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Targeting material exchanges in industrial symbiosis networks

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Abstract

Industrial symbiosis plays an important role in the process industry, where an effective management of resources can bring both economic and environmental benefits. Traditionally, the design and extension of eco-industrial parks has been mainly based on intuition and experience; yet, the number of actors involved, the number of flows to manage and the different nature of the materials and energy exchanged lead to complex problems that can benefit from the use of systematic decision-making methods. The aim of this contribution is to produce useful tools to identify the most favourable synergies and transformations for a process network. The proposed model has been tested on a case study that consists of an ethylene and chlorine based eco-industrial park. Results confirm the capabilities of the proposed targeting methodology to match sources and sinks of resources.

Keywords: Industrial symbiosis, process networks, targeting, eco-industrial parks, optimization, sustainability.

1. Introduction

In the last years, there has been a growing awareness of the importance of applying circular economy approaches to close material, energy and water cycles (Merli et al., 2018). With their focus on closing loops in industrial processes, Industrial Symbiosis (IS) principles have been widely applied in many specific sectors (van Ewijk et al., 2018; Deschamps et al., 2018). A shared concern is engaging industries to join: the more participants are involved, the better environmental performance is achieved.

However, current eco-industrial parks (EIP) and resource exchange designs are mainly ad-hoc Industrial Symbiosis approaches, based on identifying opportunities through expert analysis. These strategies, even after a systematic local search, usually lead to sub-optimal solutions. In light of this, there is a need of systematic methods aimed at coping with the complexity of the problems by exploring only feasible and promising alternatives. Previous works have focused on the development of tools for transformation companies that might make profit of connecting sources and sinks of resources, and thus reducing the final waste involved (Somoza-Tornos et al., 2017 and 2018).

The aim of this work is to develop efficient targeting methods that identify the most promising synergies for industrial symbiosis while discarding infeasible links. A material network is designed to model the exchange of materials that become profitable for the involved actors (sources, transformers and sinks). Conservation laws and thermodynamic constraints are used to discern between the resulting alternatives.

2. Problem statement

The system under study is illustrated in Figure 1.

The targeting problem can be stated as follows: Given a set of waste streams *j* that could be potentially treated to satisfy the raw materials demand of streams *k*; a set of chemical reactions that may take place between the *i* products composing the mentioned streams: and other available data, including complete economic data, technical constraints and thermodynamic parameters. The decisions to be made comprise the amount of waste processed by the system, whether or not it is transformed, the requirements of external feeds or demands, how the products are distributed to satisfy the needs of customers and which side products have to be disposed.

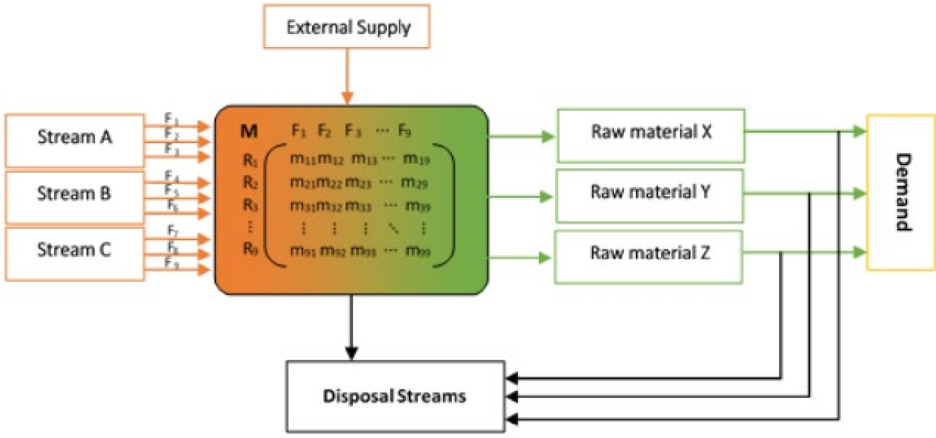

Figure 1. Material network scheme.

3. Mathematical formulation

The problem is formulated as a MILP that finds the optimal synergies between waste producers and raw materials consumers.

The total inlet to the system includes waste streams W_{ji} and potential supply of products required to complete the transformation ES_i (Eq. (1)).

$$\sum_j W_{ji} + ES_i = F_i^{in} \quad \forall\, i \tag{1}$$

Eq. (2) defines the mass balance of the system considering the inlet, outlet and generation terms, the last one calculated through stoichiometric coefficients R_{mi} and the extent of the reaction F_m^{gen}.

$$F_i^{in} + \left(\sum_m R_{mi} \cdot F_m^{gen}\right) = F_i^{out} \quad \forall\, i \tag{2}$$

The result of the transformation F_i^{out} is then divided in two, the amount sent to customers F_{ki}^{rm} and the side products that are unassigned F_{li}^{d} (Eq. (3)). This balance is completed with the introduction of the term F_i^{ed} to represent the external demand that new partners may have.

$$F_i^{out} = \sum_k F_{ki}^{rm} + \sum_l F_{li}^{d} + F_i^{ed} \quad \forall\, i \tag{3}$$

z_k is defined in Eqs. (4,5) as a binary variable that takes a value of 1 if the amount sent to the customers, F_{ki}^{rm}, is greater than the demand.

$$D_{ki} \cdot z_k \leq F_{ki}^{rm} \quad \forall k, i \tag{4}$$

$$F_{ki}^{rm} - D_{ki} \leq M \cdot z_k \quad \forall k, i \tag{5}$$

Hence, when the demand is surpassed, the profit of selling C_k it is penalized with a cost for the excess of delivery C_k^d.

$$f_k^1 \leq M \cdot z_k \quad \forall k \tag{6}$$

$$f_k^1 \leq \left(\sum_i D_{ki} \cdot C_k\right) - C_k^d \cdot \sum_i (F_{ki}^{rm} - D_{ki}) \quad \forall k \tag{7}$$

On the contrary, when demand is not covered, only the amount sent to the customer must be taken into account for the profit calculation.

$$f_k^2 \leq M \cdot (1 - z_k) \quad \forall k \tag{8}$$

$$f_k^2 \leq \left(\sum_i F_{ki}^{rm} \cdot C_k\right) \quad \forall k \tag{9}$$

The energy balance of the system is calculated as in Eq. (10), where Q_m^{exc} denotes the amount of energy added or extracted from the system.

$$\left(\sum_i R_{m,i} \cdot F_m^{gen} \cdot H_i\right) = Q_m^{exc} \quad \forall\, m \tag{10}$$

Binary variable y_m is defined in Eqs. (11,12) to differentiate processes that require heating or cooling and apply costs accordingly.

$$Q_m^{exc} \leq M \cdot y_m \quad \forall m \tag{11}$$

$$-Q_m^{exc} \leq M \cdot (1 - y_m) \quad \forall m \tag{12}$$

Eqs. (13,14) apply when heat is extracted from the system, and cost parameter CQ_{out} is considered.

$$f_m^3 \leq M \cdot y_m \quad \forall m \tag{13}$$

$$-f_m^3 \leq Q_m^{exc} \cdot CQ_{out} \quad \forall m \tag{14}$$

Conversely, when heat is added to the system, the cost is calculated through Eqs. (15,16).

$$f_m^4 \leq M \cdot (1 - y_m) \tag{15}$$

$$-f_m^4 \leq -Q_m^{exc} \cdot CQ_{in} \tag{16}$$

The objective function to be maximized is the economic balance shown in Eq. (17). It considers the profit obtained from satisfying the demand of current companies and potential new partners. Aggregated cost parameters associated with the different transformation routes are considered at this step. These aggregated costs, including capital and operational costs plus indirect costs like transportation and management, must be estimated according to the specific circumstances, and the sensibility of the results to these estimations must be adequately assessed.

$$OF = -\left(\sum_i \sum_l F_{li}^d \cdot C_l\right) - \left(\sum_i \sum_j W_{j,i} \cdot C_j\right) - \left(\sum_m F_m^{gen} \cdot C_m^R\right) - \left(\sum_i Es_i \cdot C_i^{es}\right) + \left(\sum_i F_i^{ed} \cdot C_i^{ed}\right) + \sum_k f_k^1 + \sum_k f_k^2 - \left(\sum_m f_m^3 + \sum_m f_m^4\right) \quad (17)$$

The resulting model for the targeting can be posed as follows:

TSym min [OF]

s.t. Eqs. (1-17)

4. Case study

The capabilities of the model are illustrated in a case study consisting of an eco-industrial park based on ethylene and chlorine, with 10 available waste streams and 7 demands of raw material have been defined. The considered compounds include acetic acid, benzene, chlorine, vinyl chloride, ethanol, ethylbenzene, ethylene, ethylene dichloride, ethylene oxide, hydrochloric acid, oxygen, tetrachloroethylene, trichloroethylene, vinyl acetate and water. Eqs. (18-26) show the reactions that the park would consider can take place between the components by a transformation company.

$$C_2H_4 + Cl_2 \rightarrow C_2H_4Cl_2 \quad (18)$$

$$3Cl_2 + C_2H_4Cl_2 \rightarrow 4HCl + C_2Cl_4 \quad (19)$$

$$2C_2H_4 + 4HCl + O_2 \rightarrow 2C_2H_4Cl_2 + 2H_2O \quad (20)$$

$$C_2H_4Cl_2 \rightarrow C_2H_3Cl + HCl \quad (21)$$

$$C_2H_4Cl_2 + Cl_2 \rightarrow C_2HCl_3 + 3HCl \quad (22)$$

$$C_2H_4 + H_2O \rightarrow CH_3CH_2OH \quad (23)$$

$$C_2H_4 + \frac{1}{2}O_2 \rightarrow CH_2OCH_2 \quad (24)$$

$$C_2H_4 + CH_3COOH + \frac{1}{2}O_2 \rightarrow CH_3CO_2CHCH_2 + H_2O \quad (25)$$

$$C_6H_6 + C_2H_4 \rightarrow C_6H_5C_2H_5 + H_2O \quad (26)$$

5. Results

The resulting MILP problem, featuring 1209 equations, 1064 continuous variables and 159 binary variables, has been modeled in GAMS 23.8.2 and solved with CPLEX 12.4.

Four different scenarios have been defined to examine the chances of incorporating new participants in the symbiotic network. These new participants can either be a source of waste or raw materials consumers, all presenting their own capacity limitations.

a) Base case of the existing eco-industrial park (EIP)

b) New companies could join the EIP and offer new sources of waste
c) New partners could join the EIP and take advantage of generated waste
d) New companies could both as a source and sink of resources

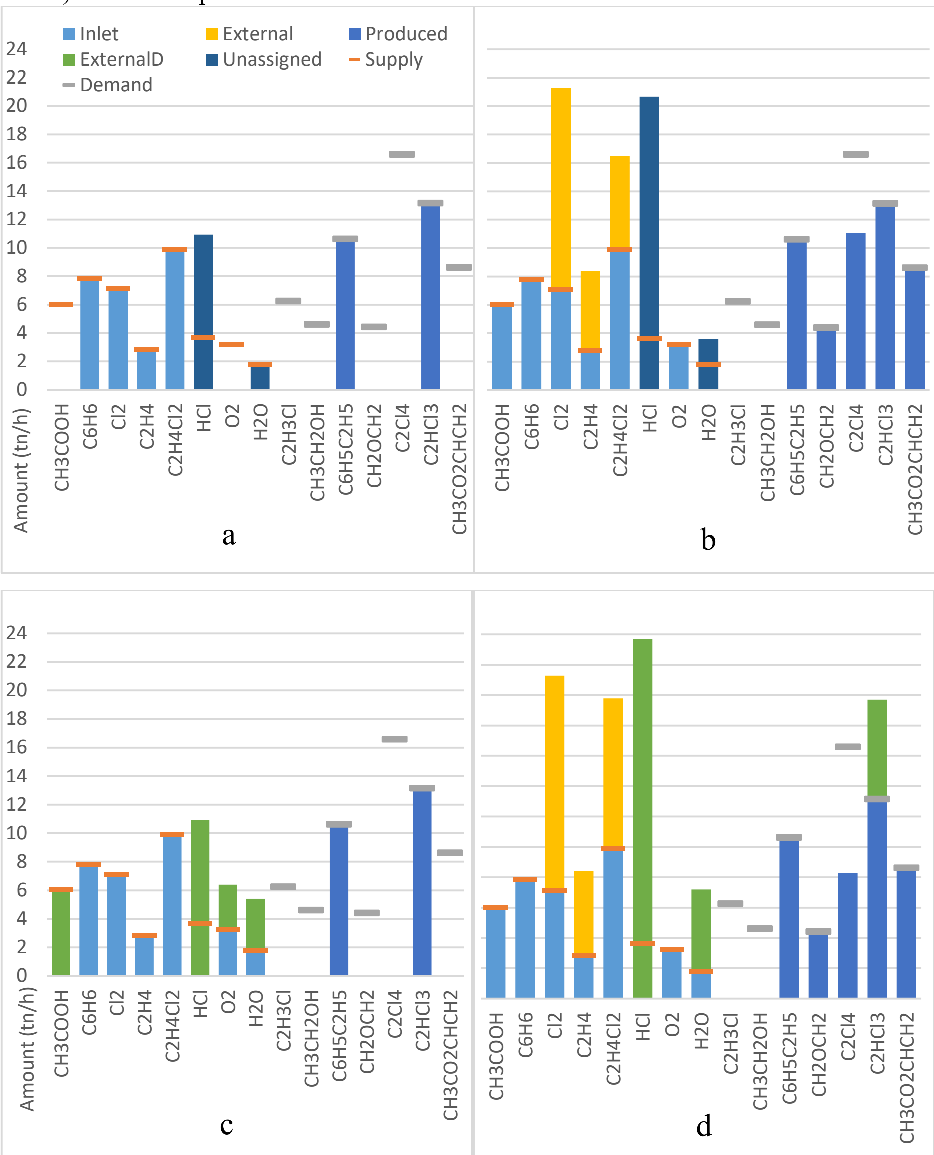

Figure 2. Waste usage and raw materials satisfaction for scenarios a, b, c, d.

Figure 2.a depicts the waste usage and the raw materials demand satisfaction for the existing EIP. The first case, where no external supply is available, is constrained by the limit in the waste supply. Reactions (22) and (26) are active to produce ethylbenzene and trichloroethane. The lack of ethylene does not allow acidic acid to be used in reaction (25) and there are sources of an excess of HCl and water that is not reused. Figure 2.b shows the effect of finding new partners that may be a source of waste. By adding new producers of chlorine, ethylene and ethylene dichloride to the park, more of

the demands are internally covered and thus the external requirements of raw materials are reduced. Transformations (19), (24) and (25) would have to be activated to produce ethylene oxide, tetrachloroethylene and vinyl acetate, thus increasing the amount of waste processed and the profit of the entire complex. This would increase even more the excess of side products. In Figure 2.c the opposite case is represented, where new partners would only be interested in raw materials production. As the waste supply was limiting the base case, only the side products in excess can be used, resulting in a reduced grow of the EIP. When these limitations are overcome in Figure 2.d, the most promising ways of making the EIP grow are identified, and so are the transformations that the policy-makers should foster.

6. Conclusions

This work has addressed the development of a tool to identify the most promising routes to match sources and sinks of resources, even when a transformation step is required. This will help to reduce the complexity of the analysis required during the synthesis and design of industrial processing networks. Hence, the model offers policy-makers a method to systematically identify and assess opportunities for increasing the integration of process networks in industrial complexes. Thus, Administrations may use their resources to incentive partners that will ensure economically feasible synergies with the ultimate goal of reducing waste. An adequate reformulation of the objective function may also allow these companies to identify their opportunities, and even the different members of the industrial network the best cooperation opportunities (multi-objective approach). Future work will also focus on the application of combined targeting-synthesis methodologies to systematically analyse in detail the resulting proposals.

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