441c Dynamic Optimization of an Integrated Multi-Unit System under Failure Conditions

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Shutdowns in a chemical processing plant are detrimental both to plant economics and critical product characteristics. These situations can be due to routine maintenance, or due to the more extreme case of equipment failure due to wear. Nevertheless, both are cases of non-normal plant operation and are often unavoidable. These situations are complicated further when many units are linked and subjected to a high degree of integration. Extensive unit integration is a common characteristic of modern chemical processing plants. In this case, the shutdown of any unit within the plant can have immediate and potentially severe impacts on other areas of the operation. Since these events are unavoidable, the challenge is to minimize their economic impact through careful design of operating practices, and potentially plant design retrofits. The work described in this paper focuses on the development of generic and systematic methods for determining economically optimal operating policies and plant designs in the face of failures in multi-unit operations. This includes determining the optimal trajectories of critical plant variables (flows through units, flows between units, buffer tank levels, etc.), as well as determining whether plant design changes would improve plant economics during such events.

The Kraft pulping process, in which several cycles interact, was chosen for this study. A dynamic model of the Kraft pulping process is presented, accounting for the major flows of process materials through units, between units, as well as the accumulation of these in the intermediate buffer capacities. A pseudo-steady-state assumption was used for the processing units, with dynamics confined to the intermediate buffer capacities. The models developed were based on a combination of empirical and fundamental elements. The model equations were discretized and incorporated as equality constraints in the optimization problems described next.

Two broad problem types were considered – optimal operation and optimal design. The optimal operation problems were again categorized into two classes for study – planned shutdowns and unplanned shutdowns. The former occur mainly for planned maintenance and allow for a period of preparation time so that the plant can be moved to a more favorable operating point prior to the outage. The preparation time is followed by the shutdown period, and a subsequent restoration period, during which the plant operating point is moved back to the nominal operation. Unplanned shutdowns occur without warning. Consequently, preparation time is not available for these scenarios. For optimization, an economic objective function was employed, with path constraints on manipulated and state variables, and end-point constraints on the buffer tank levels. The latter are necessary to force the system back to the nominal operating point by the end of the time horizon, failing which the system can be left in an undesirable state in the event of subsequent shutdowns. Optimal operating strategies were computed for failures in different units, and sensitivity to preparation time, shutdown length, and restoration time investigated.

The design problem includes the buffer tank steady-state levels as optimization variables. A multiperiod formulation was used in which scenarios corresponding to different failure types and duration were incorporated into a single optimization problem based on a probability distribution of failure scenarios. It was further extended to consider the inclusion of additional buffer capacity within the plant, resulting in a MINLP. Results of a case study demonstrating the application of the design formulation are discussed.

Two interesting computational issues arose during the execution of these studies. These involve problem initialization and solution non-uniqueness respectively. Shutdowns were effected by fixing the production rate through the affected unit to zero for a chosen time period. The simultaneous solution approach adopted requires initialization of the variable trajectories, which if inappropriately done, could result in convergence difficulties. Such difficulties were overcome by employing a homotopy-type initialization strategy in which the flow through an affected unit was systematically transformed from a nominal level to the shutdown scenario. At each step, the system was solved and its solution used as the initial guess for the next iterate. Nonunique input profiles were handled by following a two-tiered approach in which the plant economics were maximized first, and input action subsequently minimized as a secondary objective. By including the optimal economic performance as a constraint in the second problem, the solution of the second tier is guaranteed not to compromise the optimality of the first. Examples from the Kraft mill case study demonstrate these strategies.