SENSITIVITY ANALYSIS OF CHANGING PARAMETERS IN METHANOL PROCESS

Anita Kovač Kralj and Peter Glavič

Faculty of Chemistry and Chemical Engineering, University of Maribor,
Smetanova 17, Maribor, Slovenia
Phone: +386 02 2294454 Fax: +386 02 2527 774 E-mail: anita.kovac@uni-mb.si

Abstract

In this work the objective function of the optimization model is enlarged to perform sensitivity analysis in simultaneous approach to process optimization using nonlinear programming (NLP) model. The optimal structure is depending on the costs of utility and depreciation of equipment. The sensitivity analysis of the objective function is including the effects, which can influence the optimal process structure, production rate and profit. The pessimistic profit is 1,055 MEUR/a and the effects can bring additional profits.

1. Introduction

The proper process optimization can lead to considerable saving of energy consumption in process industries. The two major approaches for optimization are pinch analysis (Linnhoff, 1982; Tjoe and Linnhoff, 1986; Ahmad and Hui 1991), and mathematical optimization methods (Biegler et al., 1997). The former is based on thermodynamic insights, while the latter involves the formulation of a constrained optimization problem. The pinch analysis does not guarantee the global optimal solution because it cannot be used simultaneously with material balances but it quickly proposes good integrated structures between nontrivial complex processes. Mathematical optimization methods can be classified as simultaneous approaches. The simultaneous approach can account for capital and energy trade-off accurately and can thus yield better solution, but it is difficult to converge for complex and energy intensive processes because the number of variables increases with the number of combinations. We used the NLP model, which included both methods and with them the problem was easier to solve. But good solution of both methods are depending on the costs of utility and equipment.

In this paper, we are concerned with the design using simultaneous NLP mathematical optimization techniques influenced by the sensitivity analysis of the objective function.

2. The sensitivity analysis

The superstructure was optimized using the mathematical NLP model subject to the sensitivity analysis of the NLP model containing equations for structural and parametric optimization of the plant. The superstructure and optimal solution are depending on the costs of utilities and depreciation of equipment. The published cost equations for the heat exchangers are usually not adjusted to the real, higher industrial costs even if the inflation indices are applied to the NLP model. We must analyse the effects, which influence the solution. The objective function of the NLP model is maximizing the annual profit, in which the costs of utility and depreciation of equipment are restricted either by pessimistic or optimistic values. The objective function is based on the pessimisic costs, but it classifies the possible additional profit with optimistic costs and process operating conditions changes (Fig. 1). The sensitivity analysis of the objective function is including the effects, which can change the optimal process structure, production rate and profit. We can classify the effects into:

- the effect of the inlet flow composition,
- the effect of the temperature regarding night/day and winter/summer working condition,
- the effect of the raw material inlet amount flow rates,
- the effect of the equipment depreciation costs and
- the effect of the utility costs and product price.

All the effects can be included in the objective function of the NLP model of the sensitivity analysis. Simultaneous optimization can give additional annual profit which is strongly influenced by the changing parameters.

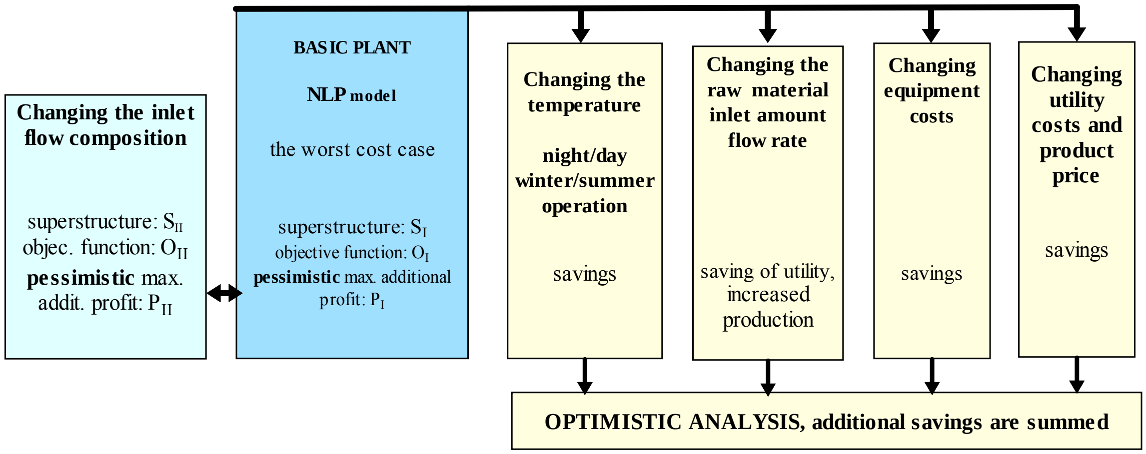

Figure 1: Diagram of sensitivity analysis.

The effect of the inlet flow composition

The primary inlet flow composition is contained in superstructure S_I connected with the set of equations E_I and objective function O_I. E_I represents process equations, which are including mass and energy balances for all the process units. The pessimistic objective function O_I maximizes additional profit, which is the difference between the additional annual revenue and the additional annual depreciation and energy cost. The superstructure can be formulated as an NLP model. The change of the inlet flow composition is formulated in a new superstructure S_{II} connected with the new set of equations E_{II} and the new pessimistic objective function O_{II}. The process parameters (amount flow rates, heat flow rates, temperatures, pressures, etc.) are remaining unchanged.

The effect of the temperature regarding night/day and winter/summer working condition

The ambient temperature affects the utility consumption especially the cooling water one. In the objective function time activation parameters (night – N, winter – W, day – D and summer – S) are included. They can be represented by the corresponding active time for different night/day and winter/summer operation. The flow rate of cooling water (ΔF_{CW}) can be reduced during the night (N) and winter (W) working condition. The flow rate of steam (ΔF_S) can be saved during the day (D) and summer (S) working condition. The pessimistic objective function is taking into account the cooling water consumption in the hottest summer day and the steam consumption in the coolest winter night. The optimistic objective function is computing the possible flow rate savings of cooling water in winter and steam in summer. The heat exchanger areas are accounted for heaters in night/winter and for coolers in day/summer condition.

The effect of the raw material inlet amount flow rates

The inlet flow rates of any basic raw material (ΔF_{RM}) can be decreased to marginal value, with them the cost of raw material can be reduced. The lower flow rate of raw material influences the reaction equilibrium, as well as conversion of product (ΔF_P). The optimistic objective function is taking into account the savings of the reduced flow rate of the raw materials and increased production in the same reactor volume.

The effect of the equipment costs

The published equipment costs are usually not adjusted to the real data. The pessimistic objective function of the NLP model is calculated with higher equipment depreciation cost (C_E). The published equipment costs (Tjoe and Linnhoff, 1986) are multiplied by 2. The optimistic objective function does not consider the factor 2 by using the secondhand equipment.

The effect of the utility cost and product price

The utility costs and product price are changing very much. In pessimistic cost analysis the highest value of utility cost is applied and the lowest one for product price and the opposite for optimistic analysis.

The optimistic objective function can include possible optimistic savings and profits as compared to the pessimistic value (Eq. 1). The NLP model can optimize the plant by fixing inlet flow composition (to C_I or C_{II}).

In the model the worst objective function is selected. The changing parameters are analysed stepwise with one parameter being varied and another being constant. The possible profit of different effects in the optimistic objective function can not be sumed up because of the correlation of the raw material, utilities and product prices.

Optimistic maximum additional annual profit =

$$O_I \cdot C_I + O_{II} \cdot C_{II} + \Delta F_{CW} \cdot C_{CW} \cdot W + \Delta F_{CW} \cdot C_{CW} \cdot N + \Delta F_S \cdot C_S \cdot D + \Delta F_S \cdot C_S \cdot S + \Delta F_{RM} \cdot C_{RM} + \Delta F_P \cdot C_P + C_E/2 + \Delta F_{CW} \cdot \Delta C_{CW} + \Delta F_S \cdot \Delta C_S + \Delta F_P \cdot \Delta C_P \quad (1)$$

In the objective function universal symbols of matrixes for additional saving and profit are used for easy understanding. The combined symbols: $O_I \cdot C_I$ represent the pessimistic objective function (O_I) with the known inlet flow composition (C_I) and superstructure (S_I). The symbols: $O_{II} \cdot C_{II}$ represent the pessimistic objective function (O_{II}) with the known inlet flow composition (C_{II}) and superstructure (S_{II}). In the NLP model only one superstructure, S_I or S_{II} and only one objective function (O_I or O_{II}) can be activated. The symbols in the sum: $\Delta F_{CW} \cdot C_{CW} \cdot W + \Delta F_{CW} \cdot C_{CW} \cdot N$ represent additional profit because of the cooling water saving (ΔF_{CW}) in the winter (W) and night (N) active times. The symbols of the sum: $\Delta F_S \cdot C_S \cdot D + \Delta F_S \cdot C_S \cdot S$ represent the daily (D) and summery (S) additional profit because of the steam saving (ΔF_S). The symbols: $\Delta F_{RM} \cdot C_{RM}$ represent the increased profit because of the inlet flow rate of raw material saving (ΔF_{RM}). The symbols: $\Delta F_P \cdot C_P$ represent the profit because of the increased production (ΔF_P). The symbol: $C_E/2$ presents the additional profit because of the cheaper equipment costs. The symbols of the sum: $\Delta F_{CW} \cdot \Delta C_{CW} + \Delta F_S \cdot \Delta C_S$ represent the additional profit because of the cheaper utility costs. The symbols: $\Delta F_P \cdot \Delta C_P$ represent the additional profit because of the increased product costs. The parameters: C_{CW}, C_S, C_{RM} and C_P represent the prices of utilities, raw material and product. The parameters: N, W, D and S (night, winter, day and summer) represent the time activation parameters.

3. Case study

We applied this idea to a methanol plant to formulate the optimal retrofit in the simultaneous approach (Kovač Kralj et al., 2000) using sensitivity analysis. Methanol is often produced from synthesis gas in low-pressure Lurgi plants. In the optimistic objective function the NLP model is including all the effects. The pessimistic and optimistic costs are given in Table 1.

Table 1: Pessimistic and optimistic costs data for example processes.

	Pessimistic cost	Optimistic cost
Installed costs of heat exchanger */EUR:	$(8600{,}0 + 670 \cdot A^{0{,}83}) \times 3{,}5 \times 2$	$(8\,600{,}0 + 670 \cdot A^{0{,}83}) \times 3{,}5$
Price of 37 bar steam producted (C_{RM}, C_S)**/EUR/(kW · a):	106,3	136,0
Price of methanol production (C_P)/EUR/t:	+115,0	++360,0
Price of cooling water (C_{CW})**/EUR/(kW · a):	&6,2	6,2

* Tjoe and Linnhoff, 1986; A = area in m^2

** Swaney, 1989

\+ ten years average

++ Hoffman, 1995

& the cost of cooling water is unity

The effect of the inlet flow composition

The inlet flow composition of the natural gas is varied and it can affect the optimal structure of the plant and the methanol production. The primary inlet flow composition of the natural gas contained 92 % of methane, the formulated superstructure being S_I and the pessimistic objective function O_I giving 1,055 MEUR/a of additional profit (Kovač Kralj et al., 2000). The new gas composition with 98 % methane, the formulated superstructure S_{II} and the pessimistic objective function O_{II} is giving 0,700 MEUR/a of additional profit. The composition of the natural gas with 98 % methane can produce less additional methanol. The pessimistic objective functions O_I or O_{II} are giving different additional production of methanol and steam, and different utility savings.

The effect of the temperature regarding night/day and winter/summer working condition

The ambient temperature affects the utility consumption, especially the cooling water flow rate. In the optimistic objective function the cooling water flow rate saving is computed. The temperature drop can be approximately 5 K in the night and 10 K in winter saving 0,1 MW of the cooling water flow rate with additional 0,62 MEUR/a of profit. In the profit the 90 days time of winter activation is considered.

The effect of the raw material inlet amount flow rates

Synthesis gas is produced from natural gas using 33 100 kg/h of high pressure steam in a steam reformer. The flow rate of high pressure steam (as the raw material) can be decreased to the lower operating bound constraint of 32 000 kg/h and the flow rate of the high pressure steam can be reduced by 9 192 t/a. All the other process units can be operated at the existing parameters. The lower flow rate of high pressure steam influences the reaction equilibrium, as well as conversions in the reformer and methanol synthesis reactor. The higher equilibrium conversion in both reactors can increase the conversion of methanol by 0,12 %, producing 156 t/a of additional methanol. The increased profit is 0,08 MEUR/a.

The effect of the equipment costs

The pessimistic objective function of the NLP model is optimized using the highest equipment depreciation cost (Table 1). The difference in the equipment cost can bring additional optimistic profit of 0,143 MEUR/a with the same optimal structure.

The effect of the utility cost and product price

The increased utility costs for steam produced in the process can increase the profit for 0,043 MEUR/a. The increased product price for the additional methanol production can increase the profit for 2,563 MEUR/a, which is very high because of the high price of methanol in one short period. The ten years average price is 115 EUR/t. The methanol price is depending on the price of the natural gas.

Changing temperature, reducing raw material (the high pressure steam) flow rate, buying cheaper equipment and changing the utility costs and product price do not change the optimal structure S_I. The pessimistic basic objective function of 1,055 MEUR/a. The possible additional optimistic profits of the effects can bring: 0,62 MEUR/a from temperature changing, 0,08 MEUR/a from reducing raw material, 0,143 MEUR/a from buying cheaper equipment, 0,043 MEUR/a from changing the utility costs and up to 2,563 MEUR/a from changing the product price.

4. Conclusions

The objective function of the methanol plant was studied using sensitivity analysis in simultaneous process optimization approach using the NLP model. The objective function is including the effects: changing of ambient temperature, reducing the flow rate of high pressure steam, buying cheaper equipment and changing the utility cost and product price, which can affect the optimal process structure, production rate and profit. The pessimistic additional profit is 1,055 MEUR/a and the effects can bring the different additional optimistic profits.

5. References

Ahmad S. (1985). Heat exchanger networks: Cost tradeoffs in energy and capital. Ph. D. Thesis, University of Manchester, Manchester, 113 –306.

Ahmad S. and Hui C. W. (1991). Heat recovery between areas of integrity, Computers Chem. Engng 15, 809-832.

Biegler L. T., Grossmann I. E. and Westerberg A. W. (1997). Systematic methods of chemical process design. Prentice Hall, Upper Saddle River, New Jersey.

Hoffman J. (1995). Methanol pricing goes in “free fall”. Chemical Marketing Reporter, 247(12), 17.

Kovač Kralj A., Glavič P. and Kravanja Z. (2000). Retrofit of complex and energy intensive processes II: stepwise simultaneous superstructural approach. *Comput. chem. Engng* 24/1, 125–138.

Linnhoff B., Townsed D. W., Boland P., Hewitt G. F., Thomas B. E. A., Guy A. R. and Marsland R. H. (1982). A User Guide on Process Integration for the Efficient Use of Energy. The Institution of Chemical Engineers, Rugby.

Swaney R., 1989. Thermal integration of processes with heat engines and heat pumps. AIChE Journal 35/6, 1010.

Tjoe T. N. and Linnhoff B. (1986). Using pinch tehnology for process retrofit. Chem. Engng 28, 47–60.