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Integrated design and control of chemical processes – Part II: An illustrative example

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ABSTRACT

In this paper, several methodologies of integrated design are proposed and applied to the design of wastewater treatment plants and their control system, focusing on the activated sludge process, within a novel multiobjective framework. The scope of the problem considers both fixed plant layout and plant structure selection by defining a simple superstructure. The control strategy chosen is a linear Model Predictive Controller (MPC) with terminal penalty. The evaluation of the controllability has been performed using norm based indexes, and the robustness conditions for different uncertainty sources have been considered, in the frequency and time domains. The optimization strategies used are based on the integration of stochastic and deterministic methods, as well as genetic algorithms. The presented methodologies and their application to wastewater treatment plants can be considered as an illustrative example in the universe of integrated design techniques presented in the Part I article of this series.

1. Introduction

The design of chemical processes is an extensive and challenging task that begins with the description and definition of a product and its specifications. The task is completed once the quantitative definition of all the structural and operating variables of the production plant satisfying the product requirements and process restrictions is achieved. The process design is, typically, based on steady state analysis and economic considerations. The control-systems design is carried out in a subsequent stage, separated from the process design itself. Sometimes, in this stage, the engineers realize that the possibilities of the control systems may be significantly reduced due to adverse plant dynamics. This problem is usually solved by process re-design or by increasing the size of process units and equipment to achieve acceptable process operation in suboptimal conditions.

Therefore, nowadays is widely accepted that the process controllability analysis must be an integral part of the process design, in order to satisfy the economic and plant dynamics objectives simultaneously. In the last thirty years, several researchers have been focused on the study of controllability and its metrics (Ziegler and Nichols, 1943; Skogestad and Wolff, 1992; Luyben, 1993; Skogestad and Postlethwaite, 1996; Soloyev and Lewin, 2003; Ochoa, 2005; Araujo and Skogestad, 2006; Alvarez, 2012) as well as the development of different methodologies to include controllability criteria in the early stages of process design, establishing the idea of Integration of Design and Control (ID).

The *Integrated Process Design and Control approach* has emerged as a systematic procedure where the process and control system design are carried out simultaneously. Several methodologies assessing the tradeoff between economic benefits and controllability in process design have been reported in the literature. They focus on different aspects of the problem, such as the scope, the controllability issues, the way to quantify the dynamic performance, the formulation of the optimization problem and the resolution techniques. Some reviews can be found (Lewin, 1999; Sakizlis et al., 2004; Seferlis and Georgiadis, 2004; Ricardez-Sandoval et al., 2009; Yuan et al., 2012; Sharifzadeh, 2013). Furthermore, due to the wide variety of works presented in the literature and the continuous advances in the field, a detailed classification of the different approaches and developments on the Integrated Design and Control Methodology supported on a comprehensive review is contained in Part I of this study. Such classification is helpful to systematize the research in the area, showing up the most interesting developments and identifying the challenging aspects to be assessed and the possibility to integrate other approaches.

This paper is dedicated to present several new methodologies of simultaneous process and control system design applied to the activated sludge process in a Wastewater Treatment Plant (WWTP),

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including frequency and time domain robustness conditions for different uncertainty sources. The evaluation of the controllability has been performed using H_∞ and l_1 norm based indexes. The nonlinear characteristics of the process model, makes the activated sludge process an interesting application to test the integrated design approach. The construction and operation costs of these plants must be as low as possible selecting the most efficient control strategies simultaneously. However, the minimization of the investment and operational costs and the achievement of the effluent quality requirements may result into conflicting objectives. Therefore, a novel multi-objective approach is proposed in this work, helping the process designer to get suitable plant designs depending on the requirements imposed, balancing the tradeoff of economic costs and controllability by simply tuning scalar weights.

Some traditional optimization based integrated design approaches characterize the full process by means of nonlinear dynamic models and a mixed-integer dynamic optimization problem (MIDO) including uncertainty is solved. Mohideen et al. (1996) formulates the integrated design and control as a general problem, comprising costs, the differential and algebraic equations of the process model, the feasibility of the operation and the variability of the process due to disturbances and uncertainties. This formulation results into a MIDO problem that requires the decomposition in two sub-problems and the application of an iterative procedure, starting with the determination of the optimal process design and control structure to end with the evaluation of the feasibility of the process operation throughout the possible range of perturbations and uncertainties. This general framework is also adopted in the works of Bansal et al., 2000 for a large scale process, and in Sakizlis et al. (2004). The methodology of Kookos and Perkins (2001) is similar to Mohideen et al. (1996), but proposes another decomposition algorithm based on upper and lower limits to the economic performance of the plant for solving the problem. Although these methodologies are quite comprehensive, their computational load is usually high, particularly for large systems.

The integrated design methodologies typically consider the tuning of the controllers and their performance evaluation. Although in most works classical feedback control systems are used, some applications with advanced control techniques, particularly model predictive control (MPC), have been proposed (Brengel and Seider, 1992; Loeblein and Perkins, 1999; Sakizlis et al., 2003, 2004; Chawankul et al., 2007; Francisco et al., 2011). In Brengel and Seider (1992) a coordinated optimization strategy to solve the simultaneous design and control with a MPC is proposed. The economic objective function is penalized by deficient controllability. This translates into a bi-level programming problem (BPP) which is later on simplified to obtain a solution. In Loeblein and Perkins (1999) a non-constrained MPC is used, and Sakizlis et al. (2003, 2004) implement a parametric predictive controller (MPC), and develop a method that considers a single economics-based performance index, while representing the system operation and system specifications with dynamic models. Baker and Swartz (2006) introduce the quadratic problem (QP) of the controller in the integrated design formulation, by replacing it with constraints associated to the Karush–Kuhn–Tucker optimality conditions.

In recent years, robustness conditions have been included in the ID methodology in order to account for robust stability and performance in presence of external disturbances, noise and modeling uncertainty. In Chawankul et al. (2007), a measure of the closed loop output performance is introduced based on the output widest variability caused by model uncertainties, and constraints related to the robust stability of the plant are imposed, considering unconstrained MPC control laws. In Ricardez Sandoval et al. (2008), a linear state space model with uncertain parameters is considered, and robust control tools are applied to calculate bounds on the process stability, the process feasibility and the worst case scenario. The process output variability is calculated by solving a linear matrix inequality (LMI) obtained with a Lyapunov function and the uncertain model. In Ricardez-Sandoval et al. (2009), robust stability and performance measures based on Lyapunov theory are used, along with the structured singular value analysis (SSV), to estimate bounds on process worst case variability, process feasibility, and process stability. A variation of this work is in Ricardez-Sandoval et al. (2010, 2011), where the methodology is extended to large scale systems and parametric uncertainty, introducing a hybrid approach that combines the analytical calculation of the SSV of the worst case disturbances and dynamic simulations to calculate the variability. In Trainor et al. (2013), the methodology is extended further to take into account structural decisions, including a dynamic flexibility analysis, a robust dynamic feasibility analysis, and nominal and robust stability analyses. The dynamic flexibility analysis aims to search for an optimal process flowsheet and control design configuration that maintain process feasibility in the presence of the critical time trajectories in the disturbances. This problem, including control structure synthesis using MPC, has been tackled in Sánchez-Sánchez and Ricardez-Sandoval (2013a), where the dynamic flexibility and dynamic feasibility are integrated into a single optimization formulation. The methodologies presented in this paragraph tackle the robustness issues in a comprehensive way within the time domain.

The development of robust ID methodologies that include any source of uncertainty, considering frequency and time domains, is one of the main objectives of this work. As it is well known, the model uncertainty can have different sources. Firstly, the use of linear time invariant models describe the plant only approximately when the real process is nonlinear. As far as the process models are obtained via linearization, they are accurate only in the neighborhood of the reference state chosen for the linearization. Moreover, different operating conditions due to unpredictable disturbances and changes in the plant dimensions could lead to changes in the parameters of the nominal transfer function. Finally, there is always some “true” uncertainty even when the underlying process is essentially linear: the physical parameters are never known exactly and fast dynamic phenomena (e.g. valve or sensor dynamics) or unknown dynamics are usually neglected in the model. Therefore, at high frequency, even the model order is unknown.

Uncertainty can be expressed in many different ways. To account for the model uncertainty we will assume in this work that the dynamic behavior of the plant is described not only by a single time invariant model but by a family of linear time invariant models assuming that the magnitude and phase of the process transfer function is confined to a Nyquist band. This is a classic way of representing “unstructured” uncertainty, which allows for the consideration of all the uncertainty sources described in the previous paragraph, particularly the neglected high frequency dynamics that cannot be modeled in a “structured” manner using parametric uncertainty, which is a novelty of this work. Physically, this uncertainty may account for the ignored (or unknown) dynamics. As for the works of Ricardez-Sandoval’s group, the uncertainty sources are only associated with the maximal rate of changes of the disturbance variables and the linearized model coefficients, as well as parametric uncertainty. As mentioned above in the methodologies proposed in the present work more sources of uncertainty can be included.

The consideration of frequency domain characteristics of the uncertainty is also relevant in comparison to other previous works in order to state properly the robust requirements in the ID. For example, uncertainties caused by the process nonlinearity when the operating point or process load change, may affect at low frequencies and can be represented as inverse multiplicative uncertainty, or the unmodeled dynamics of some sensors or actuators