MPC Control of a Sugar House

Daniel Sarabia and Cesar de Prada and Smaranda Cristea and Rogelio Mazaeda and William Colmenares[†]

Dpt. Systems Engineering and Automatic Control. Faculty of Sciences, c/ Real de Burgos, s/n, University of Valladolid, Spain,
dsarabia@autom.uva.es, Prada@autom.uva.es, Smaranda@autom.uva.es, Rogelio@cta.uva.es
[†] *Universidad Simón Bolívar, Dpt. Procesos y Sistemas, Apartado 89000, Caracas 1080, Venezuela,*
williamc@usb.ve

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This paper deals with the MPC control of an industrial hybrid process where continuous and batch units operate jointly: the crystallization section of a sugar factory. The paper describes a plant-wide 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. The MPC is formulated avoiding the use of integer variables, so that a more efficient NLP optimization technique could be applied. Simulation results of the controller operation are provided.

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 characterized by complexity in terms of the number and type of equipments involved, diversity of aims, and lack of adequate models and control policies [1]. In this paper, the 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 are involved, 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.

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. The paper focus on these overall decisions, and describes a controller that takes into account both continuous control of key process variables as well as the logic and 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.

Many approaches have appeared in the literature in recent years for hybrid predictive control. A natural approach is integrating 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]. The fact that the internal model of the MPC controller includes continuous and integer variables lead to a mix-integer optimization problem [3], which in many cases is difficult and time consuming to solve. An alternative is to work out the associated optimization problem off-line as a function of the process state, a formulation known as multi-parametric programming, [4]. Nevertheless, this is limited in practice to small size problems, far away from the plant-wide situation.

This paper focus the problem from a different perspective and re-formulates it in terms of prescribed patterns of the batch units variables and time of occurrence of the events, instead of using integer variables, which allows to solve the optimization problem as a NLP one, saving computation time. The paper is organised as follows: After the introduction, section 2 describes the process considered, the sugar end of a factory and presents the control aims. Then, section 3 shows the control policy and the overall architecture that allows decomposing the control tasks in a hierarchical way. The MPC controller is presented in section 4. Finally, its implementation and simulation results are given in section 5. The paper ends with some brief conclusions and bibliography.

2 The sugar end

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, see Figure 1 a), 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. Then, after a final tightened of the cooked mass or massecuite, which is the mix of crystals and non crystallized syrup (the later called mother liquor), is unloaded into an agitated heated vessel named a "malaxador". The cooking stage is the most important one. Good operation implies: maintaining the supersaturation of the mother liquor, a proper growing speed of the sugar crystals and the whole mass in the unit. For this purpose, a combination of a continuous flow of fresh syrup, (this stage is semi-batch), a constant vacuum and a flow of low pressure steam into the "calandria" of the tacha is used. Assuming that condenser power, supply steam and syrup are not scarce, the main source of variability in the operation of the tachas comes from the quality of the syrup. The processing time increases if the solid content of the syrup, which is known as brix, decreases, and the crystal growth increases with the purity of the syrup, that is, the percentage of pure sacharose in the dissolved solids.

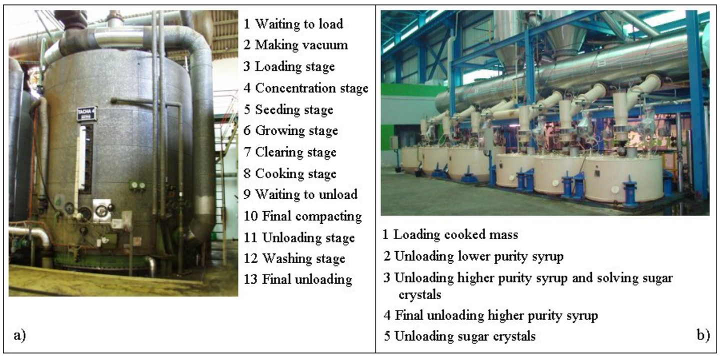

Figure 1: a) A typical vacuum pan and sequence of stages of it. b) Centrifugal separators of a sugar house and sequence of stages.

From the malaxadors, the mix of mother liquor and crystals is separated by means of a set of centrifugals, Figure 1 b). 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 of tachas A. On the contrary, the lower purity syrup is sent to another storage vessel and processed again in tachas named B. The proportion between both kinds of syrup can be adjusted using a timer in the local centrifugals control.

In tachas 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 centrifugal separators B, beet sugar B, is not commercialised but recycled to a melter due to its color and impurities. In the factory, lower purity syrup B is processed again in tachas C, with a set of additional operations, being the final products from its centrifugals the sugar C that is also recycled, and a by-product called molasses.

The sugar end process is quite complex, so, in order to make things simpler, in our study, instead of the three kind of tachas A, B and C, only two of them, A and B, has been considered. Also, other units have being merged into a single one, giving rise to the schematic of Figure 2. In this simplified view, feed syrup arrives from the continuous part of the factory with variable flow, brix and purity. Then it is mixed with the recycled sugar B in the melter, which acts also as a feeding tank of tachas A. We have considered three of these batch vacuum pans acting in parallel and unloading to a common malaxador and seven centrifugals. Each tacha is provided with an automatic control system that implements its operating sequence. Local controls of the centrifugal separators allow to fix the flow of the cooked mass processed and the percentage of higher and lower purity syrup produced.

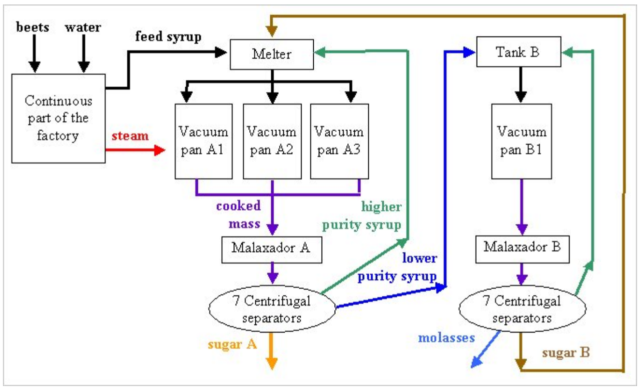

Figure 2: A simplified schematic of the sugar end section.

Lower purity syrup is sent to the feeding tank B, where it is mixed with higher purity syrup from centrifugals B an it is processed in a single tacha B. Again the same scheme of a malaxador and seven centrifugals applies as mentioned above, but, this time, in addition of higher purity syrup and sugar B, that it is recycled to the melter, the lower purity syrup is discharged as a by-product called molasses. The overall control aims of the sugar end section are summarised next:

- Processing the flow of feed syrup coming from the previous continuous sections of the factory avoiding bottlenecks in production.
- Maintaining the quality of the crystals in terms of size and size distribution.
- Maximizing the amount of sugar A produced or, alternatively, minimizing the sugar losses in the molasses.

The first aim implies an adequate scheduling of the vacuum pans operation, as well as a proper use of the shared resources, such as avoiding excessive steam demand, and the melter, feeding tank B and malaxadors A and B from being either empty or overflow. Indirectly, it also implies a proper control of the brix and purity of both feeding tanks, because the processing time and capacity of the tachas depend on them.

The second aim is an important one, but it is solved locally in every vacuum pan, where the operation of the crystallization is managed in order to obtain a proper conditions for sugar crystal growth.

The third aim implies in fact two different problems: an adequate regulation of the purity in the feeding tanks around its set points, and determining the maximum feasible value of these set points so that the transfer of sacharose from the higher purity syrup to the crystals is maintained as high as possible. The first problem is a control one, but the second implies global optimization of the section. Only the control problem has been considered in this paper. Notice that this focus can also be applied to the first aim in order to maximize the production capacity.

3 Control architecture

When faced with complex systems, a common strategy is to decompose the problem in several levels or compartments 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 a long time effect on the whole system. In our case, this hierarchical decomposition recognised al least three layers or types of control problems in the sugar end:

- Local SISO controllers such as the temperature control in the malaxadors, flow controls, etc. These are managed by the DCS of the plant and have fast dynamics compared with the ones of the sugar end. They are suppose to operate well using standard controllers and won't be considered in the sequel.

- Sequence control of each batch (or semi-batch) unit: tachas and centrifugal separators. They are implemented also in the DCS or local PLCs and operate according to predefined parameters and external orders, such as load and unload. These local controllers are assumed to do its best, according to its tuning, in order to complete its tasks each cycle, for instance rejecting disturbances on steam pressure or vacuum. Typical processing times are 2.5 and 4 hours in tachas A and B respectively, while cycle time is about 3 minutes in a centrifugal separator.
- Plant wide-control. This layer is responsible for the scheduling of the batch units and for deciding the values of the parameters in the centrifugal separators that fix the flows of higher and lower purity syrup, with the aim of maintaining certain levels of brix and purity in the feeding tanks as well as a proper operation of the whole section. This task is performed very often manually by the person in charge of the section.

Notice that, from the point of view of the plant-wide control, the sequence and low level controls can be considered as included in the process, operating in cascade over them. So, the internal operation of the vacuum pans or centrifugal separators is not of direct interest for the plant-wide controller that sees them as some kind of black boxes where what is important is not the inside but the interaction with the outside. The control tasks in this layer can be summarized as follows:

- Schedule the operation of the vacuum pans, that is, decide when every unit must load and unload its cooked mass.
- Maintain of brix and purity in each feeding tank (melter and B) as close as possible to given set points.
- Maintain the levels in the malaxadors and feeding tanks between certain upper and lower limits.

In spite of the changes in the flow and quality of the incoming syrup.

For this purpose, besides the scheduling of the tachas, the controller can manipulate the proportion between lower and higher purity syrup in the centrifugals as well as the number of them in operation, which is equivalent to establishing its total processing flow. Thus, it is a hybrid control problem involving continuous and discrete variables.

4 Hybrid MPC 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 behaviour 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.

4.1 The internal model

In complex systems like the one of our problem, it is very important that the internal model that relates controlled and manipulated variables be 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. Consequently, the model includes only those variables and phenomena relevant to the above mentioned plant-wide control aims. It combines dynamic mass balances of total mass, solid content and sacharose in the continuous units with abstractions and further simplifications of the other parts of the process. Specifically, the centrifugal separators, in spite of being batch units, have being modelled as two continuous separators, one in every subsection A and B, due to its relative high number and short operating cycle, being the task of an associated "software actuator" to translate total flow and percentage of high and lower purity syrup into number of units in operation and settings of the timers.

The modelling of the vacuum pans and its associated scheduling problem requires a separate discussion. First, the kind of model will be considered and then we will discuss the time model related to the scheduling.

Notice that the model of a tacha must provide the demands to its feeding tank and the flows of crystals and honey to the downstream malaxador as a function of the schedule as well as of brix and purity of feed. 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. Instead, an abstract view of the tacha is employed that makes explicit use of the special patterns that its input and output flows must follow as well as of results obtained off-line from the first principles model. Input (q_{in}) and output (q_{out}) flows of a vacuum pan in a real evolution, where 2 batches are produced, can be seen in Figure 3 a) and b). For simplicity in the graphic, we have named only three stages: loading (stage 3), cooking (stage 8) and unloading (stage 11) of all nine, see Figure 3 a). Figure 3 c) and d) also shows, the shape approximation of (q_{in}) and (q_{out}) used in the simplified model of the vacuum pan.

In Figure 3 a), flow q_{in} is different from zero in several situations: The first one is when a loading order arrives at time t_{load1}, q_{in} having a known value for the also known loading period. Another one is when the semi-batch cooking stage starts. The duration of the loading stage T_{load1} can be estimated fairly well, but for the value of the flow and the duration of the cooking stage (T_{cook1}) and for the rest of stages, another procedure must be used. This is a key point in obtaining a reduced model of the vacuum pan, and the approach followed has been to use tables like the one in Figure 4 a) and b) relating the main variables of the vacuum pan with the properties of its feed, purity (P) and brix (B). The value of these variables can be computed by interpolation from the tables. These have been obtained off-line integrating a full first principles model of the vacuum pan starting from a syrup with different values of purity and brix. Notice that the variability of operation of every tacha, once a given policy is implemented in the batch control layer, depends only on the state of the feed, making it possible to obtain the above mentioned tables for a range of reasonable operating conditions.

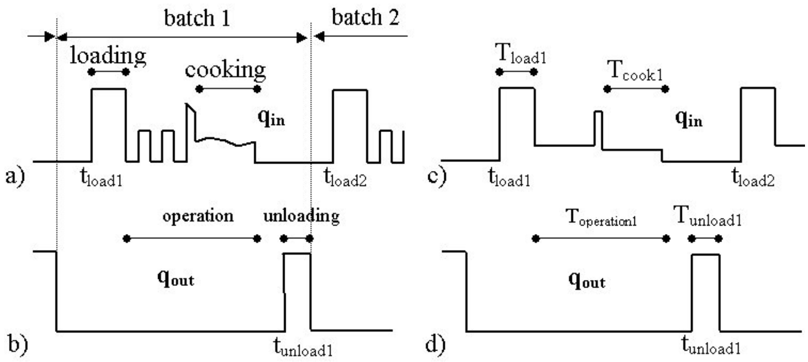

Figure 3: a) and b) q_{in} and output q_{out} flows of a real evolution of vacuum pan. c) and d) Temporal patterns of input and output flows of simplified model.

The other signal in Figure 3 b) corresponds to the outflow q_{out} which is zero except for the unloading period $T_{unload1}$. Obviously 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 sum of stages duration (from 3 to 7), included T_{cook1}. These periods can be computed as before from interpolation in a table $T_i(B, P)$ (i=4,...,8) 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. Obviously, these two constraints are necessary for each batch predicted and for each vacuum pan. Also additional tables are needed, see Figure 4 c), such as the ones relating brix and purity in the feeding tank with the total cooked mass and the proportion between crystals and mother liquor in it, that is to say brix and purity of mother liquor and percentage of crystals of cooked mass.

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 stars it operation in period j. The scheduler solves a MIP problem to determine the optimal start and ending times of the batch units.

	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_{load1} of cooking stage (sec.)					Inflow q_{in} in cooking stage (Kg/sec.)					Purity of mother liquor				

Figure 4: A typical table obtained off-line from the first principles dynamic vacuum pan model.

In this paper we have applied an alternative approach that is coherent with the use of the temporal patterns shown in Figure 3 c) and d). 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 [5]. 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 problems is avoided, being substituted by an NLP one that includes among its decision variables the time instants in which every tacha must load and unload along the prediction horizon. The other decision variables are the total flow and proportion of higher and lower purity syrup of the two centrifugal separators in production lines A and B.

4.2 NMPC controller

Before the non-linear MPC 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 cycles performed for all batch units(a cycle is the evolution of each batch unit from the state measured, the instant of called to controller, to the next future same state). Notice that the capacity of the vacuum pans can be different, so, each one can perform a different number of batches in the same period of time.

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 cycles of each batch unit i 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 cycle. 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 Nbi will fix the number of unknown time instants t_{load} and t_{unload}, two per cycle 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 of the type:

$$J = \int_0^{tstop} \left[\sum_i \alpha_i \left(y_i(t) - y_i^{ref} \right)^2 + \sum_j \beta_j \Delta u_j(t)^2 \right] dt$$

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 brixes and purities in the feeding tanks as well as the levels in these tanks and the two malaxadors, total 8 variables), and $tstop$ is the total time of prediction. Respect to the future manipulated variables u_j: times of load and unload the vacuum pans operation plus total flow and proportion of higher and lower purity syrup in the centrifugal separators of section A and B. α_i and β_j are given values of weights. The optimization is subjected to the internal model of the controller and additional constraints imposed by the range and operation of the vacuum pans and other units. The problem is solved every sampling period by an SQP algorithm, where the cost function J is computed by integration of the dynamical internal model. State and output constraints are included as penalty functions in J.

5 Simulation results

The control strategy described in the previous sections was tested in simulation using the state-of-the-art EcosimPro environment. The process was represented by a detailed simulation built using validated models of the Sugar Processes Library, [6] including sequential and local controls of all units. The controller was programmed in C++ and contained the SQP algorithm which, in turn, was able to call another EcosimPro simulation with the MPC internal model for computing the cost function J each time it was needed. The sampling period was chosen as 3 min. Several experiments were performed, we present an experiment of four hours and a half (16000 sec.), with an inflow of feed syrup of 18 Kg/sec. and with 94.4 of purity and 72 of brix. Prediction horizon (Np) and all control horizon were fixed in 2, that is to say 6 hours of prediction. Figure 5 a) and c) shows the levels of the melter and the malaxador A, and its minimum and maximum values allowed, Figure 5 b) shows purity, brix and its references in the melter. Figure 5 d) e) and f) shows the same variables but for the section B, that is to say tank B and malaxador B.

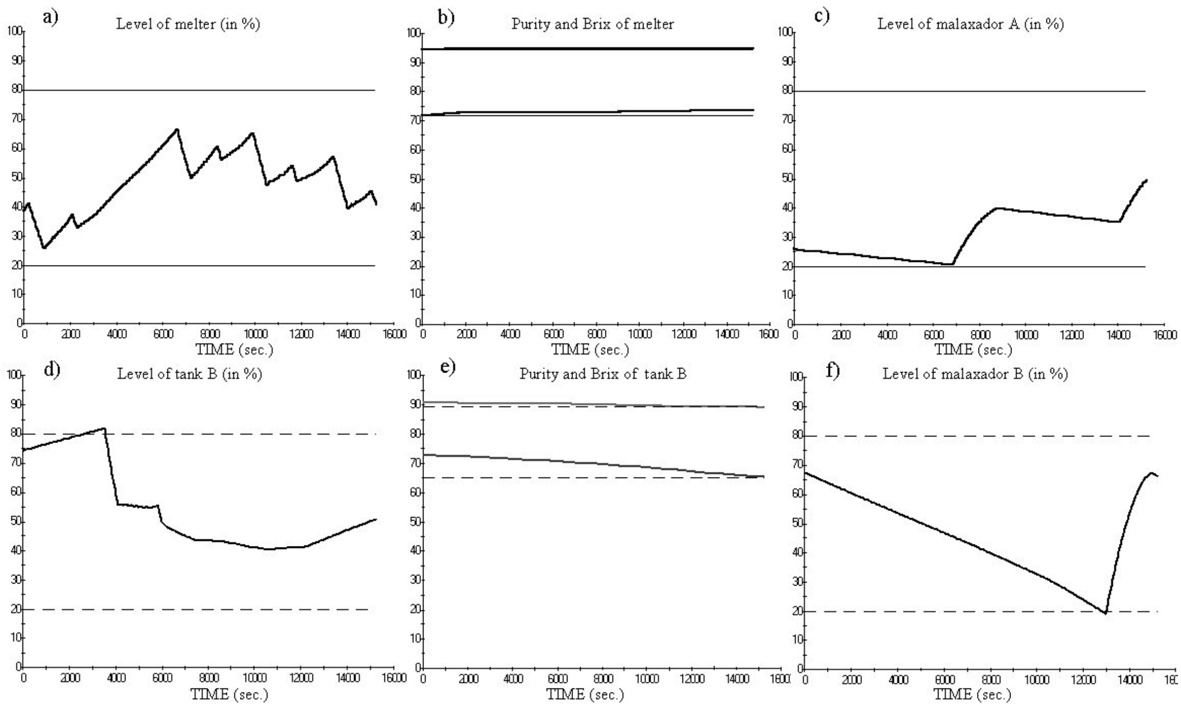

Figure 5: a), b) and c) principle controlled variables for section A. d), e) and f) controlled variables for section B.

The sequence of stages of vacuum pans A2, A3 and B1 can be seen in Figure 6 a), b) and c). One bath was produced in each tacha. Time of stage 1 is the manipulated variable for load syrup and time of stage 9 is the manipulated variable to unload cooked mass. In Figure 7 we can show the rest of manipulated variables, associated with centrifugals of section A and B. In Figure 7 a) the time of start of each centrifugal, in continuous line for centrifugals A1 to A7, and in dashed line for centrifugals B1 to B7. On the other hand, Figure 7 b) shows in continuous line the time of unload high purity syrup in centrifugals A and in dashed line for centrifugals B.

6 Conclusions

In this paper a plant-wide control strategy for the crystallization section of a beet sugar factory has been presented. It is based, first, in a hierarchical view of the problem and, then, 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, which allows

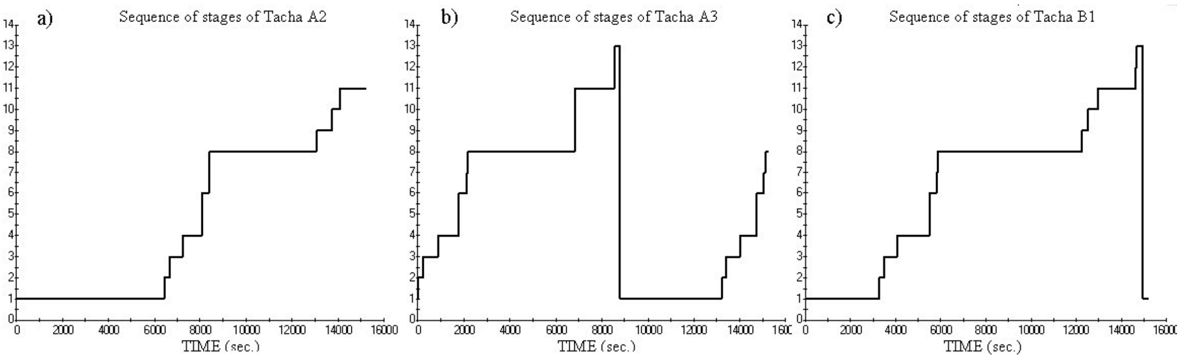

Figure 6: a) and b) sequence of stages of tachas A and c) sequence of stages of tacha B.

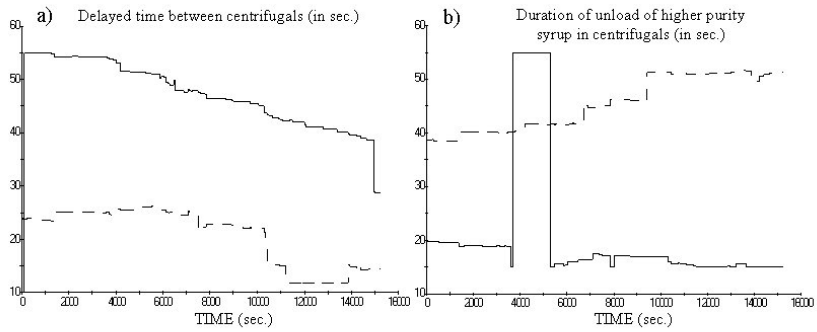

Figure 7: Manipulated variables of centrifugals A and B

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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