Discrete event modeling and dynamic optimization of a sugar plant

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Abstract

This paper describes the modeling and optimization of a sugar plant. Some parts of the model are driven by events, modeled as discrete event dynamic systems (DEDSs), and the rest we modeled in a continuous setting. After that, we transformed the DEDS to a mixed integer system, using a new methodology. The obtained system was used for model-based optimization in a Model Predictive Control (MPC) framework.

Keywords

Batch processing, modeling, discrete event dynamic systems, hybrid systems, optimization, model predictive control.

1.Introduction

In the sugar industry, a lot of plants are operated in a batch-wise manner. The reason for this is, that continuous crystallization is a complex technology and it is not a commonly used technology in the sugar industry. In this paper, we have modeled the so-called sugarhouse, i.e. the crystallization and evaporator sections of a sugar plant. The one-product plant has normal capacity.

It is a hybrid model, consisting of batch and continuous vacuum pans and intermediate storage buffers. Relevant pan-program stages such as filling, graining, boiling-up and emptying have been included. The product flows and volumes are calculated for each of the mass components: water, sugar, non-sugar and crystal.

First, we modeled the pan-program stages as discrete event dynamic systems (DEDSs), i.e. systems driven by events, and the rest we modeled in a continuous setting. After that, we transformed the DEDS to a mixed integer system, using a new methodology.

Hybrid systems are generally not suitable for control and optimization, one of main reasons being that controllers work in real time. For this reason we have to transform the 'logic part' of the system into real-time parts. The obtained system was used for model-based optimization. There are two reasons why model-based optimization is of high importance in the sugar industry. Using model-based optimization, one is able to predict a regular sugar quality and one can handle the large amount of energy involved. Uncertainty reduction and process restrictions motivate the choice of Model Predictive Control (MPC), a control technique that calculates a sequence of control signals in such a way that it minimizes a cost function over a prediction horizon.

For the validated model, control variables and process restrictions have been identified. With the use of MPC the objective function pans has been optimized in the sense that the system is more stable, i.e. has less fluctuations as before.

2.Modeling of the sugar plant

The sugar house and evaporation section of a sugar plant in Groningen (The Netherlands) consists of the following units (see Figure 1). In the A, B and C-pans (also called the vacuum pans) the crystallization takes place, which are being fed by the S-1, S-A, S-B and S-C pans (also called the seed-station), in which the seed crystals used in the vacuum pans are grown. The purified juice stream passes through the evaporators (in which the solids content is typically increased from 15%-18% (thin juice) to

68%-74% (thick juice)), and subsequently through the vacuum pans. The thick juice is mixed with re-melted B- and C-sugar to obtain so-called Standard Liquor, which is processed in the A-pans (batch process) to end up with a solids content of typically 92-96 %, which after centrifugation leads to white sugar and A-syrup. The syrup is processed in the continuous B-pan to yield B-sugar and B-syrup, which in turn is processed in the continuous C-pan and separated into C-sugar and molasses (C-syrup). Molasses, with a solids content of 80%-85%, is used in cattle-feed and in the production of alcohol. The B-and C-sugar are re-melted in thin juice and returned to the A-pans.

Between the different pans, there are intermediate storage buffers, in order not to overflow a level in a certain pan. The B- and C-pans are mainly used to dispose of pollution in the juice stream. Most of the crystallization is done in the A-pans, and this happens in a batch-wise manner, to have a better control of the crystal size and high super-saturations. The A- and S-pans are operated in a batch-wise manner, which consists of the following steps: filling, concentrating, seeding, stabilising, boiling up, emptying steam cleaning and ready for the next strike. It should be added that the processing time of the A- and S-pans is variable, which is generally the case for batch operations (Nott and Lee, 1999).

3.Modeling of the pan program stages

In first instance, the modeling of the pan program stages of the A- and S-pans has been done using logic rules. In the following, we describe the pan program stages in detail.

The pan programme consists of an order-control with the following steps:

1.Pan is ready for start-up. This stage is either the beginning of a strike or the next stage after the cleaning.
2.Pan is filled with Standard Liquor. It can only start after the first step.
3.Thickening. The Standard Liquor is thickened using a fixed amount of time. This can only be done if the level of the buffer, in which thick and mixed juice is caught (see Figure 1) is high enough.
4.The seed-grain slurry is moved in. It can only start after the third step. This can only be done if the level of the S-buffer (see Figure 1) is high enough.
5. Stabilization of the seed-grains and the Standard Liquor within a fixed time.
6.Crystallization. The seed-grains are growing to become sugar. This stage can only start after the fifth step.
7.Down-boiling. The sugar-crystals are big enough and the boiling is slowly put off within a fixed amount of time.

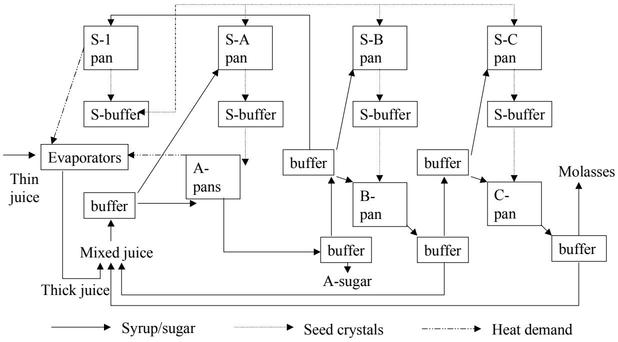

Figure 1. Units and streams of a sugarhouse and evaporation-section. Note that the heat demands of the B-, C- and S-pans are not indicated in the Figure.

8. Cooling down. The sugar crystals have to wait a fixed amount of time before the pan is emptied.
9. Emptying the pan. The sugar crystals are removed from the pan.
10. Cleaning the pan within a fixed amount of time.

The pan stages are dependent on conditions on the levels of different buffers or time. Basically, the above 10 steps can be shortened to 5 steps (see Figure 2), if we only look at the level in the pan. In detail:

- In step 1 the waiting-time for start-up is given (step 1 of the above).
- In step 2 the pan is filled with Standard Liquor and seed-grain slurry (step 2-4).
- In step 3 the crystallization takes place (step 5-8).
- In step 4 the pan is emptied (step 9).
- In step 5 the pan is cleaned and ready for the batch (step 10 and 1)

We have chosen for this set-up, because we only look at the pan-level in the optimization. One can argue that step 1 and 5 are the same, but in the optimization we make a distinction between the starting-time of a pan (step 1) and the time between two batches (step 5).

4.Transformation of the pan program stages

In the obtained simplified model of the pan-program stages, the system is still driven by logic rules, like on/off switches and if-then-else rules. Since this is the only place in the model, in which its behaviour is governed by state events, we transform this part to a mixed integer setting by the use of Mixed Logical Dynamical system theory (Bemporad and Morari (1999), Bemporad *et al.*(2000)).

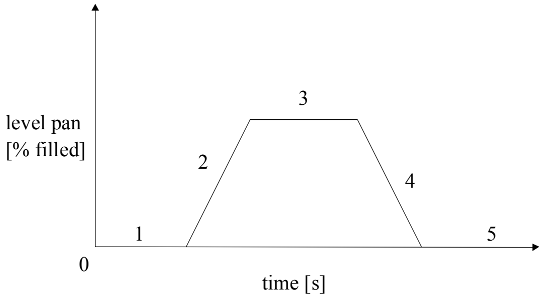

Figure 2. Schematic of basic steps in A- and S-pans.

We show how a ‘if-then-else’ construct is translated to mixed-integer linear equalities.

Consider a statement $X \equiv [f_1(x) \leq 0]$ (which has a truth value TRUE or FALSE) where f is a linear (affine) function, assume that $x \in X$, where X is a given bound set, and define

$$M_i \equiv \max_{x \in X} f_i(x), m_i \equiv \min_{x \in X} f_i(x), i = 1, 2. \qquad (1)$$

By associating a binary variable $\delta \in \{0,1\}$ with the literal X, which has a value of either 1 if $X = \text{TRUE}$, or 0 otherwise, one can transform $X \equiv [f_1(x) \leq 0]$ into mixed integer inequlities. For the ‘if-then-else’ construct,

$$\begin{aligned} &IF\ X\ THEN\ z = f_1(x)\ ELSE\ z = f_2(x) \\ &(z = \delta\ f_1(x) + (1-\delta)\ f_2(x)), \end{aligned} \qquad (2)$$

we obtain

$$\begin{aligned} &(m_2 - (m_2 - M_1)\delta + z \leq f_2(x) \\ &(m_1 - M_2)\delta - z \leq -f_2(x) \\ &(m_2 - M_1)(1-\delta) + z \leq f_1(x) \\ &(m_2 - M_1)(1-\delta) - z \leq -f_1(x)\,. \end{aligned} \qquad (3)$$

Note that we introduced an auxiliary variable z for the translation. Using this method, one can transform more logic rules into mixed integer linear inequalities.

The results can be generalized for relations involving an arbitrary number of discrete variables combined by an arbitrary number of connectives (like ‘ $\wedge$ ’ (and), ‘ $\vee$ ’ (or) and ‘ $\rightarrow$ ’(implies)) .
After the transformation, we obtain the following Mixed Logical Dynamical (MLD) system:

$$\begin{aligned} &x(t+1) = A\,x(t) + B_1u(t) + B_2\delta(t) + B_3z(t) \\ &y(t) = C\,x(t) + D_1u(t) + D_2\delta(t) + D_3z(t) \\ &E_2\,\delta(t) + E_3z(t) \leq E_1u(t) + E_4x(t) + E_5, \end{aligned} \qquad (4)$$

In which x is the state, y the output and u is the input of the system. Moreover, we assume matrices A, B_1, B_2, B_3,C, D_1,D_2,D_3, E_1,E_2,E_3,E_4 and E_5 to be constant.

We transformed the pan program stages using the MLD framework and replaced the logic rules with equations of the form (4). Doing so, we obtained an overall mixed integer model, on which we applied Batch Model Predictive Control.

5.Batch MPC

The widespread use of Model Predictive Control (MPC) in chemical industries is because it has several nice features (see Garcia *et al.* (1989), Morari and Lee (1999)). MPC can be used for handling multivariable and/or constrained problems and its concepts are easy to understand for operators with only a limited knowledge of control (Bordons and Camacho (2000)).To our knowledge no MPC-application combined with a scheduling-algorithm applied to a mixed batch/continuous system is applied.

The case of scheduling a problem in a sugar factory, used to illustrate a hybrid scheduling approach, has been done by Nott and Lee (1999), but no MPC was involved here. Applications of MPC to mixed integer problems in sugar plants have been reported by several authors, e.g. Bordons and Camacho (2000) and Prada *et al.* (2000. In our approach, we have reduced the complex problem to a simpler problem (the seed-station with only the relevant inputs and outputs), with all the characteristics of the more complex problem, such as its hybrid character. For this problem, the proposed objective function (OBJ) to be maximised is

OBJ= profit - batch costs - idle penalty - change flow penalty (5)

in which ‘profit’ is the turnover for the production through the system, ‘batch costs’ are the costs associated with beginning a batch, ‘idle penalty’ is the penalty for scheduling idle batch units and ‘change flow penalty’ is the penalty for changes in the flowrate. The constraints under which the objective function OBJ (5) is maximised are

1. The model is limited to numerical stable domains of operation.
2. Physical constraints, such as bounds on the flows and levels in the vacuum-pans and seed-station.
3. Bounds on the (variable) cycle times of the A- and S-pans.
4. The start-frequency of the batch-section (A-, S-1-, S-A-, S-B- and S-C- pans) is chosen in such a way that the waiting time between pans is constrained.

Using this objective function and constraints, the ratio between vapor input from the evaporators in the sugar mill and the steam demand of the sugarhouse is optimised.

6.Results

In the simple problem, we have taken the model of the seed-pans and applied Batch MPC with an objective function of the form (5).

Figures 3 and 4 show the results of the optimization. The total amount of steam in the pans is never allowed to exceed 10 ton, which is one of the constraints. Indeed, the last subplot shows that it stays under 10 ton. In Figure 4 we show when pans are active (filled). We have denoted 'active' with 1 and 'non-active with 0. It is possible that there is no steam-production for the S-C pan, although the pan is active.

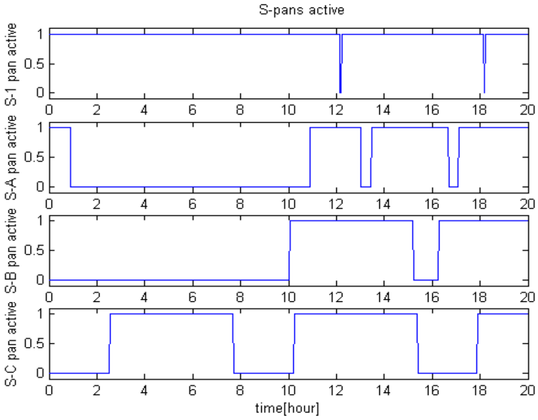

Figure 3. Activity of the S-pans: 1 means in practice, 0 means idle.

It is possible that there is no steam-production for the S-C pan, although the pan is active.

The results of applying Batch MPC are satisfactory for the simple problem. The results are given in the next section. Hence, we expect an increased on-spec time with tighter specs. But, more importantly, a much more stable process-operation is achieved within a time-horizon of 6-8 hours, which is the largest time in the process.

7.Conclusions

In the present paper we modeled the sugarhouse and evaporation-section of a sugar plant with the purpose of determining the heat streams in the process. We modeled a part of the system as discrete event dynamic systems (DEDSs), i.e. systems driven by events and the rest we modeled in a continuous setting. After that, we transformed the DEDS to a mixed integer system, using the MLD-framework. After that a reduced model has been used for Batch MPC, and the results are satisfactory for that model. The results are now going to be applied to the more complex model.

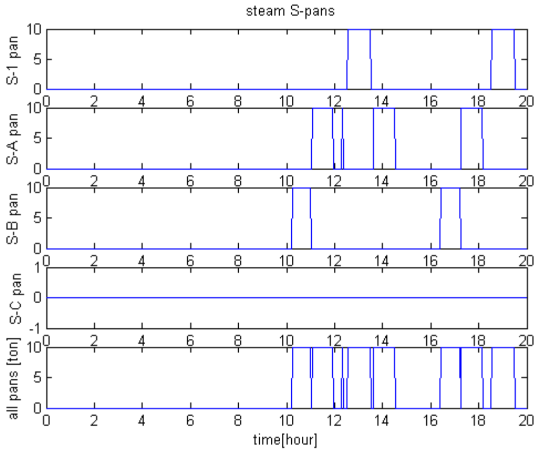

Figure 4. Steam production of the S-pans. In the last subplot the cumulative steam-production of the all the S-pans is given.

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