

# Multiple Model-Based Control of the Tennessee–Eastman Process

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This work addresses the model-based control of the Tennessee–Eastman (TE) challenge problem using a state-shared model. A detailed mechanistic nonlinear model is developed and validated with data taken from the original Downs and Vogel work [Downs, J. J.; Vogel, E. F. *Comput. Chem. Eng.* **1993**, *17* (3), 245–255] and their accompanying Fortran programs. Two plantwide model predictive control (MPC) strategies that differ in the types of models used are applied to address regulation and transition control. The first employs multiple fixed-parameter models, identified at known grades, and the second uses an adaptive state-shared model [Tian, Z.; Hoo, K. A. *Comput. Chem. Eng.* **2003**, *27* (11), 1641–1656] constructed from three fixed-parameter models and one specialized adaptive model. The first MPC strategy demonstrates closed-loop regulation and grade-transition performance especially when the worst disturbance, the loss of the A feed, is present. The second MPC strategy provides a better closed-loop performance for grade transitions when compared with the first MPC strategy.

## 1. Introduction

The Tennessee–Eastman (TE) challenge problem provides a plant flowsheet (see Figure 1), seven possible operating states of three product grades, a list of expected disturbances, and a Fortran-based computer program that represents implicit dynamic models of the unit operations present in the flowsheet.<sup>1</sup>

The multiple operating states pose a significant transition control problem, while the different types of disturbances present a challenging regulation problem. Since the initial publication of the TE process more than 10 years ago,<sup>1</sup> at least 60 publications have appeared in the open literature in which a plethora of control formulations have been tried, as well as statistical process monitoring, sensor fault detection, and optimal scheduling.<sup>3–9</sup>

McAvoy and Ye<sup>10</sup> developed a decentralized plantwide control design based on multiple single input/single output (SISO) control loops. The methodology involved the screening of various pairs of control and manipulated variables using steady-state techniques, such as relative gain array.<sup>11</sup> Ricker and Lee<sup>7</sup> tested this strategy and found that the compressor power loop is often saturated during transient operations. This control scheme did not demonstrate transition control among the three product grades and among the different operating modes.

Luyben and co-workers<sup>5</sup> used their nine-step plantwide control design approach to develop SISO feedback control loops for both on-demand production and on-supply of reactants. The control system developed is demonstrated for regulation. In the case of the extreme disturbances (e.g., loss of the A feed), the usual industrial mode of applying overrides and high and low selectors is applied. This control scheme also did not address grade-transition control. Papers related to this work can be found in refs 12 and 13.

The most extensive studies of the TE process have been reported by Ricker and co-workers. Ricker and Lee<sup>8</sup> have derived nonlinear, mechanistic models of the major

unit operations that reproduced the essential dynamic process characteristics. However, a key simplification, omission of the energy balance, is applied. An extended Kalman filter is developed to provide continuous adjustments of the dynamic model parameters (and states) during transients. This simplified model was used by Ricker and Lee<sup>7</sup> to formulate a MPC. The control strategy when compared with the typical SISO multi-loop strategy shows a better closed-loop performance especially for transition control (grade and operating state changes) and constraint handling. Although the models that represent the plant are nonlinear, the MPC uses approximate linear models found by linearization of the nonlinear models at every sample point. In this fashion, the MPC uses linear time-varying models of the plant.

In ref 9, Ricker developed a decentralized control structure that gave results superior to those in the study done in ref 7. Ricker suggests that the most important criterion for a successful control strategy lies with the selection of the set of controlled variables. Similar statements in this regard can be found in the publications of Skogestad and co-workers<sup>13–15</sup> and Shinnar and co-workers.<sup>16–18</sup>

Besides the base mode, there are six optimal steady-state modes of process operation for three different production mass ratios (see Table 1). This work addresses disturbance rejection at known operating modes and transition control among the three product grades.

The organization of the rest of the paper is as follows. Section 2 presents a very brief overview of the TE process necessary to understand the process and the control development. More details can be found in the Appendix. Section 3 provides the detailed mechanistic nonlinear model development. Section 4 presents a system analysis of the models in section 3. Section 5 presents two approaches to MPC. The first uses fixed-parameter linear models identified at the known operating modes and switching to demonstrate the performance of the controller for regulation and single and multiple transitions among the product grades. The second uses an adaptive state-shared linear model

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