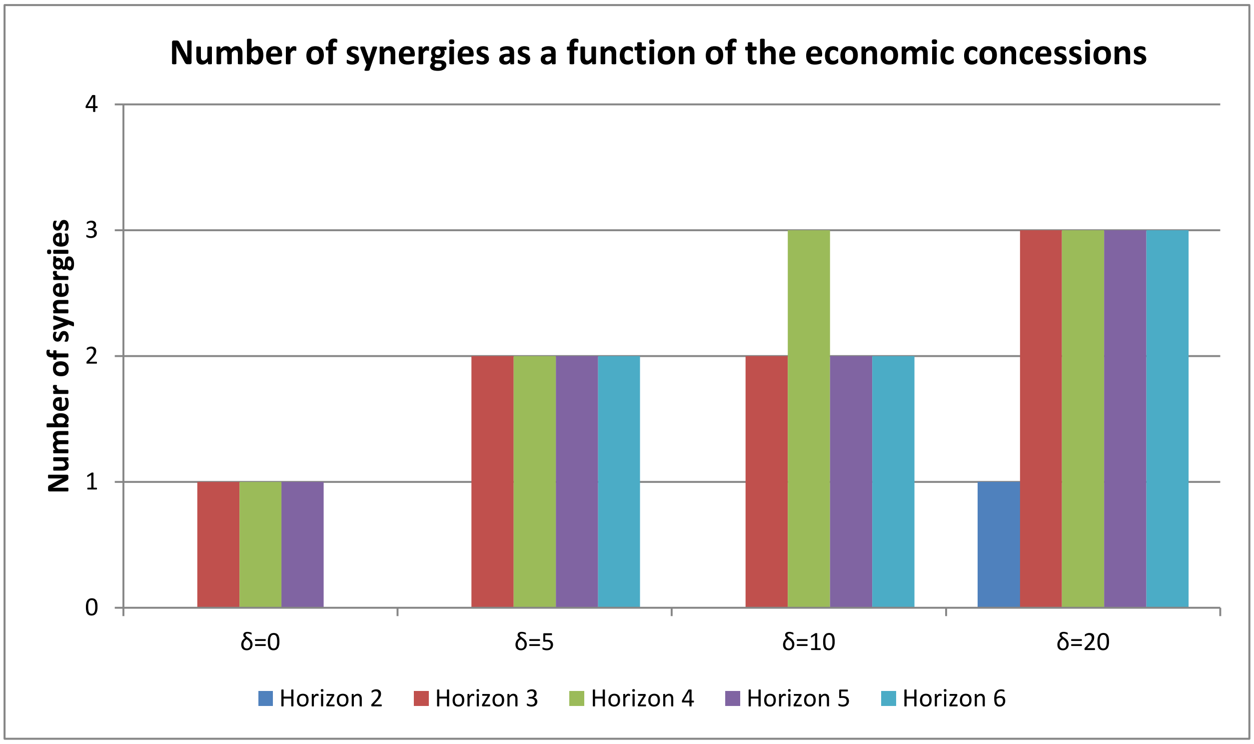

Figure 4: Effect of the δ parameter on the number of synergies proposed

Table 6: Critical water types and parameters of synergies

Synergy	A	B	C	D	E	F
Critical type of water	Surface water	Wastewater	Groundwater			Boiler water
Critical parameter	Selling price	Discharge fee	Selling price			Discharge fee

Table 7: Water prices in the municipality of Kalundborg

	Discharge fee (DKK/m^3)	Surface water (DKK/m^3)	Groundwater (DKK/m^3)	Cooling water (DKK/m^3)
1990	11,07	0,88	3,00	0,44
1991	11,07	0,88	3,00	0,44
1992	11,07	0,85	3,51	0,43
1993	10,77	0,86	5,00	0,43
1994	10,77	2,14	6,00	1,07
1995	10,77	3,25	7,00	1,63
1996	12,91	4,39	8,00	2,20
1997	15,31	5,37	9,00	2,69
1998	15,63	7,32	10,00	3,66
1999	15,63	6,00	10,00	3,00
2000	15,63	7,32	15,19	3,66
2001	15,65	6,41	15,19	3,21
2002	13,13	6,50	15,19	3,25

Table 8: Economic and environmental benefits of different planning horizons computed in the second experiment

Planning horizon (Time frame)	Initial price p_0 (DKK)	Annual rate	Final price (DKK)	Non-synergistic water (m^3)	Water saved (m^3)	Total network cost (DKK)	Cost variation (DKK)	Shared cost of water saved (DKK/m^3)	Synergies proposed	Init. year
2 (1993-1997)	3,51	0%	3,51	17 067 681		15 985 412				
		22%	9,49	16 576 681	491 000	27 982 197	11 996 784	24,43	D	1997
		29%	12,54	15 376 681	1 691 000	32 339 098	16 353 685	9,67	D	1997
									E	1997
		41%	19,56	15 054 681	2 013 000	34 479 857	18 494 445	9,19	C	1997
									D	1997
									E	1997
3 (1994-1998)	5,00	0%	5,00	20 995 855		35 048 915				
		9%	7,69	20 085 522	910 333	47 009 129	11 960 214	13,14	C	1998
		13%	9,21	19 275 855	1 720 000	52 187 023	17 138 108	9,96	C	1997
		15%	10,06	18 784 855	2 211 000	54 422 247	19 373 332	8,76	C	1997
									D	1998
		17%	10,96	18 293 855	2 702 000	56 523 507	21 474 592	7,95	C	1997
									D	1997
		21%	12,97	17 093 855	3 902 000	60 111 114	25 062 198	6,42	C	1997
									D	1997
									E	1998
		25%	15,26	15 893 855	5 102 000	61 773 239	26 724 324	5,24	C	1997
									D	1997
									E	1997

Table 8: Economic and environmental benefits of different planning horizons computed in the second experiment

Planning horizon (Time frame)	Initial price p_0 (DKK)	Annual rate	Final price (DKK)	Non-synergistic water (m^3)	Water saved (m^3)	Total network cost (DKK)	Cost variation (DKK)	Shared cost of water saved (DKK/m^3)	Synergies proposed	Init. year
4 (1995-1999)	6,00	0%	6,00	24 913 659		88 677 644				
		5%	7,66	23 265 159	1 648 500	101 609 547	12 931 902	7,84	C	1999
		6%	8,03	20 482 659	4 431 000	103 331 982	14 654 337	3,31	C	1995
		17%	13,15	19 991 659	4 922 000	124 466 187	35 788 542	7,27	C	1995
									D	1999
		19%	14,32	18 566 659	6 347 000	127 827 929	39 150 284	6,17	C	1995
									D	1999
									E	1999
		20%	14,93	17 584 659	7 329 000	128 863 835	40 186 190	5,48	C	1995
									D	1995
									E	1999
		23%	16,89	16 184 659	8 729 000	131 179 455	42 501 810	4,87	C	1995
									D	1995
									E	1998
		25%	18,31	14 809 659	10 104 000	131 599 696	42 922 052	4,25	C	1995
									D	1995
									E	1995
5 (1996-2000)	7,00	0%	7,00	23 536 551		114 185 271				
		7%	9,82	18 846 151	4 690 400	136 267 729	22 082 458	4,71	C	1996
		15%	14,08	16 882 151	6 654 400	155 587 795	41 402 523	6,22	C	1996
									D	1996
		17%	15,35	11 402 151	12 134 400	159 676 412	45 491 140	3,75	C	1996
									D	1996
									E	1996

Table 8: Economic and environmental benefits of different planning horizons computed in the second experiment

Planning horizon (Time frame)	Initial price p_0 (DKK)	Annual rate	Final price (DKK)	Non-synergistic water (m^3)	Water saved (m^3)	Total network cost (DKK)	Cost variation (DKK)	Shared cost of water saved (DKK/m^3)	Synergies proposed	Init. year
6 (1997-2001)	8,00	0%	8,00	20 156 033		122 801 252				
		11%	13,48	16 503 533	3 652 500	162 582 613	39 781 361	10,89	C	1997
		12%	14,10	14 048 533	6 107 500	165 452 681	42 651 429	6,98	C	1997
									D	1997
		15%	16,09	7 298 533	12 857 500	171 454 664	48 653 412	3,78	C	1997
									D	1997
									E	1997