Hybrid NMPC Control of a Sugar House

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1 Introduction

Plant-wide control is attracting considerable interest, both as a challenging research field and because of its practical importance. It is a topic [1] characterized by complexity in terms of the number and type of equipments involved, diversity of aims, and lack of adequate models and control policies. In this paper, the MPC control of the final part of a beet sugar factory, the so-called sugar house or sugar end, where sugar crystals are made, is presented. Perhaps the most characteristic aspect of its operation is that batch and continuous units operate jointly, which introduce the need for combining on-line scheduling with continuous control. As such, it is a hybrid process that requires non-conventional control techniques. The paper presents a methodology and a predictive controller that takes into account both, the continuous objectives and manipulated variables, as well as the ones related to the discrete operation and logic of the batch units, and, at the end, simulation results of the controller operation are provided.

Many approaches have appeared in the literature in recent years for hybrid predictive control. A natural approach integrates in a single mathematical formulation the different elements of a hybrid process by using integer variables for representing on/off decisions and integer equations for the logic relations between variables [2] besides the continuous equations. The fact that the internal model of the MPC controller includes continuous and integer variables leads to a mix-integer optimization problem [3], which in many cases is difficult and time consuming to solve.A natural way of approaching complex systems is using a hierarchical point of view, separating the problems that can be solved locally at a lower level from the ones that require a global consideration. This paper focuses on these overall decisions, and describes a controller that takes into account both continuous control of key process variables as well as the scheduling involved in the operation of the crystallizers, which operate in batch mode. The controller follows the MPC paradigm, solving a non-linear model-based optimization problem on-line every sampling time. Moreover, the problem is re-formulated in terms of prescribed patterns of the batch units variables and time of occurrence of the events (real variables), instead of using integer variables, which allows to solve

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the optimization problem as a NLP one, saving computation time. The interest of this contribution comes not only from the fact that it is a challenging control problem, but because problems with a similar structure are present in many industrial process factories.

2 The Sugar End and Control Architecture

Sugar factories produce commercial sugar in a set of vacuum pans or "tachas" from an intermediate solution called feed syrup. Each tacha operates in a semi batch mode following a predefined sequence, which main stages are: loading of syrup; heating it with steam; concentration until supersaturation is reached; seeding and growing of the crystals until they reach the desired size and the vacuum pan is full, this stage being known as cooking, and finally unloading the massecuite or cooked mass, which is the mix of crystals and non crystallized syrup (mother liquor). The main source of variability in the operation of each vacuum pan comes from the quality of the feed syrup. The processing time increase if the percentage solid content of the syrup, which is known as brix, decrease, and crystal growth increases with the purity of the syrup, that is, the percentage of pure sacharose in the dissolved solids.

A scheme of the sugar house of the particular case that has been considered can be seen in fig. 1. From the three vacuum pans A, the cooked mass, is unloaded into an agitated heated vessel named "malaxador". From this one, the mix of mother liquor and crystals is separated by means of a set of seven centrifugals. Cooked mass from tachas type A, gives way to commercial white sugar and two kinds of syrup: the so-called lower purity syrup and the higher purity syrup. The later has a small percentage of dissolved crystals and, so, a higher purity, and its is recycled to the feeding tank (melter) of tachas A. On the contrary, the lower purity syrup is sent to another storage vessel (tank B) and processed again in one tacha named B. The proportion between both kinds of syrup can be adjusted using a timer in the local centrifugals control. In tacha B the whole process is repeated, this time with longer operation times due to the lower purity of the syrup, but with an important difference: the sugar produced in the three centrifugal separators B, sugar B, is not commercialised but recycled to a melter due to its color and impurities, while the lower purity syrup is discharged as a by-product called molasses. The overall control objectives of the sugar end section are summarised next:

1. Processing the flow of syrup coming from the previous continuous sections of the factory avoiding bottlenecks in production. This objective implies an adequate scheduling of the vacuum pans operation and a proper use of the shared resources, such as, avoiding the feeding tanks (melter and tank B) and malaxadors A and B from being either empty or overflow. This implies to maintain levels in the previous units between certain lower and upper limits.
2. Maintaining the quality of the crystals in terms of size and size distribution. This is an important objective, but it is solved locally in every vacuum pan, where the operation of the crystallization is managed in order to obtain proper conditions for sugar crystal growth.

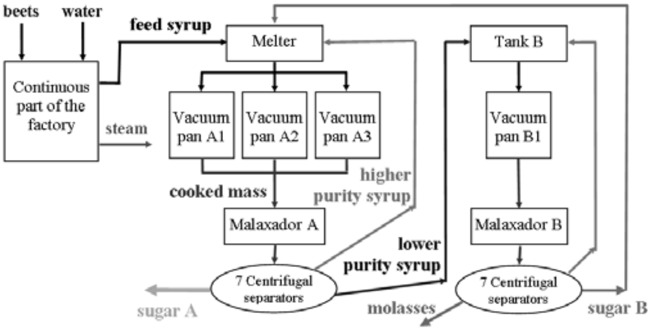


Fig. 1. A simplified scheme of the sugar end section

3. Maintaining brix and purity in melter and in tank B as close as possible to given set points, in order to maximize the amount of sugar A produced, because the processing time and capacity of the tachas depend on both variables. This has also an influence in the first objective.

From control architecture point of view, a common strategy in complex systems, is to decompose the problem in several levels or time scales, so that what can be solved locally, involving a limited set of resources or decision variables is separated from those decisions that involve variables having an effect on the dynamics of the whole system. In our case, this hierarchical decomposition recognisees at least three layers or types of control problems:

Local SISO controllers: Such as the temperature control in the malaxadors, flow controls, etc. These are managed by the Distributed Control Systems (DCS) of the plant and have fast dynamics compared with the ones of the sugar end. They are supposed to operate well using standard controllers.

Sequence control of each batch unit: Such as tachas and centrifugal separators. For every vacuum pan, this control executes the cyclical sequence of stages described at the beginning of this section, necessaries to obtain the final product: sugar (objective number 2 in the previous list). It is implemented also in the DCS as a GRAFCET chart with additional local control of pressure, level, concentration, etc, and operate according to predefined parameters and external orders, such as load and unload each tacha. These local controllers are assumed to do its best in order to complete its tasks each cycle, for instance rejecting disturbances on steam pressure or vacuum. For centrifugal separators, another GRAFCET chart executes the consecutive operations of loaded cooked mass, unloaded low purity syrup, unloaded high purity syrup and unloaded sugar. In this case, the external orders are the frequency of operation of every centrifugal separator and the percentage of lower and higher purity syrup obtained.

Plant wide-control: This layer is responsible for objectives 1 and 3 of the previous list, in spite of changes in the flow and quality of the feed syrup, and it is the objective of this paper. For this purpose, besides the scheduling of the tachas, the controller can manipulate the proportion between lower and higher purity syrup in the centrifugals and its operating frequency, which is equivalent to establishing its total processing flow. These tasks are performed very often manually by the person in charge of the section. From the point of view of this layer, the SISO controllers and sequence control can be considered as included in the process, operating in cascade over them.

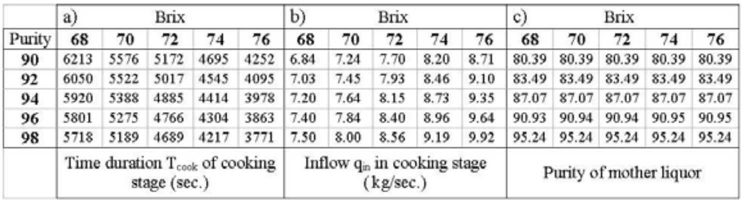
3 Hybrid Control

A natural approach to many decision problems is the one of Model Predictive Control (MPC): A model of the process is used to predict its future behavior as a function of the present and future control actions, which are selected in order to minimize some performance index. The optimal control signals corresponding to the present time are applied to the process and the whole procedure is repeated in the next sampling period.

In MPC of complex systems, it is very important that the internal model that relates controlled and manipulated variables being as simple as possible while still being a good representation of the process. On the other hand, it must correspond to the view and purpose of the plant-wide control. A full first principles model implementing mass and energy balances, as well as crystal growth and local control functions can perform this task, but this approach will lead to a huge model, useless for MPC. Consequently, the model includes only those variables and phenomena relevant to the above mentioned plant-wide control objectives. It combines dynamic mass balances of total mass, solid content and sacharose in the continuous units (feeding tanks and malaxadors) with abstractions and simplifications of the other parts of the process, tachas and centrifugals, because, what is important, is the relationship between these units and the continuous ones are given through the input and output flows and its principal characteristics like purity, brix and percentage of sugar.

A key point is then, the abstract model of the tacha. Notice that, when a tacha is started, the inflow of syrup, the flow and characteristics of the cooked mass unloaded and the time consumed in the operation depends only on the properties of the feed (purity and brix), so, the approach followed has been to use tables like the one in fig. 2 relating these main variables of the vacuum pan with the properties of its feed, purity (P) and brix (B). These tables have been obtained off-line, and for a range of reasonable operating conditions, integrating a full first principles model of the vacuum pan starting from a syrup with different values of purity and brix. For example, fig. 2 a) and b) shows the time duration and inflow of syrup of cooking stage. Also additional tables are needed, see fig. 2 c), such as the ones relating brix and purity in the feeding tank with the total cooked mass obtained, the percentage of crystals in it and brix and purity of mother liquor, and the duration of the rest of stages of the sequence.

This abstract view, makes possible includes the explicit use of the special patterns that input and output flows must follow. Fig. 3 a) and b) show the shape approximation of $q_{in}(P, B)$ and $q_{out}(P, B)$ used in the simplified model of



	a) Brix					b) Brix					c) Brix				
Purity	**68**	**70**	**72**	**74**	**76**	**68**	**70**	**72**	**74**	**76**	**68**	**70**	**72**	**74**	**76**
90	6213	5576	5172	4695	4252	6.84	7.24	7.70	8.20	8.71	80.39	80.39	80.39	80.39	80.39
92	6050	5522	5017	4545	4095	7.03	7.45	7.93	8.46	9.10	83.49	83.49	83.49	83.49	83.49
94	5920	5388	4885	4414	3978	7.20	7.64	8.15	8.73	9.35	87.07	87.07	87.07	87.07	87.07
96	5801	5275	4766	4304	3863	7.40	7.84	8.40	8.96	9.64	90.93	90.94	90.94	90.95	90.95
98	5718	5189	4689	4217	3771	7.50	8.00	8.56	9.19	9.92	95.24	95.24	95.24	95.24	95.24
	Time duration T_{cook} of cooking stage (sec.)					Inflow q_{in} in cooking stage (kg/sec.)					Purity of mother liquor				

Fig. 2. Typical table obtained off-line from the first principles dynamic of a tacha

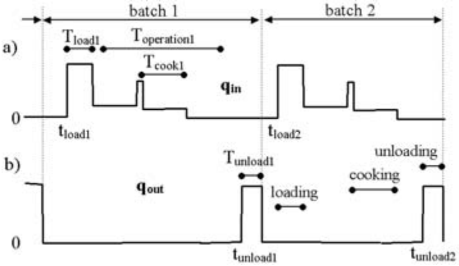


Fig. 3. a) and b) Temporal patterns of input and output flows (q_{in} and q_{out}) of the simplified model of a tacha

the vacuum pan, where two batches are predicted. For simplicity in the graphic, we have named only three stages: loading, cooking and unloading. In fig. 3 a), flow q_{in} is different from zero in several situations: for example, when a loading order arrives at time t_{load1}, and for cooking stage. T_{load1} and T_{cook1} are the duration of the loading stage and cooking stage respectively. The other signal in fig. 3 b) corresponds to the outflow q_{out} which is zero except for the unloading period $T_{unload1}$. The logic of operation implies that the unloading time $t_{unload1}$ must be placed after the operation has finished, which can be translated into a constraint such as $t_{unload1} > t_{load1} + T_{load1} + T_{operation1}$, the latest being the intermediate operation period for the current feeding conditions and it is formed by the sum of the duration of several stages, included T_{cook1}. These periods can be computed as before from interpolation in a table $T_i(P, B)$ (i=every stage) that has also been obtained off-line. In order to complete the vacuum pan model, other constraints must be added reflecting its logic of operation, such as $t_{load2} > t_{load1} + T_{load1} + T_{operation1} + t_{unload1} + T_{unload1}$ that indicates that the next batch 2 must start after the previous batch 1 has been unloaded. These two constraints are necessary for each batch predicted and for each tacha.

In relation with the subjacent time model and the scheduling policy, the classical approach considers the time axis divided in sampling periods, where each sampling time j has an associated integer variable indicating if unit i starts or not its operation in period j. The scheduler solves a MIP problem to determine the optimal start and ending times of the batch units. In this paper we have applied an alternative approach that is coherent with the use of the temporal patterns shown in fig. 3 a) and b). It assumes as unknowns the time of occurrence of the events, t_{load1} and $t_{unload1}$, which are real variables, instead of using integer variables in every sampling period [4]. In this way, all the decision variables of the internal model are continuous. Notice that this approach means that the scheduling problem is not computed separately but it is integrated into the overall predictive control and the need for solving mix integer optimization problem is avoided, being substituted by an NLP one.

3.1 NMPC Controller

Before the non-linear model predictive control problem can be solved, it is necessary to adapt some concepts used in standard continuous MPC to the context of mix continuous-batch processes. The first one is the prediction horizon ($N2$) that will be translated into Np minimum number of full bathes performed for all batch unit. The concept of control horizon (Nu) is split into batch control horizon (Nb_i) and continuous control horizon (Nc). The first refers to the number of batches performed of each batch unit i ($i = A1, A2, A3, B1$) in which the decision variables t_{load} and t_{unload} will be computed. From Nb_i until the end of the prediction horizon (Np), these values will be equal to the ones of the last batch. Notice that this implies the assumption that a stable cyclic pattern will be reached at the end of the prediction horizon, in a similar way to how the future control signal is treated in continuous MPC. Each Nb_i will fix the number of unknown time instants t_{load} and t_{unload}, two per batch performed and per unit. Finally the Nc horizon has the classical meaning for the classical continuous manipulated variables. The control decisions are computed solving an NLP optimization problem where the aim is to minimize a quadratic cost function J, subject to the decision variables u_j:

$$J = \int_{0}^{Tstop} \sum_{i} \alpha_i \left(y_i(t) - y_i^{ref} \right)^2 dt \tag{1}$$

with the usual constraints $y_i^{min} \leqslant y_i(t) \leqslant y_i^{max}$ and $u_j^{min} \leqslant u_j(t) \leqslant u_j^{max}$, where the y_i's extend to purities and brixes in the feeding tanks (P_A, B_A, P_B, B_B) and the levels in these tanks (L_A, L_B) and in the two malaxadors (L_{MA}, L_{MB}). $Tstop$ is the total time of prediction fixed by Np, prediction ends when at least Np full cycles are performed for all tachas. Respect to the future manipulated variables, u_j are times of load and unload every vacuum pan plus total flow and proportion of higher and lower purity syrup in the centrifugal separators of section A and B. In total the decision variables are $2 \times Nb_{A1} + 2 \times Nb_{A2} + 2 \times Nb_{A3} + 2 \times Nb_{A3} + 4 \times Nc$. α_i and β_j are given values of weights. The optimization is subjected to the internal model of the process and additional constraints imposed by the range and operation of the vacuum pans and other units.

4 Simulation Results and Conclusions

The control strategy described in the previous sections was tested in simulation using the state-of-the-art EcosimPro environment. The process was represented

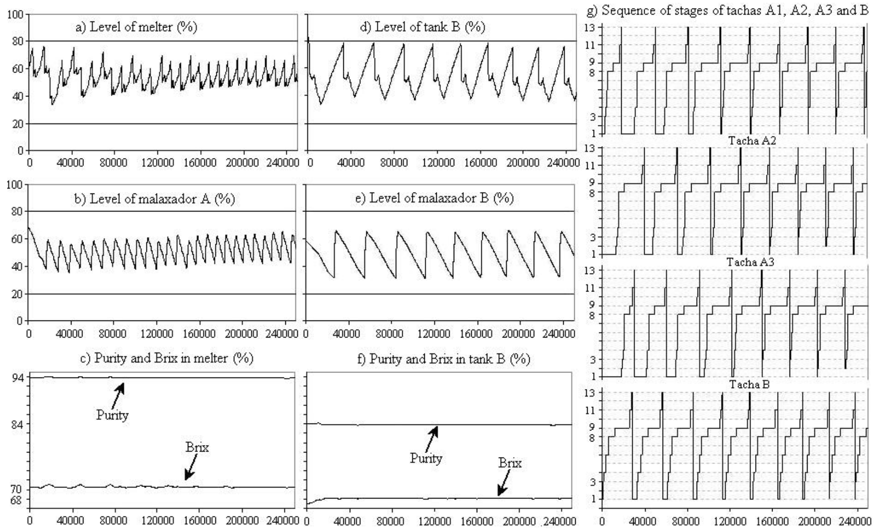


Fig. 4. a), b) and c) Controlled variables for section A. d), e) and f) Same variables but for section B. g) Sequencing of each tacha.

by a detailed simulation built using validated models of the Sugar Processes Library [5] including sequential and local controls of all units. This model involves 14719 variables and 5652 differential-algebraical equations (DAES). The controller was programmed in C++ and contains the SQP algorithm which is able to call another EcosimPro simulation with the MPC internal model (only 1823 variables and 130 DAES) for computing the cost function J each time it was needed. The sample time was chosen as 15 min. We present an experiment of 69.4 hours (250000 sec.), with an inflow of feed syrup of 6 kg/sec. with 94.4 of purity and 72 of brix. All batch control horizons ($Nb_i, i = A1, A2, A3, B1$) were fixed in 2, and continuous control horizon (Nc) was fixed in 4, so, the number of decision variables is 32. On the other hand prediction horizon (Np) was fixed in 3, that is to say, 25 hours of predictions. Control objectives (references and maximum/minimum values permitted for controlled variables) and weights in cost function (1) are:

	$L_A(\%)$	$P_A(\%)$	$B_A(\%)$	$L_{MA}(\%)$	$L_B(\%)$	$P_B(\%)$	$B_B(\%)$	$L_{MB}(\%)$
maximum	80	-	-	80	80	-	-	80
minimum	20	-	-	20	20	-	-	20
reference	50	94	70.5	50	50	84	68	50
weight	0.1	1	1	0.1	0.1	1	1	1

Fig. 4 a) and b) shows the levels of melter and malaxador A, and its minimum and maximum values allowed, fig. 4 c) shows purity and brix in the melter. Fig. 4 d) e) and f) shows the same variables but for section B. The sequence of stages of vacuum pans A1, A2, A3 and B can be seen in fig. 4 g). Time of stage 1 is the manipulated variable to load syrup and time of stage 9 is the manipulated variable to unload cooked mass. Cooking, load and unload stages correspond with numbers 8, 3 and 11. The hybrid controller is able to operate well the process: performing an adequate scheduling of tachas and maintaining purities and brixes close of its set points and levels within permitted range.

In this paper a plant-wide control strategy for the crystallization section of a beet sugar factory has been presented. It is based in a hierarchical view of the problem and, in the use of MPC with a simplified model that combines material balances of the continuous units and an abstract model of the batch ones. This is described in terms of tables computed off-line and prescribed patterns of the batch units variables and time of occurrence of the events, instead of using integer variables, allowing to use NLP algorithms instead of MIP ones. The strategy has proved to perform well in a simulated environment and opens the door to practical implementations at industrial scale.

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