Computers and Chemical Engineering 86 (2016) 120–135

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

Optimal response under partial plant shutdown with discontinuous dynamic models

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ARTICLE INFO

Article history:
Received 20 August 2015
Received in revised form 9 December 2015
Accepted 17 December 2015
Available online 29 December 2015

Keywords:
Dynamic optimization
Partial shutdowns
Mixed integer programming
Multitiered optimization
Model predictive control
Process control

ABSTRACT

This work describes mathematical formulations for modeling aspects of partial shutdowns in multiunit plants. The specific type of partial shutdown considered is one that permits the decoupling of affected units from the rest of the plant, thus enabling continued plant operation, albeit in a more limited fashion. Parsimonious and computationally efficient mixed-integer formulations are presented for specific discontinuous phenomena that arise in partial shutdown modeling, such as shutdown thresholds, induced shutdowns, discontinuous costs, and minimum shutdown durations. It is demonstrated that induced shutdowns (secondary shutdowns triggered by the original shutdown) can be correctly penalized in the objective by capturing the shutdown's true discontinuous economic cost. The computed optimal solution is implemented in closed-loop by employing a multitiered model predictive shutdown controller, in which a discrete-time mixed-integer dynamic optimization (MIDO) problem is embedded. Both objectives of maximizing economics and minimizing restoration (shutdown recovery) time are considered.

1. Introduction

Continuous chemical plants are characterized by a set of interconnected process units which, when operated in concert, serve to transform a raw material into a final product. During a typical course of operation, one or more of these process units may undergo a shutdown, either for maintenance or due to equipment failure. When this occurs the process is disrupted, and if severe enough, may lead to a total plant shutdown. However, not all types of process unit shutdowns necessarily lead to a complete shutdown of the plant. We refer to a *partial shutdown* as a specific type of shutdown in which a unit that is shut down (and possibly its neighboring units) can be isolated from the rest of the plant through alternative operating policies that exploit redundancies in the configuration. These operating policies comprise actions such as reconfiguring the process pathways, rerouting material streams, slowing down production, and so on.

A common strategy for addressing partial shutdowns—when buffer tanks are available—is to manage the material flow through process units surrounding the offline unit. This strategy calls for the controlled balancing of production rates, buffer inventories and recycles. When executed correctly, the buffer management strategy is one of the keys to minimizing the losses associated with partial shutdown scenarios. The end-product quality during the shutdown period may violate normal specifications, but in some cases, the material can be recycled and reprocessed. The material flow management strategy for partial shutdowns will be the focus of this work.

To illustrate this, a simplified example is shown in Fig. 1, which depicts a series of units, with Unit 2 being in a state of failure. The process is able to continue operating during the partial shutdown because Unit 1 is allowed to fill Buffer 1, while Unit 3 is allowed to draw material from Buffer 2. In some cases, Units 1 and 3 may have to throttle down production in order to avoid overwhelming or drying out the buffers adjacent to them. In this particular example, the buffer management strategy is straightforward and intuitive owing to the simplicity of the processing chain. In more complicated and integrated plants which incorporate recycle streams, arriving at a buffer management strategy is less straightforward, motivating the employment of a model-based optimization strategy, as promoted in this work.

An early articulation of this strategy for partial shutdowns can be found in Pettersson (1969), where a systematic scheme for coordinating the production and buffer tanks in a pulp and paper mill was considered. An optimization problem was posed and solved using methods from optimal control theory. Pettersson (1970) extended the original work by considering an optimal plantwide production

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http://dx.doi.org/10.1016/j.compchemeng.2015.12.011
0098-1354/

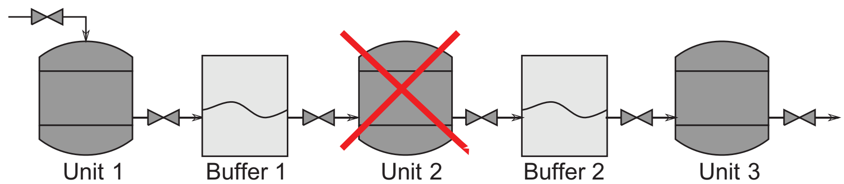

Fig. 1. Example of partial shutdown in unit 2. Units 1 and 3 are able to continue operating due to the presence of buffer tanks.

scheme that accounted for maintenance shutdowns, limited buffer capacity and steam restrictions. Lee and Reklaitis (1989) proposed a method for systematically utilizing buffer capacities to decouple upstream equipment failures from downstream processes and vice versa. A model predictive level control algorithm that attenuates the downstream propagation of flow disturbances (termed "flow filtering") was the subject of Campo and Morari (1989). Constraints at the end of the prediction horizon drive levels back to their nominal ranges. The horizon length is a tuning parameter that trades off good flow filtering and rapid integral action or settling.

Huang et al. (2000) outlined the idea of using dynamic optimization for fault accommodation, in contrast to the manual table-lookup approach typically adopted by operators. In a follow-up work, Huang et al. (2002), briefly discussed handling process unit shutdowns—considered a type of fault by the authors—within the above-mentioned framework. The authors supplied a sketch of a possible shutdown formulation which entails removing all equations related to the unit, and then activating a set of discrete transition equations by means of settings values to a set of integer variables. These integers, being constant, do not participate in the final dynamic optimization problem and hence are not degrees-of-freedom to be optimized. No detailed formulation or case studies on the dynamic optimization shutdown formulation were presented.

Continuing on the theme of partial shutdowns, Dubé (2000) studied a buffer storage operation strategy that minimizes time away from normal operation and aims to prevent plant section shutdowns. This strategy was carried out on a simulation of a highly integrated Kraft pulp mill. A method was outlined for determining the longest feasible shutdown time, that is, the duration after which a total shutdown is triggered. The coordination of buffer capacities for handling planned and unplanned shutdowns was illustrated. The flexibility gained by anticipatory actions prior to shutdown was also quantified and formalized. A numerical optimization procedure was employed, with the objective of throughput maximization. Balthazaar (2005) expanded on the previous work by investigating pre-emptive and reactive responses to shutdowns in detail. In the pre-emptive case, the control problem is solved assuming knowledge of the shutdown ahead of time (as is the case in a scheduled maintenance scenario), thus allowing the plant to take preparatory action in anticipation of the shutdown. In the reactive case, the plant shutdown occurs without warning, and the control system is expected to respond immediately. Additional issues addressed included the problem of determining the location and capacity of additional buffer tanks and the computation of the optimal steady-state tank levels using the probability distributions of different failure types and durations. These studies were undertaken by situating the problem in a numerical optimization framework, with the final objective of maximizing economics. In Chong and Swartz (2013), uncertainty in the downtime estimate was handled by treating the downtime estimate as a feedback parameter utilized in reoptimization. This work also introduced a closed-loop framework—based on model predictive control using multitiered models—for executing partial shutdown policies under uncertainty.

We note that the above works do not explicitly discuss discontinuous mathematical formulations for modeling specific phenomena in partial shutdowns. This paper extends previous work by Chong and Swartz (2013) by considering aspects of partial shutdowns requiring discontinuous constructs to be posed within a discrete partial shutdown optimization problem. The specific constructs considered are shutdown thresholds (in the context of induced shutdowns), discontinuous costs and minimum shutdown durations. The minimization of the restoration time from a shutdown state is also considered. A custom model predictive controller is utilized for implementing results from the partial shutdown optimization problem in closed-loop.

The remainder of the paper is organized as follows. The next section presents a general mixed-integer dynamic optimization framework for the partial shutdown problem. This is followed by formulations for including the cost of induced shutdowns in the objective function, and for specifying a minimum shutdown duration. A multitiered optimization formulation is then presented as a mechanism for prioritizing objectives and for addressing nonuniqueness of solutions. This is followed by a model predictive control framework for the partial shutdown problem. The next section considers optimal restoration time as an alternative objective. Several case studies demonstrate the application of the described framework to the fiber line of a pulp-and-paper plant and a full pulp-mill inventory model. Conclusions are presented in the final section.

2. Mixed-integer dynamic optimization problem formulation

The phases of a shutdown for a process unit as utilized in this work are shown in Fig. 2. The process unit is considered to be initially at steady-state. It encounters a disruption that forces a shutdown at time t_{start}. During the shutdown, input and output flow rates to the process unit (and adjacent unbuffered process units) are 0. Note that during this period, other units in the plant that are decoupled from this shutdown are able to continue operating. The shutdown phase ends at t_{end}, and it is assumed that the necessary measures to repair and restart the unit occur between t_{start} and t_{end}. At t_{end}, the unit is deemed ready to operate, and the restoration phase commences. During restoration, a control system will attempt to steer the plant back to its original steady-state operating point. The restoration phase ends at t_{res}, at which point the plant will have been successfully restored to nominal operating conditions.

In the partial shutdown problem, the goal is to find a set of economically optimal control trajectories to restore a plant from shutdown to some nominal operating state. The problem can be formulated mathematically as a mixed-integer dynamic optimization (MIDO) problem which incorporates a differential algebraic equation (DAE) system:

$$\max_{u(t)} \quad \Phi_{\text{econ}}(x(t), z(t), u(t)) \tag{1}$$

$$\text{s.t.} \quad \dot{x}(t) = f(x(t), z(t), u(t), \delta(t), \theta), \quad x(0) = x_0 \tag{2}$$

$$h(x(t), z(t), u(t), \delta(t), \theta) = 0 \tag{3}$$

$$g(x(t), z(t), u(t), \delta(t), \theta) \leq 0 \tag{4}$$