CHEMICAL ENGINEERING TRANSACTIONS
VOL. 35, 2013
Guest Editors: Petar Varbanov, Jiří Klemeš, Panos Seferlis, Athanasios I. Papadopoulos, Spyros Voutetakis
Copyright © 2013, AIDIC Servizi S.r.l.,
ISBN 978-88-95608-26-6; **ISSN** 1974-9791
A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet
DOI: 10.3303/CET1335012

Dynamic Multi-Objective Synthesis of Companies' Renewable Biomass and Energy Supply-Networks

Annamaria Kiraly[a,*], Bojan Pahor[a], Lidija Čuček[b], Zdravko Kravanja[b]

[a]Perutnina Ptuj d.d, Potrčeva 10, Ptuj SI-2250, Slovenia
[b]Faculty of Chemistry and Chemical Engineering, University of Maribor, Smetanova ulica 17, SI-2000, Maribor, Slovenia
annamaria.kiraly@perutnina.eu

This contribution presents a dynamic multi-objective synthesis of companies' supply-networks for improving companies' energy-supplies and environmental impacts by integrating renewables (biomass and other waste, and solar energy), based on Mixed-Integer Linear Programming (MILP).

The previously developed model for achieving energy self-sufficiency by integrating renewables into companies' supply networks (Kiraly et al., 2013a) has been extended for the usage of variable supply and demand. In the case of variable supply, monthly durations of sunlight hours regarding different locations have been taken into account and, therefore, electricity production differs according to time and space. In the case of variable demand, monthly variations have been taken into consideration regarding demands for the more important products.

For evaluating the sustainability of the companies' supply networks, different environmental footprints, such as carbon, water, and nitrogen footprints have been included (Kiraly et al., 2013b). An approach measuring the environmental footprints within an LCA-based synthesis was carried-out by considering the total-effects (burdening and unburdening) on the environment (Čuček et al., 2012).

1. Introduction

Nowadays more and more companies are developing technologies for using clean and renewable energy resources for improving their energy efficiencies and costs, whilst significantly decreasing environmental burdens. Not only do they gain competitive advantage within the global market by reducing environmental pollution but also by making nearby surroundings better places to live. Planning is of major importance when utilising alternative energy sources. Renewable energy sources are limited locally and the quantities available differ over time.

Since the main intention of companies is to maximise profit on the one hand, whilst decreasing environmental burdens on the other hand, this leads to multi-objective optimisation (MOO) problems. In addition, they also have to satisfy variable demands by using variable supplies. There is, therefore, a need for dynamic multi-objective optimisation in order to synthesise optimal production.

The objective was to maximise the economic performance of multi-objective synthesis as the main criterion, and to minimise environmental footprints as additional criteria. Several total environmental footprints (Čuček et al., 2012) were evaluated, such as carbon, water, and nitrogen footprints. Total footprints consider both direct and indirect effects on the environment in order to provide an overall assessment of environmental impacts. Direct footprints only measure directly harmful effects (burdens), whilst indirect footprints measure those indirect unburdening effects caused by harmful products substitution with benign products, and by the utilisation of harmful products rather than discarding them. Considering total effects enables the obtaining of more realistic solutions (Kravanja et al., 2013). Obtained solutions from multi-objective optimisation are those that are simultaneously economically-efficient and environmentally unburdening and/or benign.

Please cite this article as: Kiraly A., Pahor B., Cucek L., Kravanja Z., 2013, Dynamic multi-objective synthesis of companies' renewable biomass and energy supply-networks, Chemical Engineering Transactions, 35, 73-78 DOI:10.3303/CET1335012

2. Problem Formulation

This synthesis model is formulated as an multi-period one in order to take into account market, seasonal, and other changes (van den Heever et al., 1999). The general form of the multi-period model, defined over time periods $\boldsymbol{tp} \in \boldsymbol{TP}$ (Čuček, 2013), is as follows:

$$\begin{aligned}
&\min_{x,y} \text{ or } \max \quad \boldsymbol{c}^{\mathrm{T}}\boldsymbol{y} + \sum_{\boldsymbol{tp}\in \boldsymbol{TP}} \boldsymbol{f}_{\boldsymbol{tp}}(\boldsymbol{x}_{\boldsymbol{tp}},\boldsymbol{d}) \\
&\text{s.t.} \quad \left.\begin{aligned} &\boldsymbol{h}_{\boldsymbol{tp}}(\boldsymbol{x}_{\boldsymbol{tp}},\boldsymbol{d},\boldsymbol{y}) = 0 \\ &\boldsymbol{g}_{\boldsymbol{tp}}(\boldsymbol{x}_{\boldsymbol{tp}},\boldsymbol{d},\boldsymbol{y}) \le 0 \\ &\boldsymbol{g}^{\mathrm{D}}_{\boldsymbol{tp}}(\boldsymbol{x}_{\boldsymbol{tp}},\boldsymbol{y}) \le \boldsymbol{d} \end{aligned}\right\} \forall \boldsymbol{tp} \in \boldsymbol{TP} \qquad \text{(Multi-period MILP)} \\
&\qquad \boldsymbol{x}_1 = \boldsymbol{x}_{|\boldsymbol{T}|} \\
&\qquad (\boldsymbol{x}_{\boldsymbol{tp}},\boldsymbol{d}) \in \boldsymbol{R}^n, \forall \boldsymbol{tp} \in \boldsymbol{TP}, \boldsymbol{y} \in \{0,1\}^m
\end{aligned}$$

where $\boldsymbol{x}$ denotes a vector of involved continuous variables and $\boldsymbol{y}$ a vector of involved binary variables. The objective function is composed of fixed charge ($\boldsymbol{c}^{\mathrm{T}}\boldsymbol{y}$) and variable charge ($\boldsymbol{f}$) terms. $\boldsymbol{h}$ denotes the equality constraints and $\boldsymbol{g}$ the inequality process specifications or constraints. Continuous variables $\boldsymbol{x}$ and constraints $\boldsymbol{f},\boldsymbol{g},\boldsymbol{h}$ are indexed over time period $tp \in TP$, whilst design ($\boldsymbol{d}$) and binary ($\boldsymbol{y}$) variables are not. Constraint $\boldsymbol{g}^{\mathrm{D}}_{\boldsymbol{tp}}(\boldsymbol{x}_{\boldsymbol{tp}},\boldsymbol{y}) \le \boldsymbol{d}$ defines that the value of a design variable should be greater than or equal to its maximal value from time periods $tp \in TP$. $\boldsymbol{x}_1 = \boldsymbol{x}_{|\boldsymbol{T}|}$ represents the continuity equation which means circular operation over time (Čuček, 2013).

The dynamic multi-objective synthesis for improving companies' energy-supplies and environmental impacts is performed over two steps. During the first mixed-integer linear programming step (MILP-1) the synthesis model is solved with the objective of maximising profit. MILP-1 solutions are used as a reference solution, representing the maximum profit possible. Then the second MILP step (MILP-2) is solved for obtaining the MOO solution(s).

MOO is performed separately for each footprint *f*, $\forall \boldsymbol{f} \in \boldsymbol{FP}$ at MILP-2 by applying the ε-constraint method for each iteration $\boldsymbol{k}$, $\boldsymbol{k} \in \boldsymbol{K}$. A sequence of constrained single-objective $(\mathrm{MILP}-2)_{f,k}$ problems is solved for each footprint *f*, as the maximisation of the profit subjected to a relative footprint $(\boldsymbol{F}^{r}_{f,k})$. The relative footprint is defined as the footprint obtained at MILP-2 $(\boldsymbol{F}^{r}_{f,k}(\boldsymbol{x}_{tp},\boldsymbol{y}))$ divided by the footprint obtained at MILP-1 $(\boldsymbol{F}^{0}_{f}(\boldsymbol{x}_{tp},\boldsymbol{y}))$. It decreases sequentially from the maximal footprint obtained at MILP-1 by a suitable step-size until there is no feasible solution. The synthesis problem at MILP-2 takes the following form (Čuček, 2013):

$$\begin{aligned}
&\min_{x,y} \text{ or } \max \quad \boldsymbol{c}^{\mathrm{T}}\boldsymbol{y} + \sum_{\boldsymbol{tp}\in \boldsymbol{TP}} \boldsymbol{f}_{\boldsymbol{tp}}(\boldsymbol{x}_{\boldsymbol{tp}},\boldsymbol{d}) \\
&\text{s.t.} \quad \left.\begin{aligned} &\boldsymbol{h}_{\boldsymbol{tp}}(\boldsymbol{x}_{\boldsymbol{tp}},\boldsymbol{d},\boldsymbol{y}) = 0, \\ &\boldsymbol{g}_{\boldsymbol{tp}}(\boldsymbol{x}_{\boldsymbol{tp}},\boldsymbol{d},\boldsymbol{y}) \le 0, \\ &\boldsymbol{g}^{\mathrm{D}}_{\boldsymbol{tp}}(\boldsymbol{x}_{\boldsymbol{tp}},\boldsymbol{y}) \le \boldsymbol{d} \\ &\boldsymbol{F}^{r}_{f,k}(\boldsymbol{x}_{\boldsymbol{tp}},\boldsymbol{y}) \le \varepsilon_k \end{aligned}\right\} \forall\, \boldsymbol{tp} \in \boldsymbol{TP} \qquad (\mathrm{MILP}-2)_{f,k}, \forall \boldsymbol{f} \in \boldsymbol{FP} \\
&\qquad \boldsymbol{x}_1 = \boldsymbol{x}_{|\boldsymbol{T}|} \\
&\qquad (\boldsymbol{x}_{\boldsymbol{tp}},\boldsymbol{d}) \in \boldsymbol{R}^n,\ \forall\, \boldsymbol{tp} \in \boldsymbol{TP},\ \boldsymbol{y} \in \{0,1\}^m \\
&\qquad \varepsilon_{k-1} = \varepsilon_k - \Delta\varepsilon,\ \ \Delta\varepsilon = \frac{1}{\boldsymbol{N}},\ \ \varepsilon_1 = 1,\ \ \boldsymbol{k} \in \boldsymbol{K} = \{1,\ldots,\boldsymbol{N}+1\}
\end{aligned}$$

where relative footprint $(\boldsymbol{F}^{r}_{f,k}(\boldsymbol{x}_{tp},\boldsymbol{y}))$ is defined as $\boldsymbol{F}^{r}_{f,k}(\boldsymbol{x}_{tp},\boldsymbol{y}) = \dfrac{\boldsymbol{F}_{f,k}(\boldsymbol{x}_{tp},\boldsymbol{y})}{\boldsymbol{F}^{0}_{f}(\boldsymbol{x}_{tp},\boldsymbol{y})}$.

3. Description of dynamic industrial supply-network

The industrial supply-network includes three different renewable energy sources – solar energy, low-grade heat, and animal and organic wastes, as a side-product from a large poultry processing industry. Electricity is being produced at four biogas plants (BGP1, BGP3, BGP4, and BGP5) combined with heat and power (CHP1, CHP3, CHP4, and CHP5) units, and the majority of the rooftops of industrial complexes are exploited for electricity production by photovoltaic (PV) panels, see Figure 1.
When the complete available manure was used for energy production within biogas plants, self-sufficiency regarding electricity supply had been exceeded by 13 %. By adding all the other alternative energy-sources, the company's energy self-sufficiency was exceeded by 88 %. A more detailed description of the industrial case-study can be found in the previous paper (Kiraly et al., 2013a).

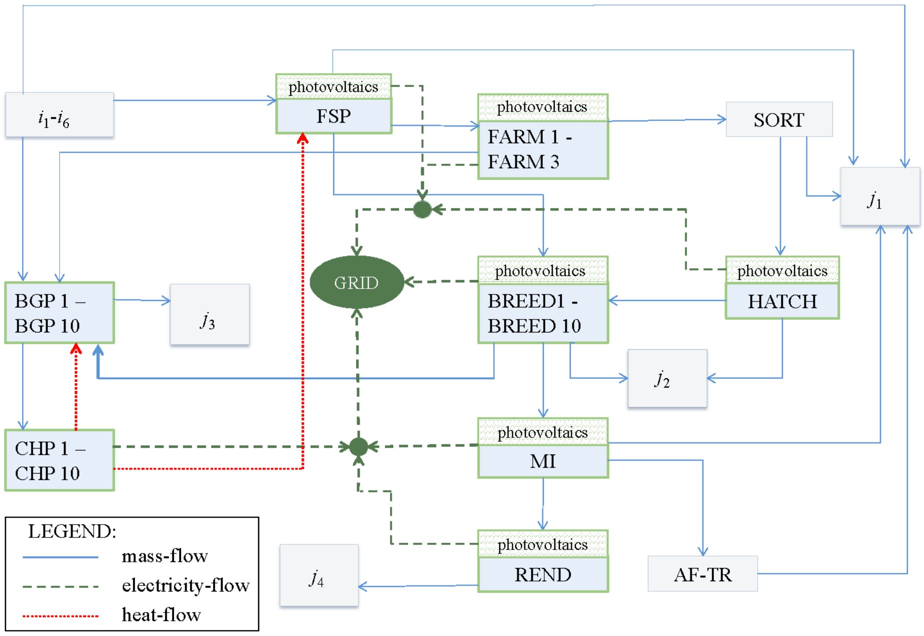

Figure 1: Utilisation of renewables within the industrial supply-network (after Kiraly et al. (2013a))

The synthesis of the company's supply-network was performed over a time period of one year, divided into twelve time periods (months). Only those variables, the values of which differed the most throughout the time periods and had the more important impacts on the company's profit, were included as dynamic ones, whilst all the others were regarded as steady-state variables. The dynamic variables can be defined as:

1) Key products: fresh poultry meat, and processed poultry meat products. Their demand is specified on a monthly basis, and their monthly prices are also considered.
2) PV panels placed on the rooftops of breeding facilities (BREED1-BREED10), farms (FARM1-FARM3), feeding-stuff plant (FSP), hatchery (HATCH), meat industry (MI), and rendering plant (REND). These facilities are located across four areas of the region, and therefore, their electricity production differs from location to location. Electricity production also differs on a monthly basis due to different sunlight durations (Ministry of Agriculture and Environment; Slovenian Environment Agency, 2012).
3) Monthly-averaged heat demands of the settlements nearby additional BGPs are investigated. The trade-off between the cost for cooling the excess heat (if not sold for district heating), and the costs are set for transporting the manure from breeding facilities to biogas plants.

4. Results and discussion

Three scenarios were applied when optimising the dynamic industrial supply-network:

- Scenario 1: It should implement maximisation of profit by considering the listed enhancements for multi-periodic synthesis of the supply-chain.
- Scenario 2: It should exclude the possibility of selling generated heat for district heating to nearby settlements. All the generated heat should therefore be cooled.

- Scenario 3: It should represent the option that the total amount of available manure should be used for energy production. In this case four BGPs with given capacity should be installed.

The optimal solutions from different scenarios were found by a mathematical programming approach using a MILP model. The single-objective model consisted of approximately 19,000 constraints, 38,000 single variables, and 55 binary variables. All MILPs were solved using the GAMS modelling system (Brooke et al., 2005) and the CPLEX MILP solver (CPLEX Optimization Inc., 1993).

The comparisons between different scenarios in terms of relative profit, selected CHP plants, the amounts of used waste, and sold heat and electricity, can be seen in Table 1.

Table 1: Comparisons between different scenarios

Scenarios	Relative profit	Selected biogas cogeneration plants	The amount of used waste (t/y)	Sold electricity (GWh/y)	Sold heat (TJ/y)
1	1	1, 4, 5	30,473.6	47.5	95.1
2	0.9901	1, 6, 7	30,473.6	47.5	0.0
3	0.9888	1, 3, 4, 5	34,536.7	51.4	96.2

Table 1 shows the comparisons between Scenarios 1 – 3. For Scenario 1, BGPs were chosen that were near those settlements needing heat greater than the BGPs production. For Scenario 2, relative profit decreased because the generated heat was taken from the process by cold utility rather than being sold, and also the different BGP locations were chosen. By forcing the model to use the total amount of available manure for energy production (Scenario 3) the relative profit decreased by 1.12 %. This indicated that the fourth added BGP (BGP3) was not economically viable. The reasons for that were the transportation costs between BGP locations and BREED2 – BREED10, and the high costs of the process operation for smaller quantities of heat and electricity production. Figure 2 shows how the monthly electricity production changed for each additional energy-producing unit.

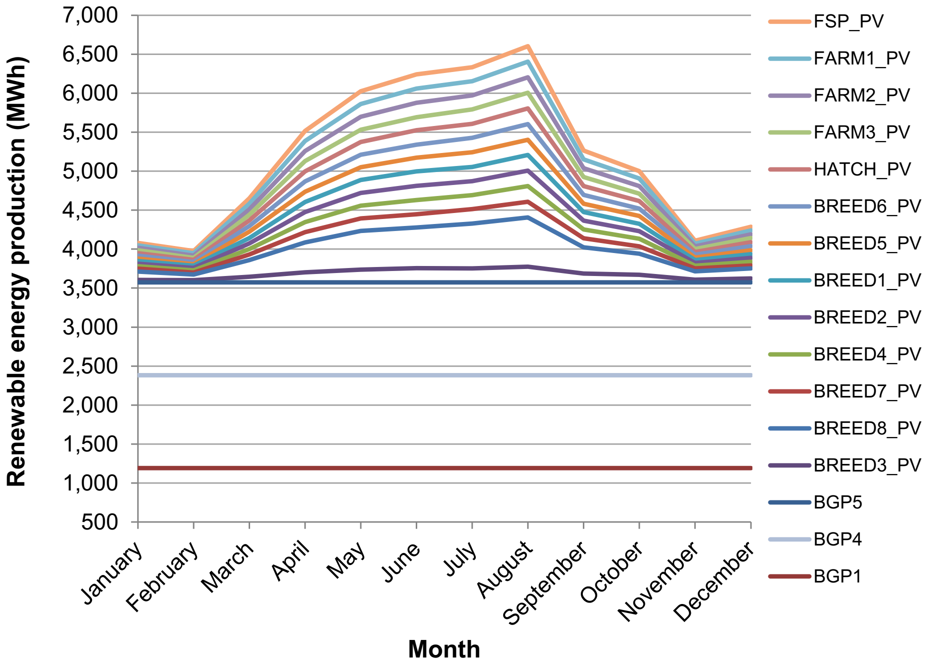

Figure 2: Monthly electricity production (MWh/month)

As it can be seen in Figure 2, energy production from BGPs was constant during the whole year. On the other hand, the energy produced from PV panels increased from February until August due to increasing monthly sunlight durations, and decreased during the other half of the year. Figure 2 shows that the peak of the electricity production was in August, as a consequence of the longer bright sunlight duration during August.

Figure 3 presents the company's monthly electricity self-sufficiency. It shows that electricity self-sufficiency was more than obtained over the whole year. The peak of it was achieved in August, when the electricity self-sufficiency was exceeded by more than 200 %.

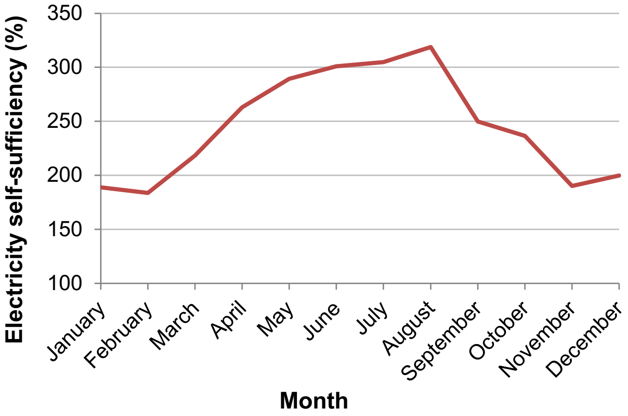

Figure 3: Electricity self-sufficiency (%) over a one year time period

4.2 Multi-Objective Optimisation

Dynamic multi-objective optimisation was implemented for improving the company's energy-supplies and environmental impacts by maximising the profit, and minimising the environmental footprints. The multi-objective optimisation was performed for the whole year. However, the profit's and footprints' monthly values, obtained from the model, were summed on a yearly-basis. Figure 4 presents the relative profit vs. relative total carbon, water, and nitrogen footprints.

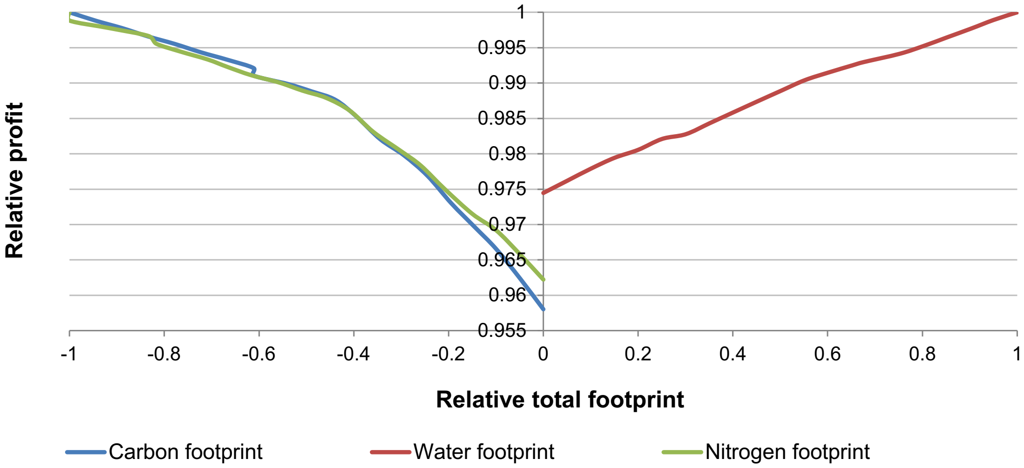

Figure 4: Relative profit vs. relative total footprints

Figure 4 shows that the total carbon and nitrogen footprints improved and increased the profit, and corresponded to the non-trade off solution curves. On the other hand, the relative water footprint worsened with increased profit because of the large water consumption during biogas production.

5. Conclusions

The generic model for achieving energy self-sufficiency by integrating renewables into companies' supply networks was extended for the consideration of variable supply and demand. In the case of variable supply, monthly durations of sunlight hours at different locations were taken into account. Also monthly-variable demand was considered for a company's key products on the market, and for electricity and heat. The obtained results from the developed dynamic model reflected continuously changing market conditions, and thereby provided more realistic economic and environmental solutions. Simultaneous multi-objective optimisation was performed with maximisation of the profit and minimisation of total environmental footprints, such as carbon, water, and nitrogen footprints. Note that it is also possible to maximise indirect unburdening effects in addition to the usual minimisation of direct burdening effects, as total footprints consist of both the burdening and unburdening effects. Using total footprints therefore enables the obtaining more accurate solutions that are more profitable and yet environmentally less harmful or even unburdening (Kravanja et al., 2012).

Acknowledgement

The financial support is gratefully acknowledged from the European Social Fund, the Slovenian Technology Agency - TIA (PhD research fellowship contract No. P-MR-10/89), and the Slovenian Research Agency – ARRS (program P2-0032).

References

Brooke A., Kendrick D., Meeraus A., Raman R., 2005, GAMS – A user's guide, The Scientific Press, Washington, US.

CPLEX Optimization Inc., 1993, Using the CPLEX callable library and CPLEX mixed integer library, CPLEX Optimization Inc., Incline Village, NV, US.

Čuček L., 2013, Synthesis of sustainable bioprocesses using computer-aided process engineering. PhD Thesis, University of Maribor, Maribor, Slovenia <dkum.uni-mb.si/Dokument. php?id=55146> Last accessed: 19.05.2013.

Čuček L., Varbanov P.S., Klemeš J.J., Kravanja Z., 2012, Total footprints-based multi-criteria optimisation of regional biomass energy supply chains. Energy, 44, 135-145.

Kiraly A., Pahor B., Kravanja Z., 2013a, Achieving Energy Self-Sufficiency by Integrating Renewables into Companies' Supply Networks. Energy, 55, 46-57.

Kiraly A., Pahor B., Kravanja Z., 2013b, Improving company's environmental impacts by integrating renewables, 6th International Conference on Process Systems Engineering (PSE ASIA), Kuala Lumpur, Malaysia, ID-188.

Kravanja Z., Čuček L., 2012, CAPE for sustainable development considering the direct and indirect environmental effects in a multiobjective synthesis of sustainable systems, CAPE Forum, Veszprém, Hungary, p. 9.

Kravanja Z., Čuček L., 2013, Multi-objective optimisation for generating sustainable solutions considering total effects on the environment. Applied Energy, 101, 67-80.

Ministry of Agriculture and Environment; Slovenian Environment Agency, 2012, Current climate - last 12 months, <meteo.arso.gov.si/met/en/climate/current/last-12-months/> accessed 10.03.2013.

van den Heever S.A., Grossmann I.E., 1999, Disjunctive multiperiod optimization methods for design and planning of chemical process systems. Computers and Chemical Engineering, 23, 1075-1095.