
# Decision support tool to identify industrial waste reuse opportunities in an industrial symbiosis context

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## Summary

By-products synergy is a growing practice worldwide. In brief, it consists in the maximization of resources use 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 a preliminary result of a project carried out in collaboration with the *Centre de Transfert Technologique en Écologie Industrielle* (CTTÉI), which includes a decision support system based upon a mathematical model optimizing by-products flows both economically and environmentally in eco-industrial networks. The use of this tool is then evaluated using data related to the case of the Kalundborg industrial symbiosis. The results are generally coherent with the actual timing of synergy initializations, although it also highlights that for a small price increase, synergies could have been initialised earlier.

**Keywords:** eco-industrial park, industrial symbiosis, multi-objective optimization, decision support system

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## 1. Introduction

Industrial symbiosis is a division 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. They consist of companies matched together based on their inputs and outputs and maintaining customer-supplier relationships. As observed by Sakr *et al*. (2011), even if a high degree of collaboration is needed between the different participants, it is not always sufficient to ensure the optimal design of the symbiotic relations and their good evolution. Lessons from past projects also demonstrate the higher efficiency of industrial ecosystem development when adopting a network perspective instead of an isolated-enterprise point of view (Haskins, 2006). Therefore, independent network facilitators can often play a critical role in the success of those initiatives (Kincaid and Overcash, 2001). In this context, this article presents a decision support system, which aims to identify partnership opportunities between enterprises with industrial residuals and enterprises likely to use them as raw materials. The tool, based on a mathematical optimization model, enables such matchmakers to optimize decisions and compute 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 feasibility and the dynamic nature of eco-industrial relations are often neglected. Therefore, since supply chain designers must also face these challenges, the use of tools generally used in supply chain design seems adapted to the context of industrial symbiosis design.

## 2. Objectives

The main objective of the decision support tool introduced in this article is to evaluate the economic and environmental sustainability of potential by-product synergy opportunities in order to optimize water, energy and solid waste flows in an eco-industrial network. In this context, it is not rational to only look at the price of waste against the price of raw materials. Logistics activities also have to be taken into account, stockings and transportation playing a key role in the supply chain. Furthermore, the mathematical optimization model at the center of the tool considers the initial investments required to initialize a synergy because this element can often carry a lot of weight in the decision making process. In fact, after the analysis of the recent industrial symbiosis projects led in the province of Quebec by the research partner, it seems that business relations involving the purchase of sorting or processing equipment are more complex to put in place. At the same time, the literature shows that the enterprises implicated in those cases are often the ones prone to the biggest savings on a medium and long-term horizon (Esty and Porter, 1998). Therefore, the design of industrial symbiosis must somehow include a cost-benefit analysis of these factors. Another frequent concern about seller-buyer relationship in an industrial ecology context is the degree of dependency with the partner. The proposed model address this question by adopting a multi-period structure, which allows users to observe the impact of fluctuating volumes waste availability on the relations' sustainability.

## 3. Optimization model

In order to better understand the different processes involved in a project dealing with the identification of potential by-product synergy within an industrial park, the first author of this paper was directly involved in such a project led by the *Centre de Transfert Technologique en Écologie Industrielle* (CTTÉI). Among other findings, the analysis of this project revealed the importance of reducing the time needed to filter the different opportunities of synergy. Next, in order to develop a model of symbiosis design decisions, the material flow and resource constraints, as well as consolidation opportunities, involved in companies' operations, such as in sorting, transporting and transforming industrial wastes, have been listed and integrated in a mathematical programming model. This model aims to support its decision makers to find a trade-off between two conflicting objectives to optimize, which are the total expenses of synergy investments and operations, and the environmental impacts modeled as the total quantity of resource savings. More specifically, the user can choose the relative importance of each objective in order to represent her willingness to compromise the economic factor over the environmental factor. The system also allows the user to change the value of parameters, as the selling price of the by-products, the efficiency of the technology used to sort or transform waste and the length of a reference period. Different scenarios can also be analysed. For example, for a potential waste supplier, the comparison between owning a sorting process and creating a partnership with a third-party recycler can be evaluated. The profitability of acquiring a resource for an enterprise, alone or with partners, can also be measured. The influence of each parameter can be analysed in a sensitivity analysis in order to let the user evaluate the value of the information they have to collect. The tool can finally be used to evaluate material flows in a network when the quantity of offered waste and waste demand evolve over time.

### 3.1 General waste and material flow model

In the model, waste represents by-products (including water and energy flows) produced by the sellers' processes, and material represents treated waste that can be directly used by buyers as inputs for their processes. The term raw material is only used for feedstock coming directly from the environment. The structure of the model is based on four types of stocks: sellers' waste, sellers' material, buyers' waste, buyers' material. A generalized view of potential flows and their status changes (from waste to material) are shown on figure 1. As shown, buyers can either purchase waste or material from a seller, as well as raw material from other sources.

In order to obtain meaningful environmental savings and interpret them easily in a decision-making context, the parameters and variables units have to be coherent with the flows they refer to. At the same time, extending the model to represent every kind of stream would make it a lot more complex while not adding much value. Therefore, the tool introduces the notion of characteristic unit, which is an attribute of each flow and is taken into account in the $\alpha$ parameter related to each (waste, material, process) triplet.

In order to take into account the resource investments that are sometime necessary to initialize a synergy, whether it is a pipeline for transportation purposes or a more complex treatment facility to remove any contaminants that could be present in the waste, different process option, as well as resource options can be captured in the model. Similarly, each resource is modeled as a finite capacity facility that can only process a certain amount per time period. Next, the model is multi-period, which allows taking into account the effect over multiple time periods of any parameter variation, including water price, waste quantity availability, as well as capacity increase requirements.

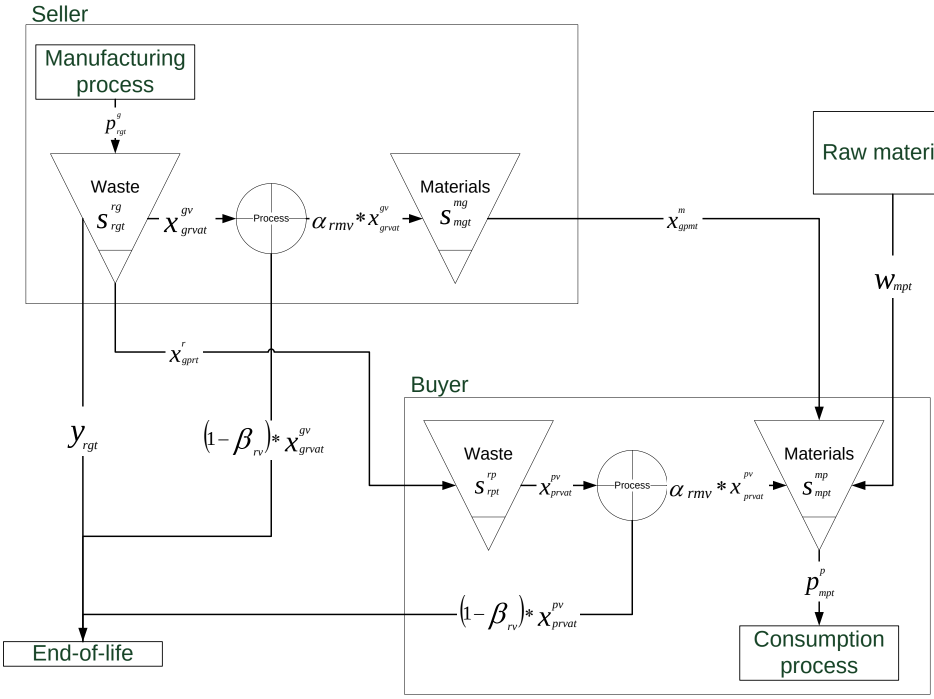


*Figure 1. Flows circulation and stock types*

### 3.1 Decision variables

In the proposed model, decision variables represent either investment decisions, or waste and material flows that can be initiated thank to investments in a resource to allow a synergy for example. The following list explains all variables used in the model and illustrated in Figure 1. However, for the purpose of clarity, the objective functions and the constraints equations are presented in the appendix.

$x_{grvat}^{gv}$: *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*

$s_{rgt}^{rg}$: *Volume of type r waste stocked by seller g at the end of period t*

$s_{rpt}^{rp}$: *Volume of type r waste stocked by buyer p at the end of period t*

$s_{mgt}^{mg}$: *Volume of material m stocked by seller g at the end of period t*

$s_{mpt}^{mp}$: *Volume of material m stocked by buyer p at the end of period t*

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

$$q_{ae} = \begin{cases} 1, \textit{if the enterprise e purchases the ressource a;} \\ 0, \textit{otherwise.} \end{cases}$$

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

### 3.2 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, which thus provides the minimum cost reference, referred as $F_1(x^*)$. Next, we change the objective function in order to minimize resource consumption with a maximum deviation δ% from $F_1(x^*)$. In 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.

## 4. Case Study

In order to evaluate the relevance of the proposed decision model, this paper presents a case study carried out using the publically available data from the eco-industrial park located in Kalundborg, Denmark. More specifically, this case study focuses on water exchanges (Figure 2). This choice was primarily made because this case is the most documented. Accurate data was therefore available for a period of over ten years. Also, many documented expenses from the participating enterprises were required during the development of the Kalundborg network. This was indeed necessary to test the capacity of the model to take long-term profitability of investments into consideration.

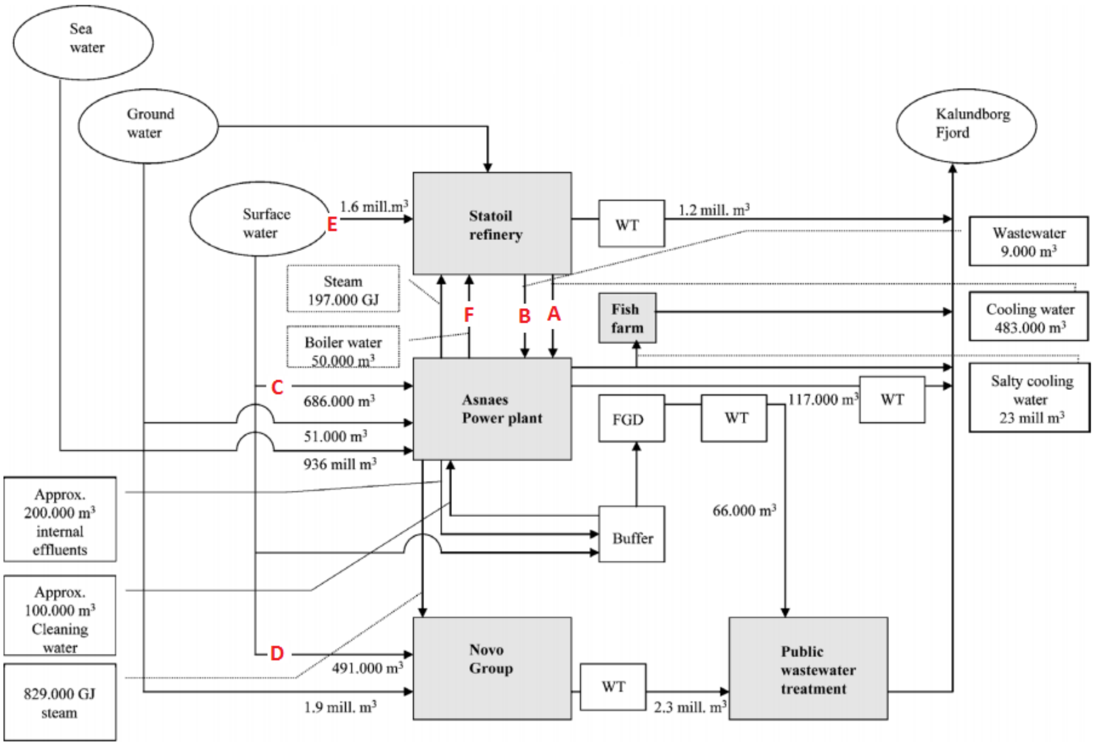


*Figure 2. Exchanges considered. Source: Jacobsen (2006)*

Letters A to F in Figure 2 identify the specific exchanges considered here. Also, although exchanges C, D and E are actually linked by a common investment in a pipeline, we intentionally split the collective investment into individual investment according to local pipeline uses, and considered those as independent pairwise synergies. This reflects a limitation of the model that cannot take into account collective investment, with more than 2 enterprises. All data concerning water price, investments cost, supply cost, etc. was gathered from publicly available papers, studies, and official websites.

The symbolic enterprise “Others” is used to represent the minor actors of the network on which there is not much public details. They are small enterprises, such as local farmers, which don’t produce waste or reject energy or water flows in interesting enough volumes. However, they are collectively able to participate in the project in order to get their supplies of materials or effluents from actors forming the core of the eco-industrial project. The location of this symbolic company has been set to the city center of Kalundborg.

In order to obtain the road distances between companies (shown in appendix), the Google Distance Matrix Application Programming Interface was used, using the address of each company. Finally, the different units of the case study are shown in appendix and are based on Jacobsen (2006).

### 4.1 Case study methodology

The application of the decision support tool was simulated over a period of nine years, from 1992, to 2000. At the beginning of each year, the tool was used in a strategic planning exercise in order to make investment decision for this year only. Because the model is multi-period, each strategic planning exercise proposes investment decisions for the first year, as well as the next two years. Indeed, we choose a planning horizon of three years, because it is the usual payback period aimed at in the case of industrial ecology projects (Bass, 2011). Because this exercise is repeated every year, it is referred to as a rolling horizon planning process.

Next, in order to be as relevant as possible, whatever the decision for the first period proposed by the model at a given exercise, the next planning cycle is always configured using the actual investment decision of the Kalundborg eco-industrial park. In other words, if a synergy was actually implemented during this year, it is considered as being there at the beginning of the next planning exercise. This allows us to better understand the context of decision-making at each planning cycle, as well as the willingness exercised by companies at that time to minimize water consumption.

Finally, although for each planning cycle the actual data was available for the entire planning horizon, we only consider the actual data for the first period, while the data for period two and three was estimated using regression analysis and data of previous periods. Also, because investment decision could be proposed earlier or later by the model, investments cost were updated with the Danish inflation rate.

### 4.2 Results

The experiments were carried out with the Gurobi solver and AMPL. Table 3 shows the water and economic savings for several scenarios (only planning cycles with proposed investments are shown). Table 3 also show that the more companies are willing to absorb a larger deviation from the minimum cost solution (larger δ), the more synergies are proposed by the model.

In the first planning cycle, the model proposes the same synergy that was actually implemented. This investment, although it generates water savings of almost half a million cubic meter, are easily justified by a substantial economic saving. In the second cycle, although nothing was actually implemented, synergies C and D could have been considered for a 7,7% cost deviation from the minimum cost solution. This cost increase would have been even larger for the fourth company to initiate synergy E, which, with C and D, were actually a single collective investment. In the third cycle, the initiation of synergies C, D and E altogether only requires a 6.8% deviation from the minimum cost solution, which is again too large to justify the investment. However, in the next cycle, this cost decreases to a 1,6% deviation, which was this time small enough for all four companies to invest in this collective pipeline. Finally, the economic savings of almost 10M DKK with the addition of the F synergy in the last cycle, is due to an avoided investment of the Statoil refinery for an extension of its water treatment facility (Jacobsen, 2006).

Therefore, it seems that water consumption reduction in the Kalundborg symbiosis was mainly driven by economic factors, with a maximum payback period of around three years.

*Table 3. Environmental and economic benefits of the Kalundborg industrial symbiosis*

| Time frame | Network Situation | δ | Savings (DKK) | Savings (%) | Water savings ($m^3$) | Synergies (existing) and proposed | Initialization year proposed | Actual initialization year |
|---|---|---|---|---|---|---|---|---|
| 1992 - 1994 | w/o new synergies | - | - | - | - | (A) | - | B (1992) |
| | with new synergies | 0 | DKK 3,664,300 | 7.3% | 474000 | AB | B (1992) | |
| | | 5 | DKK 3,664,300 | 7.3% | 474000 | AB | B (1992) | |
| | | 10 | DKK 3,664,300 | 7.3% | 474000 | AB | B (1992) | |
| | | 20 | DKK 3,664,300 | 7.3% | 474000 | AB | B (1992) | |
| 1995 - 1997 | w/o new synergies | - | - | - | - | (AB) | - | C (1997), D (1997) |
| | with new synergies | 0 | DKK - | 0.0% | 0 | AB | - | |
| | | 5 | DKK (840,191) | -1.7% | 5895000 | ABC | C (1995) | |
| | | 10 | DKK (3,731,729) | -7.7% | 7368000 | ABCD | C (1995), D (1995) | |
| | | 20 | DKK (3,731,729) | -7.7% | 7368000 | ABCD | C (1995), D (1995) | |
| 1996 - 1998 | w/o new synergies | - | - | - | - | (AB) | - | C (1997), D (1997), E (1997) |
| | with new synergies | 0 | DKK 1,837,238 | 2.5% | 2952600 | ABC | C (1996) | |
| | | 5 | DKK 778,536 | 1.1% | 5593200 | ABCD | C (1996), D (1996) | |
| | | 10 | DKK (4,950,648) | -6.8% | 9559200 | ABCDE | C (1996), D (1996), E (1996) | |
| | | 20 | DKK (4,950,648) | -6.8% | 9559200 | ABCDE | C (1996), D (1996), E (1996) | |
| 1997-1999 | w/o new synergies | - | - | - | - | (AB) | - | C (1997), D (1997), E (1997) |
| | with new synergies | 0 | DKK 664,320 | 0.8% | 3456000 | ABCD | C (1997), D (1997) | |
| | | 5 | DKK (1,337,897) | -1.6% | 7916500 | ABCDE | C (1997), D (1997), E (1997) | |
| | | 10 | DKK (1,337,897) | -1.6% | 7916500 | ABCDE | C (1997), D (1997), E (1997) | |
| | | 20 | DKK (1,337,897) | -1.6% | 7916500 | ABCDE | C (1997), D (1997), E (1997) | |
| 2000-2002 | w/o new synergies | - | - | - | - | (ABCDE) | - | F (2002) |
| | with new synergies | 0 | DKK 9,357,500 | 12.8% | 50000 | ABCDEF | F (2002) | |
| | | 5 | DKK 9,357,500 | 12.8% | 50000 | ABCDEF | F (2002) | |
| | | 10 | DKK 9,357,500 | 12.8% | 50000 | ABCDEF | F (2002) | |
| | | 20 | DKK 9,357,500 | 12.8% | 50000 | ABCDEF | F (2002) | |

## 6. Conclusion and Future Works

Industrial engineering concepts, and supply chain design modelling in particular, can be adapted to industrial ecology projects and serve to support the evaluation of waste recycling opportunities. In the recent years, optimization models have been developed to maximize the savings in by-product synergy networks. At the same time, tools to evaluate the environmental performance of such networks were proposed in the literature. However, decision makers have to handle both types of tools to measure their cost and benefit, as well as their environmental impact when participating in industrial ecology initiatives.

The proposed multi-criteria optimization model can support companies to integrate and analyse altogether economic and environmental issues. This decision model also enables decision makers to analyse through sensitivity analysis, for example, the price to which a waste should be sold, or the minimal processing capacity of a piece of equipment to buy. Data from the eco-industrial park of Kalundborg were used to illustrate the savings the decision model is able to identify. The results show that some synergies could have been initialised earlier and that, in general, the companies' behaviour is based on a payback period of three years, which confirms the fact that economic considerations are often the main driver of by-products synergy networks.

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. These impacts will become more and more important for companies as they must deal with more restrictive environmental regulations. 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. These results 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. Waste treatment technologies will also have to be carefully looked at in future research projects in order to offer more waste recycling opportunities and improve the efficiency of sorting and processing equipment. Finally, the notion of risk associated with the purchase of industrial waste, in particular concerning quantities and composition and the level of collaboration required in synergies still need to be studied further.

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# Supplement to: MAILLÉ, M., FRAYRET, J.-M. 2012. Decision Support Tool to Identify Industrial Waste Reuse Opportunities in an Industrial Symbiosis Context.

## Summary

This supplement presents the working hypotheses, the sets, the parameters and model on which is based the decision support system described in the article.

## 1. Working Hypotheses

- The solid waste is treated either by the buyer or by the seller.
- Third-party recyclers are considered as buyers or sellers, depending of their role in the synergy.
- The landfilling capacity and the available quantity of raw materials are considered sufficient.
- The buyer cannot acquire waste and directly send it to landfill.
- The environmental aspects related to waste landfilling include the transport from the enterprise to the landfill site.
- The environmental aspects related to raw material purchase include all the activities from the cradle to the buyer process (extraction, transport from the extraction site to the buyer, etc.).
- We consider the stocking capacity for waste and for raw materials as independent.
- We do not consider the stocking of end products, waste meant to be landfilled and raw materials

## 2. Sets

R = Types of waste available

M = Raw materials needed

F = {R ∪ M} = Flows in circulation in the network

G = Waste sellers

P = Potential buyers

E = {G ∪ P} = Enterprises involved in the eco-industrial network

T = Periods considered

V = Processes

A = Material resources

$V_a \in V$ = Processes that the resource a is able to accomplish

## 3. Parameters

$p_{rgt}^{g}$: *Additional volume of type r waste of seller g available at period t*

$p_{mpt}^{p}$: *Volume of material m wanted by buyer p at periode t*

$\omega_{rv}$: *Volume of waste produced by the treatment with process v of one unit of type r waste*

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

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

$\beta_{rv}$: *Volume of type r waste not rejected by the treatment with process v of one unit of type r waste*

$d_{gp}$: *Distance in kilometers between sellerg 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*

$ce_{rg}^{r}$: *Landfilling cost of one unit of type r waste of seller g*

$ce_{vre}^{v}$: *Landfilling cost of one unit of waste produced by the treatment with process v of type r waste of enterprise e*

$cm_{mt}$: *Price in dollars of one unit of raw material m at period t*

$k_{gprt}^{r}$: *Price in dollars of one unit oftype r waste sold by seller p to buyer g*

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

$st_{f}$: *Stocking 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 a 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*

$cs_{g}^{gr}$: *Stocking capacity of seller g for waste in* $m^3$

$cs_{g}^{gm}$: *Stocking capacity of seller g for materials in* $m^3$

$cs_{p}^{pr}$: *Stocking capacity of buyer p for waste in* $m^3$

$cs_{p}^{pm}$: *Stocking capacity of buyer p for materials in* $m^3$

$v_{f}$: *Volume in* $m^3$ *necessary to stock on unit of flow f*

$cap_{a}$: *Treatment capacity of resource a per period in units of waste*

$c_{a}$: *Purchase price of resource a*

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

$\partial$: *Percentage of additional cost that we accept for environmental considerations*

## 4. Model

$$F_1(x) = \sum_t \sum_p \sum_g \sum_r \left\{ \sum_m \left( cm_{mt} * w_{mpt} + st_m * \left( s^{mg}_{mg(t-1)} + s^{mp}_{mp(t-1)} \right) + d_{gp} * \left( tr_r * x^r_{gprt} + tr_m * x^m_{gpmt} \right) + k^r_{gprt} * x^r_{gprt} + k^m_{gpmt} * x^m_{gpmt} \right) + \sum_v \sum_a \left[ \sum_e (q_{ae} * c_a) + ct_{rv} * \left( x^{gv}_{grvat} + x^{pv}_{prvat} \right) + \sum_m (\alpha_{rmv} * e_{rmv}) * ep_t * \left( x^{gv}_{grvat} + x^{pv}_{prvat} \right) + \omega_{rv} * \left( x^{gv}_{grvat} * ce^v_{vrg} + x^{pv}_{prvat} * ce^v_{vrp} \right) \right] + i_{gprt} * z_{gprt} + ni_{gprt} * (1 - z_{gprt}) + st_r * \left( s^{rg}_{rg(t-1)} + s^{rp}_{rp(t-1)} \right) + ce^r_{rg} * y_{rgt} \right\}$$

$$F_2(x) = \sum_m \sum_p \sum_t (w_{mpt} * f_m)$$

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

s.t.

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

$$p^g_{rgt} + s^{rg}_{rg(t-1)} - y_{rgt} - \sum_v \sum_a x^{gv}_{grvat} - \sum_p x^r_{gprt} = s^{rg}_{rgt} \quad \forall r \in R, g \in G, t \in T$$

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

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

$$\sum_g x^r_{gprt} + s^{rp}_{rp(t-1)} - \sum_v \sum_a x^{pv}_{prvat} = s^{rp}_{rpt} \quad \forall r \in R, p \in P, t \in T$$

$$\sum_r \left( s^{rg}_{rgt} * v_r \right) \le cs^{gr}_g \quad \forall g \in G, t \in T$$

$$\sum_m \left( s^{mg}_{mgt} * v_m \right) \le cs^{gm}_g \quad \forall g \in G, t \in T$$

$$\sum_r \left( s^{rp}_{rpt} * v_r \right) \le cs^{pr}_p \quad \forall p \in P, t \in T$$

$$\sum_m \left( s^{mp}_{mpt} * v_m \right) \le cs^{pm}_p \quad \forall p \in P, t \in T$$

$$\sum_r \sum_{v \in V_a} \left( \gamma_{rva} * x^{gv}_{grvat} \right) \le cap_a * (q_{ag} + g_{ag}) \quad \forall g \in G, a \in A, t \in T$$

$$\sum_r \sum_{v \in V_a} \left( \gamma_{rva} * x^{pv}_{prvat} \right) \le cap_a * (q_{ap} + g_{ap}) \quad \forall p \in P, a \in A, t \in T$$

$$\sum_a q_{ae} \le 1 \quad \forall e \in E$$

$$\mathrm{M} * (\mathrm{z}_{\mathrm{gprt}} + \mathrm{z}_{\mathrm{gpr(t-1)}} + \mathrm{z}_{\mathrm{gpr(t-2)}}) \ge \sum_m \left( \alpha_{rmv} * \mathrm{x}^{\mathrm{m}}_{\mathrm{gpmt}} \right) + \mathrm{x}^{\mathrm{r}}_{\mathrm{gprt}} \quad \forall \mathrm{g} \in \mathrm{G}, \mathrm{p} \in \mathrm{P}, r \in R, t \in T$$

$$\mathrm{x}^{\mathrm{gv}}_{\mathrm{grvat}}, \mathrm{x}^{\mathrm{pv}}_{\mathrm{prvat}}, \mathrm{x}^{\mathrm{m}}_{\mathrm{gpmt}}, \mathrm{x}^{\mathrm{r}}_{\mathrm{gprt}}, \mathrm{y}_{\mathrm{rgt}}, \mathrm{s}^{\mathrm{rg}}_{\mathrm{rgt}}, \mathrm{s}^{\mathrm{rp}}_{\mathrm{rpt}}, \mathrm{s}^{\mathrm{mg}}_{\mathrm{mgt}}, \mathrm{s}^{\mathrm{mp}}_{\mathrm{mpt}}, \mathrm{w}_{\mathrm{mpt}}, \alpha_{rmv} \ge 0$$

$$\mathrm{z}_{\mathrm{gprt}}, \mathrm{q}_{\mathrm{ae}} \in \{0,1\}$$

*Table 1. 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 |

*Table 2. Characteristic units used for the flows of the Kalundborg industrial symbiosis*

| 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 |