Computers and Chemical Engineering 35 (2011) 245–254

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Iterative optimization of the economic efficiency of an industrial process within the validity area of the static plant model and its application to a Pulp Mill

A. Zakharov*, S.-L. Jämsä-Jounela

Aalto University, P.O. Box 16100, 00076, Aalto, Finland

ARTICLE INFO

Article history:
Received 27 February 2009
Received in revised form 1 April 2010
Accepted 29 October 2010
Available online 16 November 2010

Keywords:
Plantwide optimization
Economic efficiency
Pulp and paper production
Industrial application

ABSTRACT

Optimization of the steady state economic efficiency of an industrial process is a specific task because the decision variables of the optimization (setpoints of the control system) affect the process through the control strategy. Thus, the effects of saturation of a control system must be taken into account when the gradient of the objective function is estimated and the necessary optimality conditions are checked. In particular, because the optimality conditions cannot be checked directly in the presence of active constraints on the manipulated variables, approximations of the steady state values of the manipulated variables as functions of the setpoints (static plant model) are needed in order to be able to evaluate the optimality conditions. In this paper an iterative method for optimization of the plant profit rate is proposed avoiding the control saturation and is applied to the Pulp Mill benchmark model optimization. Three different static models describing the steady state values of the manipulated variables are constructed and used in the optimization. The results of the optimization are presented and compared against the straightforward single-step optimization of the plant economic efficiency.

1. Introduction

Due to the continuously increasing competition in the pulp and paper industry, there is a need to develop solutions that can increase the economical efficiency of the plants. According to Luyben (1989) it is usually much cheaper, safer and faster to conduct the optimization of plant operations on the basis of a mathematical model rather than experimentally. However, the significant number of studies is still concentrated on the optimization of single unit operations in Pulp Mills: Mcdonough, Uno, Rudie, and Courchene (2008) studied the optimization of the ClO_2 requirements for the bleaching process; Tang, Wang, He, and Itoh (2007) optimized the Pulp Washing process; Sarimveis, Angelou, Retsina, Rutherford, and Bafas (2003) optimized the energy management in pulp and paper mills; Smith, Christlmeier, and Van Winkle (1986) studied the possibility of increasing of the recovery boiler throughput; Sidrak (1995) optimized the Kamyr Digester towards significant reduction in the amount of off-specification pulp. Klugman, Karlsson, and Moshfegh (2007) studied the energy consumption and production by the Pulp Mill; Savulescu and Alva-Argaez (2008) minimize the energy consumption through managing the direct heat transfer related to the water streams; Westerlund et al. (1986) solved the equilibrium equations for the white liquor and optimized the lime feed rate; Santos and Dourado (1999) optimized energy consumption and the plant's production; Thibault et al. (2003) concentrated their efforts on the multicriteria optimization of the plant.

Nowadays, the trend is to optimize the whole mill with respect to production and quality, minimization of energy, chemical consumption and effluents. In a recent paper Castro and Doyle (2004) have proposed the Pulp Mill benchmark model, having the standard architecture with a Kamyr digester, a bleaching plant and a chemical recovery (see Castro and Doyle (2004) for the details). The benchmark model is well suited for performing of a wide range of the Pulp Mill studies, including the optimization problem of economical efficiency. Recently Mercangöz and Doyle (2008) have performed the optimization of the benchmark model, which deals with the whole Pulp Mill and the optimization criterion is the plant's profit rate including energy costs, cooking and bleaching chemicals costs, final products sales (pulp and steam) and which takes into account delignification and brightness requirements to the final product. However the optimization is performed in a single iteration and the simulation results are relatively far from the prediction of the static model. The attempt to update the model bias and re-optimize the plant (the bias update procedure) is not able to improve the profit rate, even though the updated model promises a significant increase in profits.

The inability of the bias update procedure to improve the profit rate may be explained by the fact that the static process model constructed in the area free of control saturation is invalid in the presence of active constraints on the manipulated variables. In

* Corresponding author at: Helsinki University of Technology, Department of Biotechnology and Chemical Technology, P.O. Box 6100, 02015 HUT, Finland.
E-mail address: alexey.zakharov@tkk.fi (A. Zakharov).

0098-1354/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compchemeng.2010.10.010

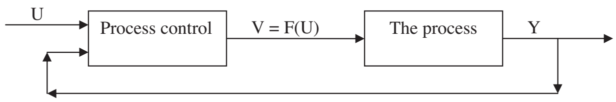

Fig. 1. Schematic diagram of the process.

addition, convergence of the iterative optimization implemented on the basis of the bias update procedure cannot be ensured and, in practice, convergence may not be reached. An iterative optimization method is proposed in this paper, which is free of the described drawbacks and provides convergence of optimization to the point where the approximated optimality conditions, introduced in the paper, are fulfilled.

The article is structured as follows: Section 2 contains a description of the iterative optimization method together with the approximated optimality conditions. Section 3 introduces the Pulp Mill benchmark model and formulation of the profit rate maximization problem. Section 4 contains the results of computations for both one-step and iterative optimizations. Finally, Section 5 contains the discussion and conclusions.

2. Iterative optimization of the economic efficiency of an industrial process under the validity limitations of the static plant model

2.1. Problem formulation

In the chemical industry, the control is organized in a hierarchical structure: at the lowest level measurements (such as temperatures, pressures and flows) are collected and the basic control loops are implemented in order to stabilize the plant. The next level includes advanced regulatory controllers such as MPC and cascade controls. At the subsequent level, short-term decisions are made by the real time optimization, which mainly adapts the process to the changing measurable and immeasurable disturbances. At the highest level, long-term optimization is performed which takes into account plant-wide planning and scheduling, as well as the plant static model. At this level the process conditions are controlled through the setpoint U (see Fig. 1), which plays a role of the decision variables of the optimization. Profit rate computation in the chemical industry mainly utilizes the steady values of the manipulated variables V_j which are functions of the setpoints:

$$V_j = F_j(U), \quad j = 1, \ldots, m.$$

Both the setpoints and the manipulated variables are limited by the following constraints, which are caused by the physical limitations of the plant and the stability requirements of the control system:

$$\begin{aligned} l_i^u \le U_i \le h_i^u, \quad i = 1, \ldots, n \\ l_j^v \le V_j \le h_j^v, \quad j = 1, \ldots, m \end{aligned} . \tag{1}$$

In fact, functions F_j may demonstrate non-smooth behaviour arising from saturation of the control. Let the plant setpoint be varied smoothly. At the moment when a manipulated variable (MV) used by a control loop reaches its limit, the control strategy no longer follows its setpoint, thereby immediately affecting to the rest of the process. If a MV used by a MPC becomes saturated, then the controller continues to try to keep the process at the setpoint by means of the other variables at its disposal. Thus, in both cases many MV's (not only the MV used by the control loop) demonstrate non-smooth behaviour at the moment of control loop saturation. Obviously, functions F_j are smooth inside the set S of the setpoints, within which the manipulated variable constraints are inactive:

$$S = \{U : l_j^v < F_i(U) < h_j^v, \quad j = 1, \ldots, m\}.$$

2.2. Approximated optimality conditions

An efficient optimization is hardly possible without easy-to-check optimality conditions. The necessary optimality conditions are based on the gradient of the objective function, which is difficult to estimate at the border of the region S. Thus, approximate optimality conditions based on the static model of the process must be used.

Let us consider the following representation of the steady values of the manipulated variables in set S:

$$V_j = F_j(U) = f_j(U) + e_j(U), \tag{2}$$

where the set of functions, f_j, is the static model constructed and valid within S, and e_j are the approximation errors. In particular, the errors e_j can be estimated at a setpoint where the correspondent MV values are known and assumed to be constant.

The optimality conditions at the setpoint U for the profit rate maximization problem are standard Karush–Kuhn–Tucker conditions involving both derivatives $(\partial V_j/\partial U_i)\big|$ and values $V_j(U)$ of the manipulated variables. At the same time, optimization of the economic efficiency involves computation of the gradient of the profit rate with respect to the decision variables, which requires estimation of the derivatives $\partial V_j/\partial U_i$. Since these derivatives cannot usually be computed explicitly, they must be estimated using the following finite difference approximation:

$$\left.\frac{\partial V_j}{\partial U_i}\right|_U = \frac{V_j(U + \Delta_i) - V_j(U - \Delta_i)}{2\Delta}, \tag{3}$$

where Δ_i is the vector with the only non-zero element at the ith place, which is equal to Δ. If both points $U - \Delta_j$ and $U + \Delta_j$ belong to S, then the error of estimation (3) is of the order Δ^2. However if $U + k\Delta_i$ is at the border of S for some k such that $-1 < k < 1$, then the manipulated variables are not smooth functions of the setpoints (as explained before), and the finite difference estimation is close to the linear combination of the left and right derivative at the point lying on the border of S:

$$\begin{aligned} &\frac{V_j(U + \Delta_i) - V_j(U - \Delta_i)}{2\Delta} \\ &\quad = \frac{1-k}{2} \left.\frac{\partial V_j}{\partial U_i}\right|_{(U+k\Delta_i)^+} + \frac{k+1}{2} \left.\frac{\partial V_j}{\partial U_i}\right|_{(U+k\Delta_i)^-} + O(\Delta). \end{aligned}$$

To conclude, the finite difference estimation cannot be used as a reliable approximation of the derivative $(\partial V_j)/(\partial U_i)\big|_U$ if some of the MV constraints are active or close to be active. Since the simulations are able to provide only approximate steady state values of the MVs, a relatively large variation step Δ should be used to achieve a satisfactory level of accuracy. This is the reason why the gradient can be accurately estimated only 'deeply' within region S.

The gradient based optimization methods face a considerable challenge because of the above-mentioned problems with the derivative estimation. In fact, it is natural to expect that the iterative optimization will come to the border of the optimization region after only a few iterations, at which time a satisfactory solution has probably not yet been found. Thus, a method is needed that is suitable for the specific problem of plant optimization.

Since the values of the manipulated variables can be taken from the real process, or accurately estimated at any setpoint by means of a single simulation of a first principles process model, the only barrier for the optimality condition check are the derivatives $(\partial V_j/\partial U_i)\big|_U$ that cannot be estimated. One option is to use the approximated optimality conditions utilizing the approximation derivatives $(\partial f_j/\partial U_i)_U$, which can be obtained analytically, instead of the $(\partial V_j/\partial U_i)\big|_U$. In particular setpoint U^* satisfies the approxi-