Start-Up Strategies And Multiple Steady States In Batch Processes

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Abstract:

The batch mode of operation is often a preferred over the continuous mode because of the flexibility and controllability it offers in the constantly changing production environment. However, in order to improve productivity, batch processes are becoming more and more integrated to efficiently use shared resources, raw materials and equipment. Like continuous processes, a batch process goes through three main stages during a production campaign: start-up, steady state and shut down.

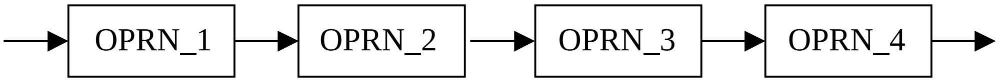
After an initial transient period, the average throughput of a process reaches a constant average value, the ‘steady state’. Under certain circumstances, the campaign start-up strategy may significantly affect the transition to the steady state as well as the average throughput attained by a process, resulting in multiple steady states. Furthermore, a disturbance in an operation may spontaneously change the steady state throughput of the process.

The logistics of operating a batch process is mainly responsible for attaining a particular steady state. In this study, the effect of various start-up strategies on the process throughput and existence of multiple steady states in a batch process operating in campaign mode are demonstrated with the help of a simulation model.

Introduction:

In comparison to the continuous processes, the area of start-up of batch processes has not received significant attention. As applied to batch processes, the term start-up typically implies the logistics and timing of initiating individual operations when starting up an idle process. The start-up and shutdown issues related to the processing of an operation in a piece of equipment are addressed as part of the recipe development. Once the recipes of all operations are finalized, the resulting cycle time and loads on shared resources provide the key inputs in determining the start-up strategy for the overall process. Very often, the products in a batch process are made in multiple campaigns. Successive campaigns may go through a complete plant shut down. In such cases, start-up strategies specific to the new campaign are developed. However, when successive campaigns are initiated back to back, strategies for transitioning to the new campaign will depend on the product slate of the preceding campaign.

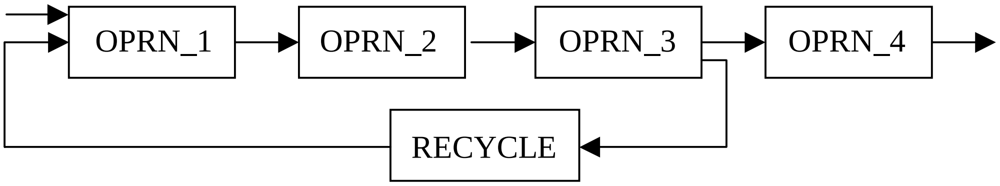
For simple, 'straight through' processes, start-up is not a major issue. An example of a simple recipe is given below.



An example of a simple recipe.

To start an idle process that manufactures this recipe, batches of operation OPRN_1 are initiated. As the batches get completed, the material is pushed downstream and the rest of the operations are initiated in succession.

Typical batch processes are rarely as simple as the example shown above. With the increased emphasis on maximizing efficiencies, modern day batch manufacturing systems are getting more and more integrated. For example, reuse of solvents, reuse of off-spec materials, simultaneously manufacturing products with different sequence of operations, plant-wide CIP systems, constraints on shared resources, minimizing storage through sharing of intermediate storage tanks by multiple products etc. are quite common. An example of a recipe with recycle of solvent stream is shown below.



An example of a recipe with recycle of material.

Introduction of recycle stream in the recipe complicates the start-up logistics. In order to start the production, the recycle operation must be primed. Therefore, either fresh solvent must be purchased or solvent from the previous campaign must be saved. In addition, decision must be made about the amount of solvent purchased initially. The amount could be influenced by several factors such as the average process throughput, lag time between the operations OPRN_1 and OPRN_3.

As the process complexity increases, the complexity of the start-up logic also increases. Therefore, a detailed analysis of process operations must be undertaken in order to develop an understanding of the interactions between various parts of the process.

After the initial transient, a batch process reaches 'steady state'. For deterministic systems an output variable either reaches a constant value or exhibits periodicity at **steady state**. For systems with variability, at steady state the probability mechanisms describing the variability of an output variable become independent of the initial condition. When an output has variability, truncating data reduces the bias due to initial transient. The truncation point is selected as the time at which the output appears to have reached steady state (1). Typically, the most important output variables are the average production rates of the finished products.

The area of multiple steady states in hybrid systems such as batch processes has not been studied to any significant depth. The development of techniques to analyze this problem would be of great value during the design and operation of batch processes. Additionally, the identification of conditions under which multiple steady states could occur in a given process will provide more value to the hazard and operability (HAZOP) studies. Typically in hybrid systems a disturbance introduced in one stage propagates through the rest of the system and eventually subsides, bringing the system back to its original steady state. However, under certain operating conditions, the system may reach a different steady state. This paper describes the multiple steady state phenomenon we observed during the simulation study of a batch process.

The relationship between start-up strategy and steady state throughput of a batch process, and the effect of disturbances on steady state throughput are described in this paper. The study was performed using the BATCHES simulator. First, the process used in this study is described. Next, a summary is presented of various simulation runs related to the effect of start-up on steady state. This is followed by a summary of the simulation runs related to the effect of disturbance on steady state.

Description of the Multipurpose Batch Process:

Two recipes, named R_1 and R_2, are manufactured in this process. The BATCHES recipe network for the recipes is shown in Figure 1.

Recipe R_1 consists of five operations, RXN_1, HOLD, FILTER_1, ST_CAT and DIRTY_A, while the recipe R_2 consists of two operations, RXN_2 and FILTER_2. Two finished products, P_1 and P_2, are produced during the manufacture of R_1 and R_2, respectively.

The RXN_1 operation of R_1 consists of 5 phases. During FILL_CAT and FILL_A, 300 kg of catalyst and 1000 kg of raw material A are filled, respectively. The total filling time is 2.0 hr. The RXN phase lasts for 6.0 hr. During DECANT, 300 kg unreacted A is transferred to the FILL phase of DIRTY_A operation. The remaining material is transferred to the FILL phase of HOLD operation. The transfer of material is assumed to be instantaneous. One piece of equipment, REACTOR_1, is suitable for perform this operation.

The HOLD operation of recipe R_1 consists of 4 phases. After transferring the contents from the RXN_1 operation, the material is aged for 2.0 hr during the AGE phase. After aging the material is fed continuously to the filter whenever it becomes available. At the end, the hold tank is cleaned for 0.8 hr. Two pieces of equipment, HOLD_01 and HOLD_02, are suitable for this operation. In addition to aging the contents, the hold tanks provide a buffer to stage the material for filtration during the third shift.

The FILTER operation of recipe R_1 consists of 2 phases. Approximately 3.2 hr is required to filter a batch in a hold tank. The yield of P_1 is 0.7 kg, while that of the catalyst is 0.3 kg per kg input. The catalyst is stored in the ST_CAT storage tank. After completing the filtration, the filter is cleaned for 0.8 hr. One operator is required during the FILTER and CLEAN phases. The operator is available only for 8.0 hr during the third shift each day. One piece of equipment, FILTER, is suitable for this operation.

The DIRTY_A operation of recipe R_1 consists of 2 phases. After collecting dirty raw material A from two RXN_1 batches, the material becomes available for downstream processing. One piece of equipment, DIRTY_A, is suitable for this operation.

The RXN_2 operation of recipe R_2 consists of 3 phases. After processing two batches of RXN_1, a batch of RXN_2 can be processed. Dirty raw material A along with 400 kg raw material C is transferred into the reactor in 2.0 hr. The RXN phase lasts for 4.0 hr. After reaction, the material is fed directly to the filter when it becomes available. One piece of equipment, REACTOR_1, is suitable for perform this operation.

The FILTER_2 operation of recipe R_2 consists of 1 phase. During the FILTER phase, the mixture from the reactor is filtered in 2.0 hr, generating 0.7 kg of P_2 and 0.3 kg of WASTE per kg input. One piece of equipment, FILTER, is suitable for this operation. Note that FILTER_2 does not require an operator. Therefore, the FILTER_2 operation can be performed any time.

The process consists of 6 pieces of equipment, REACTOR_1, HOLD_01, HOLD_02, FILTER, ST_CAT and DIRTY_A. Both recipes share the reactor and filter.

BATCHES Simulation Model:

The BATCHES simulator was used for modeling the process described above. The simulator provided the necessary functionality to model the recipe details and operation constraints (2). Some of the features of the simulator applicable to the model are discussed in this section.

The simulator allows you set a piece of equipment to a predefined initial state. This feature was used for setting the initial amount of catalyst in ST_CAT.

The operator availability was modeled as a repetitive pattern of 24 hr. duration, consisting of two segments. During the first segment of 16.0 hr operator availability is zero, while in the next 8.0 hr one operator is available. If the filter is available, it is assigned when a request is received from a hold tank. However, the filtration step is not started until the operator becomes available. This exception-handling rule puts the related pieces of equipment in *Held* state (3).

The process is driven completely by the first operation of recipe R_1. The material is pushed downstream by each operation, thus triggering the assignment of equipment to the downstream operation when an upstream batch is completed. The coordination control is managed internally by BATCHES. The simulation model is directed to initiate batches of RXN_1 as fast as possible. When two RXN_1 batches are completed, the DIRTY_A operation requests REACTOR_1 to start a batch of RXN_2 operation. In the model, the priority for starting an RXN_2 batch is set higher than that for starting an RXN_1 batch. Thus, a sequence of two batches of RXN_1 followed by one batch of RXN_2 on REACTOR_1 is guaranteed.

Start-up Strategy:

From the recipe definition of R_1 it is clear that due to catalyst recycle the catalyst storage tank must be primed before starting the process. The amount of catalyst initially set in ST_CAT affects the overall process throughput and dynamics.

Three simulation runs were made, each with different amount of catalyst in ST_CAT at the start of the run. In the first run, named STARTUP_CAT1, the initial catalyst amount was set to 300.0 kg, enough for one RXN_1 batch. In the second run, named STARTUP_CAT2, the initial catalyst amount was set to 600.0 kg, enough for two RXN_1 batches. In the third run, named STARTUP_CAT3, the initial catalyst amount was set to 900.0 kg. The recipe based Gantt chart and the ST_CAT level plots for the first two runs are shown in Figure 2. The white boxes in the Gantt chart show the operations associated with recipe R_1, while the gray boxes show the operations associated with recipe R_2.

The Gantt chart shows that when the initial catalyst amount is 300.0 kg, the process throughput is severely reduced because of the catalyst availability. Since the first RXN_1 batch uses up all the catalyst, the second batch cannot be started immediately following the first. The catalyst is regenerated by the FILTER_1 operation, which can be performed only during the third shift when the operator is available. As a result, the second batch of RXN_1 is delayed by 11.2 hours. After two RXN_1 batches, a batch of RXN_2 is started. However, after the RXN phase it has to wait for the filter to become available. As shown in the Gantt chart, the process reaches a pattern of two RXN_1 batches and one RXN_2 batch every 48.0 hours.

When the initial catalyst amount is 600.0 kg, the process reaches a steady state capacity of two RXN_1 batches and one RXN_2 batch per day. During the first RXN_2 batch in the reactor there is a brief waiting period for the filter to become available. The subsequent reactor batches have no delays, reaching the desired steady state.

When the initial catalyst amount is 900.0 kg, the overall performance of the process is not affected, except the minimum level in ST_CAT never drops below 300.0 kg.

The three runs show that the best start-up condition is 600.0 kg catalyst in ST_CAT.

Multiple Steady States:

To illustrate the phenomenon of multiple steady states in batch processes, the FILTER was taken out of commission for 4.0 hours at time 92.0 hr. This is equivalent to a loss of half a shift of production on the filter. Since the operator is available only for one shift, the second RXN_1 batch of that day is not filtered until the third shift on the following day. The delay of almost one day in the regeneration of catalyst pushes back the production in REACTOR_1. The process eventually reaches a steady production pattern that is quite different from the one before the filter breakdown. As shown by the Gantt chart in Figure 3, the initial steady state has a pattern of two RXN_1 batches and one RXN_2 batch per day. After the FILTER breakdown, the new steady state has the same pattern, but requires 35.0 hours to complete, an approximately 45% increase in the time required to produce the same amount of material.

The next step after detecting a different steady state is to devise strategies to bring the process back to the original steady state.

For the process used in this example, one of the corrective actions would be make the operator available for additional time after the disturbance is detected. This would allow the delayed RXN_1 batch to be processed immediately. As confirmed by a simulation run, this corrective action nullifies the effect of the disturbance and the steady state production pattern on REACTOR_1 continues without interruption.

However, if additional operator time cannot be allocated, then other strategies must be evolved. The analysis of the system dynamics after the disturbance shows that catalyst regeneration and consumption are critically balanced due the operator constraint. As a result, any disturbance gets amplified, pushing the process to an undesired steady state. Therefore, after detecting the disturbance if the reactor operations are delayed until the catalyst is fully regenerated, the process will return to the original steady state. Accordingly, simulation runs were made with different delay times before resuming the production of RXN_1 operation. The minimum delay time that restores the process to the original steady state is 24.0 hr. Thus, the overall loss is only one day's production, compared to a sustained decrease in throughput if no corrective action is taken. The Gantt chart for this case is shown in Figure 4. The forced delay in starting reactor batches is shown by the idle time on REACTOR_1. In this case, continuing with the normal earliest start strategyon the reactor leads to decrease in throughput, while the counterintuitive strategy of accepting short term loss leads to a long term gain.

Conclusions:

The BATCHES simulation model of a multipurpose process clearly showed that the start-up strategy could influence the steady state reached by a batch process. More importantly, the model showed that a batch process could change steady state in response to a disturbance. Both these phenomena are very important from the standpoint of process operation.

The area of start-up and multiple steady states in batch processes has received very little attention so far. The knowledge of various process characteristics that could potentially give rise to multiple steady states will be of great value in the design and operation of batch processes. When the process throughputs at two steady states are not significantly different and the process operates at the lower value, one may attribute the loss in productivity to process uncertainty instead of finding the root cause and correcting it. However, with a better understanding of the process dynamics, it is possible to recover the loss in productivity. Of course, if the loss in productivity is significant, there will be sufficient incentive to identify and correct the problem. The disturbances which might change the steady state behavior of a process could be of a wide variety, for example, equipment breakdown, random variations in process parameters, blockage due to constraints, and so on. A good understanding of the effects of these disturbances will be crucial in developing corrective responses that minimize the productivity losses. In the absence of a systems control strategy with global view, simulation is the most convenient and practical tool to study this class of problems, because a simulation model can represent the underlying process to the finest level of detail and it provides a framework to test various control strategies.

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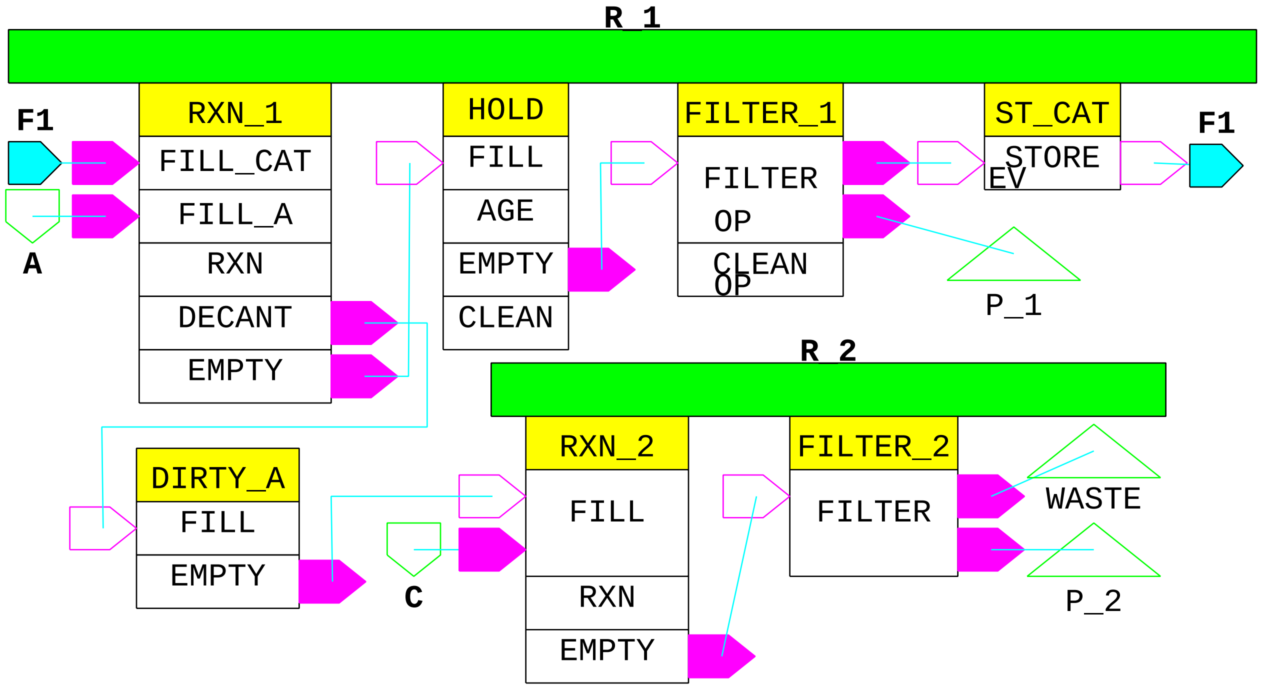

Figure 1: Recipe network used in this study.

Figure 2: Gantt chart and ST_CAT level plots illustrating the effect of startup on steady state.

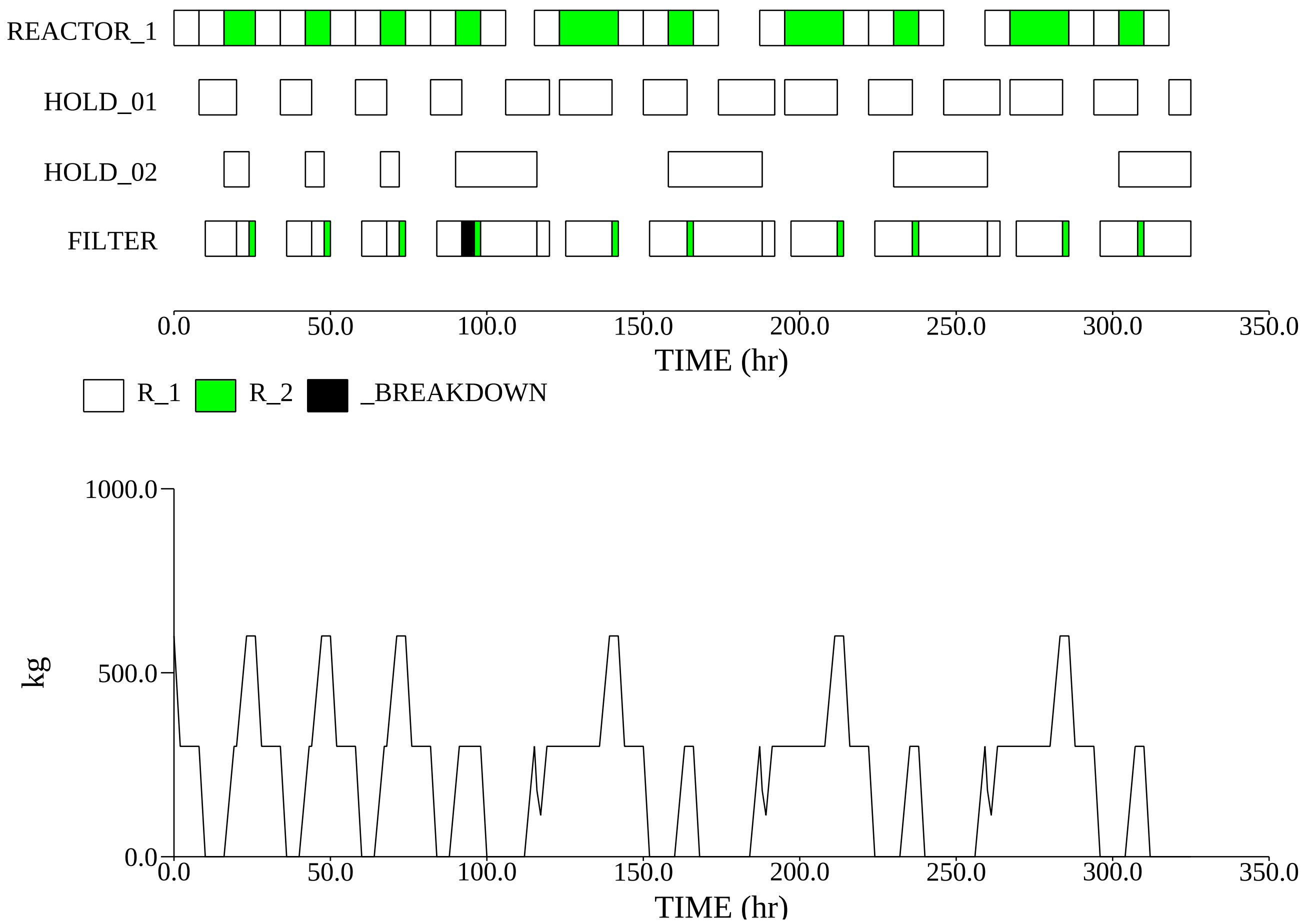

Figure 3: Gantt chart and ST_CAT level plot showing the effect of FILTER breakdown on the steady state.

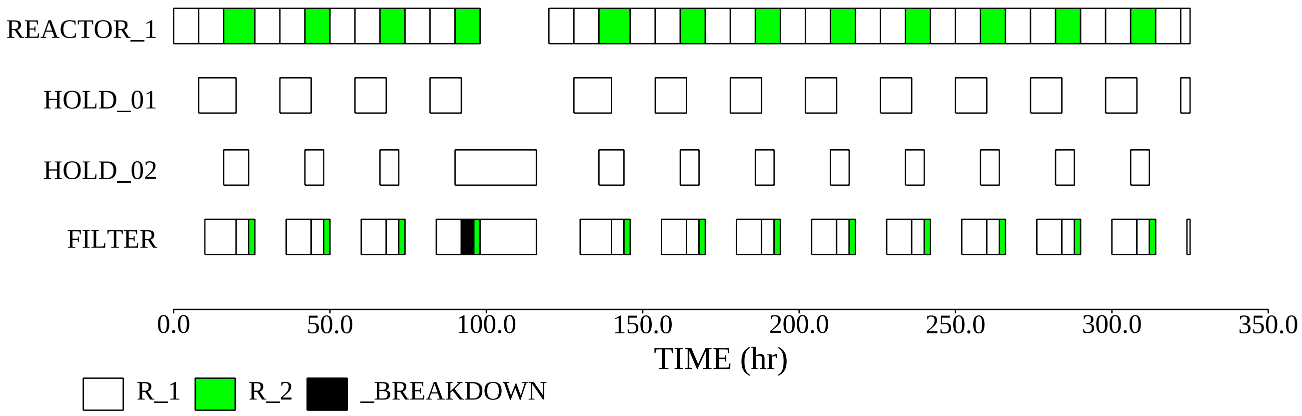

Figure 4: Gantt chart showing the effect of corrective action.