Online optimisation and detection of process upset in semi-batch reactors using a kinetic modelling approach

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Process Analytical Chemistry/Technology has tremendously evolved in the last decades due to the development of multivariate online sensors that are able to monitor the properties of industrial processes in real time [1, 2]. Online monitoring of product quality and the detection of process upsets are important for the pharmaceutical and fine chemical industry in order to maintain product specifications and meet their commitments regarding safety, health and environment.

Many methods exist to extract useful information from the vast amount of data produced by online sensors. Chemometric methods, such as Principal Component Regression (PCR) and Partial Least Squares (PLS) or Black Box modelling (e.g. Neural Networks) are commonly used during the monitoring of batch processes [3, 4]. However, for these data-driven methods, calibration conditions need to be maintained during the actual process and the calibration generally behaves poorly when extrapolated to different operating conditions. On the other hand, kinetic modelling techniques [5], based on first principal models, describing the kinetics of main and side products, do not encounter such drawbacks and can be adapted for the monitoring of highly fluctuating processes, e.g. under semi-batch conditions.

During batch and semi-batch processes, deviations from standard operating conditions can have various origins. Most frequent sources of deviations are due to slightly imprecise initial conditions (e.g. initial concentrations) or impurities in the initial reactants causing unexpected side reactions [6]. In this contribution, we propose a method for the online monitoring of semi-batch processes based on a kinetic modelling approach in order to optimise operating conditions and reduce "batch to batch" deviations. To our knowledge, this option has not yet been considered in literature.

The proposed method requires the kinetic model and the associated rate constants to be known, i.e. determined in an early phase of R&D. In the Figure below, the different steps of the algorithm, currently implemented into *Matlab*, are outlined. The algorithm assumes a first small amount of reagent to be dosed into the reaction mixture inside the reactor. Corrected initial concentrations are then determined by fitting the kinetic model to measurements, such as UV-vis, IR or heat power, using the Newton-Gauss-Levenberg/Marquardt (NGL/M) optimiser. If the optimiser fails the operator has the option to dose more reagent. Possible failure can be due to an early process upset, or to the fact that too little reagent was dosed in order to follow the kinetics reliably.

The corrected initial concentrations are then fed back into the kinetic model and the algorithm optimises the flow rate for the dosed reagent or the operating temperature in order to maximise under constraints user-defined properties of the process, such as yield, selectivity or conversion.

For this constrained optimisation, nonlinear programming (NLP) is employed (*Matlab's fmincon* function). As soon as optimum operating conditions are obtained by the algorithm, the reactor will automatically run at these improved settings. As an option, flow rate and temperature can continuously be re-optimised to adapt to possible fluctuations in operating conditions. During the whole procedure, the algorithm also tests for possible process upset. If such an incident is detected the operator is asked to take appropriate action, for example a reactor shut down.

The algorithm will be demonstrated using simulated data from mid-IR and UV-vis spectroscopy as well as from calorimetry.
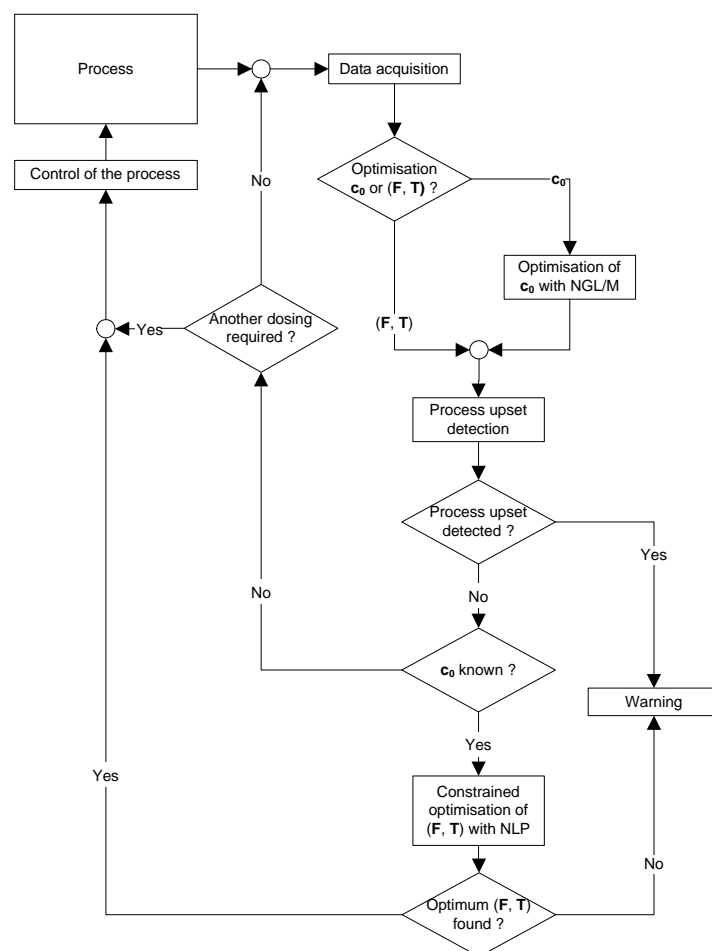

Figure. Outline of the online-optimisation procedure

[1] P. Gemperline, G. Puxty, M. Maeder, D. Walker, F. Tarczynski, M. Bosserman, Analytical Chemistry 76 (2004) 2575-2582.
[2] J. Workman, M. Koch, D. Veltkamp, Analytical Chemistry 77 (2005) 3789-3806.
[3] M. Spear, Chemical Processing 70 (2007) 20-26.
[4] T.J. Thurston, R.G. Brereton, D.J. Foord, R.E.A. Escott, Journal of Chemometrics 17 (2003) 313-322.
[5] M. Maeder, Y.M. Neuhold, Practical Data Analysis in Chemistry, Elsevier, Amsterdam NL, 2007.
[6] E.N.M. van Sprang, H.J. Ramaker, H.F.M. Boelens, J.A. Westerhuis, D. Whiteman, D. Baines, I. Weaver, Analyst 128 (2003) 98-102.