OPTIMAL START-UP OF AN EVAPORATION STATION

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Abstract: This paper describes the main results obtained so far in the problem of the optimal startup of an industrial evaporation station involving continuous as well as discrete real time decisions.

Keywords: dynamic optimization, hybrid systems, model predictive control, large-scale models, nonlinear programming.
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1. INTRODUCTION

Usually, control problems are centred in the operation of a given system around some operating point. Nevertheless, due to factors such as flexible operation, maximum service time, energy saving policies, etc., other types of operation, such as the start-up or shut-down of the processes, are gaining attention. In the start-up case, the aims are to perform the transition from idle to normal operation in an optimal way, respecting at the same time a set of constrains. Optimality can be formulated in terms of minimum time, minimum cost, minimum energy consumption, etc. or some combination of them.

This paper describes a case study currently used in the EU NoE, HYCON and gives results about the optimal start-up of an industrial evaporation station. The problem mixes continuous control of some variables with on/off decisions along time and, hence, is of hybrid nature. The proposed controller aims to minimizing transition time as well as the use of fresh steam, while maintaining the process within a range.

Key aspects of the start-up problem are related to modelling and the optimization strategy selected. One can use simple reduced models as in (Bemporad *et al*., 2000), or full models and dynamic optimization techniques as in (Barton and Lee, 2002). The evaporation problem presented here has been approached in (Stursberg, 2004) where the model is formulated as a hybrid automaton with continuous dynamics specified by large nonlinear DAE-systems and the start-up is solved by optimization using a graph-search algorithm with embedded NLP. In (Sontag, 2006) the graph search algorithm is refined adjusting time intervals for updating the controls, and introducing specific penalty functions.

In this paper, a different approach has been followed, using a full non-linear model of the plant, but the continuous control system of the process and the logic (on/off) decision policy related to the start-up have been embedded on it, so that, a sequential approach and a NLP algorithm can be used for the dynamic optimization.

The paper is organized as follows: Section two describes the evaporation station, and the control aims. Then, section three formulates de dynamic hybrid optimization problem, presenting a solution approach and giving results of the off-line solution. Section four reformulates this solution in the framework of MPC and provides graphs of the on-line transition. The paper ends with some conclusions and references.

2. THE EVAPORATION PLANT

The evaporation station consist of three evaporators, Robert type, fed by a mixture of three products: water, alcohol and a valuable product, A, being the aim to increase the concentration of A up to 82%. The heating is done in a counter current multiple effect system as the one depicted in Fig 1. The evaporators are named 2.1, 2.2 and 1.1 from left to right. The mixture enters 2.1 and goes in series through 2.2 and 1.1, while fresh steam of 5 bars and 440ºK is fed in 1.1. It is also possible to feed evaporators 2.1 and 2.2 with the same fresh steam by means of two three-way valves, V_{s1} and V_{s2}, which commute on-off between fresh steam source and the vapour produced in following evaporator. Vapours coming out of evaporator 2.1 juice chamber end at a condenser connected to it.

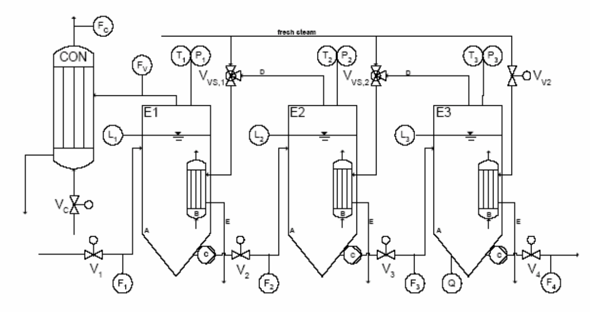

Figure 1: Simplified flowsheet of the three-stage evaporator.

Control valves V_1, V_2, V_3, V_4, allow modifying the flow of the mixture along its way. Other two continuous control valves provide control on the flow of fresh steam to evap.1.1 and vapours from evap.2.1.

A first principles model of the evaporation station is given in (Sonntag, 2005). It is derived from mass and energy balances as well as equilibrium equations for the two phases, liquid and vapour, and has the form of a hybrid high-order DAE system.

During normal operation of the evaporation station, the controlled variables are the levels in all evaporators, that must be maintained at 62%, the vapour pressure in the 2.2 evaporator and the output concentration of product A in 1.1, that must remain at 82%.

Initially, the station is empty and the start-up problem is to drive it to normal operating conditions with:

- ✓ Minimum transition time
- ✓ Minimum fresh steam consumption
- ✓ And respecting constraints on some variables

The constraints that must be respected refer to levels, which, once reached, must remain in a given range:

$$60\% \le L_i \le 64\% \qquad (1)$$

to the product concentration in the last evaporator, which must satisfy

$$0.8 \le c_A \le 0.84 \qquad (2)$$

at the end of the transition, and to pressure and temperature, which must be below 5 bars and 440ºK all times:

$$\begin{aligned} P_{evap,i} &\le 5\,\text{bar} \\ T_{evap,i} &\le 440K \end{aligned} \qquad (3)$$

Additionally, we will assume that a minimum level of 60% is required before steam or vapour can be supplied to the calandria of the evaporators.

2.1 The control policy

In order to command the system once the normal operating conditions have been reached, a basic control system such as the one of Fig.2 can be implemented. It consists of level loops manipulating the input juice valves, a concentration loop manipulating the output juice valve and a pressure one for vapour from 1.1. While the position of the on/off steam valves, under normal operation, are closed for fresh steam.

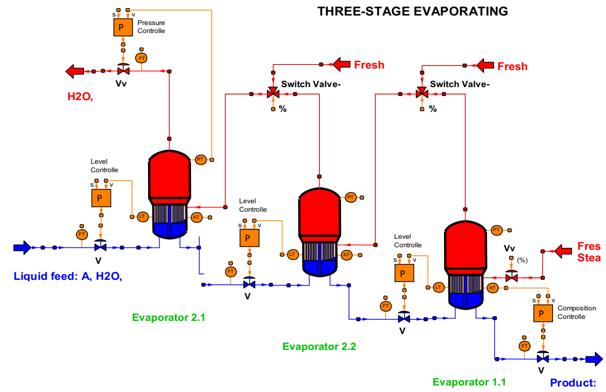

Fig.2 Schematic of the basic control system

Notice that this control system will provide by itself the right actions in order to carry the process from the initial state to normal operating conditions. For instance, initially, when the evaporators are empty, the level controllers will maintain the valves open in order to increase the level, while the concentration loop will close the output valve in 1.1. Once the level set-points are reached, these valves will be positioned by the controllers to the adequate opening in order to maintain the levels by its set points. Also the output valve in 1.1 will be opened once the concentration of A is close to 82%. Notice that the product flow to and from the evaporator station is imposed by these control loops.

Regarding the on/off steam valves, they should be opened as soon as the corresponding level reach its set-point. Notice that, as the evaporator on the right will have its vapour output closed, its pressure will increase and, as soon as it reach the supply value of 5 bars, the on/off valve should be commuted and maintained in its normal position. This logic behaviour has been implemented as part as the basic control system.

The only degree of freedom that is left corresponds to the fresh steam supply to evaporator 1.1, that can be manipulated in order to optimize the transition of the station from idle state to normal operation.

Eventually, the set point of vapour pressure in evaporator 2.2 could be considered as another degree of freedom. But, due to the particular operating conditions and sizing of the units, it has to be fixed in order to allow proper level control in evaporator 2.2.

Notice that, by embedding the logic of the start-up into the basic control structure, we have been able of converting a hybrid decision problem leading to a dynamic MINLP optimization, into a simpler one involving only a real dynamic decision variable, which can be solved by NLP with a sequential approach.

The control policy, then, is composed of two layers:

- ✓ The basic control system presented above, including the logic on the two on/off steam valves.
- ✓ An optimization module that manipulates the steam valve to evaporator 1.1 in order to fulfil the requirements of minimum transition time, minimum steam consumption and constraints satisfaction.

3. DYNAMIC OPTIMIZATION

The optimization problem is formulated as a dynamic optimal control problem (5), (6), (7) where two performance objectives are considered. The first one refers to minimizing the start-up time t_f, that is, the time needed to reach the target region:

$$\begin{aligned} c_A(t_f) &= 0.82 \\ L_A(t_f) &= 60 \end{aligned} \tag{4}$$

The second aim is to minimize the amount of fresh steam required for the start-up. The manipulated variable u (the fresh steam valve opening that governs the steam flow F_v) is designed for optimizing the start-up cost expressed as a multi objective function J, minimizing the start-up time (t_f) and minimizing the steam consumption:

$$J = \alpha t_f + \int_0^{t_f} F_v dt \tag{5}$$

where α is used as a normalization and weighting factor. The optimization is made taking into consideration the non-linear-dynamic model of the plant presented in (Sonntag, 2005) and its basic control system

$$\begin{aligned} \dot{\mathbf{x}}(t) &= f(\mathbf{x}(t), u(t)); \qquad \mathbf{x}(0) = \mathbf{x_0} \\ \mathbf{y}(t) &= g(\mathbf{x}(t), u(t)) \end{aligned} \tag{6}$$

as well as the target region (1)-(2) and the forbidden regions (3), besides other operational constraints:

$$\begin{cases} u^L \le u(t) \le u^U, & t \in [0, t_f] \\ \mathbf{x}^L \le \mathbf{x}(t) \le \mathbf{x}^U, & t \in [0, t_f] \end{cases} \tag{7}$$

where $\mathbf{x}$(t) are the state variables, $\mathbf{y}$(t) the plant outputs and u(t) is the control. An initial state $\mathbf{x}_0$ is required to define the state from which the optimization problem is considered. The time-dependent control variables $u(t)$ are the decision variable for the optimization. Furthermore, path constraints for the states representing safety and operational goals (1)-(3) must be satisfied along the entire trajectory.

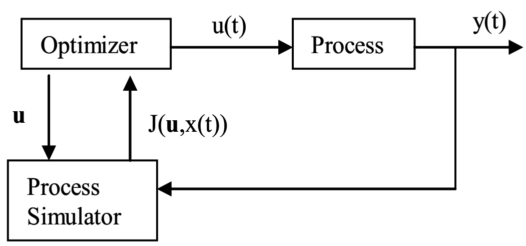

Fig. 3 Sequential optimization scheme

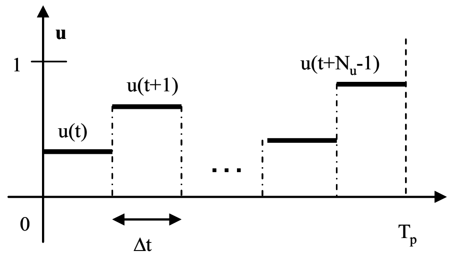

Fig. 4 Decision variable parameterization. Case 1.

The dynamic optimization problem for the start-up optimization can be converted into a nonlinear programming (NLP) problem by means of a control vector parameterization technique and a proper procedure for computing the cost function. In our case, we have used a sequential approach, represented schematically in Fig.3, where the state-of-the-art simulation language EcosimPro has been used to implement the hybrid non-linear system with its regulation and logic control elements. EcosimPro treats in a rigorous way discontinuities and uses DASSL to integrate the model providing the value of the cost function J to the optimization algorithm each time it is needed. To solve the problem, two different approaches have been used: a sequential quadratic programming (SQP) algorithm, as implemented in the NAG library, and a stochastic search method.

3.1 Control parameterization

Two decision variable parameterizations have been considered. The first one uses the control variable profile $\mathbf{u}$ discretized over N_u time intervals, each interval having the same duration $\Delta t = T_p / N_u$ (Fig.4) where T_p is the time horizon considered for the valve moves. Controls are assumed to have a piecewise constant shape in each interval with lower and upper bounds of 0.1 and 1, respectively.

The second approach (Fig. 5) considers variable lengths of the time intervals. Hence, the decison variables include now the controls $\mathbf{u}$ as well as the times of change of the control signal t_1, t_2,..., t_{Nu-1}.

This provides more flexible signal shapes at the expense of a small increment in the number of continuous decision variables.

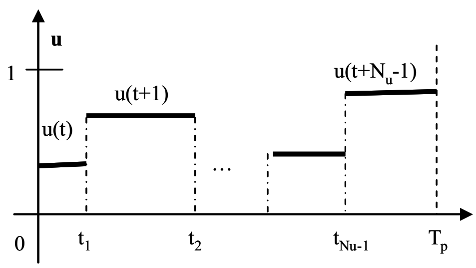

Fig.5 Decision variable parameterization. Case 2.

3.2 Optimization results

Several tests were made computing off-line the optimization under different conditions, and testing it in the EcosimPro environment. Applying the first parameterization (Fig. 4) with $N_u=4$ and T_p=10000 seconds, and using the SQP algorithm from the NAG library, the best solution founded corresponds to **u** = [0.48, 1, 1, 0.78] for which the cost (5) is J= 621384. The optimal trajectory of the decision variable is represented in Fig. 6 (solid line) and leads to a start-up time t_f=11000 seconds and a steam consumption of F_v=71336. In the same figure (dash line) it can be appreciated that no steam is supplied if the evaporator level is below 60%, while in Fig. 7 the switching times between multiple effect and steam feed in evaporators 2.1 and 2.2 are represented.

A simulation time of 15000 seconds was considered in order to observe the evolution of the process at the end of the start-up procedure too. It is important to remark that the target region is reached: the levels in all evaporators lie within the range [60%,64%] (Fig.8) and the product concentration in the last evaporator is bounded between 0.8 kg/kg and 0.84 kg/kg (Fig. 9). In the figures the solid line corresponds to the evaporator 1.1, the long dash one belongs to the evaporator 2.1 and the short dash line fit with the evaporator 2.2.

Also, the graphs in Fig.10 and 11 show the evolution of pressures and the temperatures that are bellow their upper constraints. Finally, the curves of the steam and

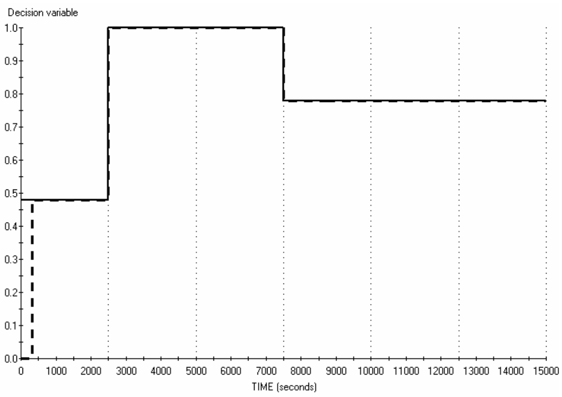

Fig.6 Evaporator 1.1 fresh steam valve opening

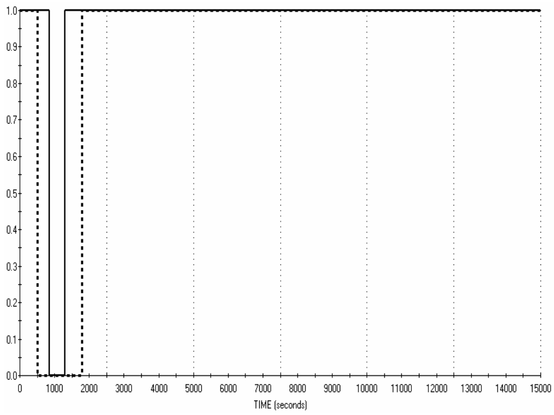

Fig. 7 Switching times

vapour flows corresponding to the three evaporators are represented in the Fig. 12, 13 and 14. The dash-dot line indicates the steam, the long-dash one is the input vapour and the solid line corresponds to the output vapour.

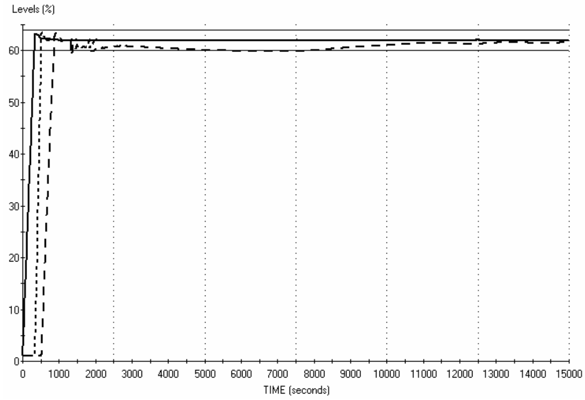

Fig. 8 Evaporators levels

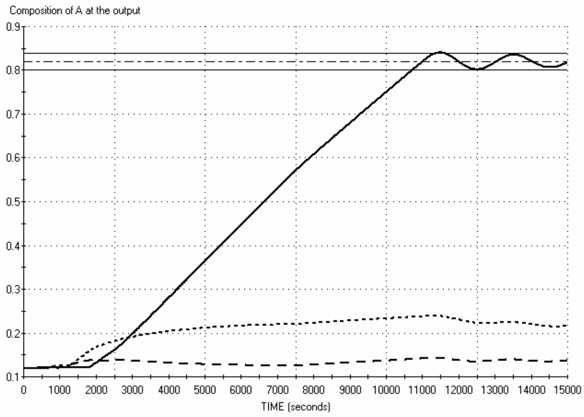

Fig. 9 Concentrations of A at the output of the evaporators

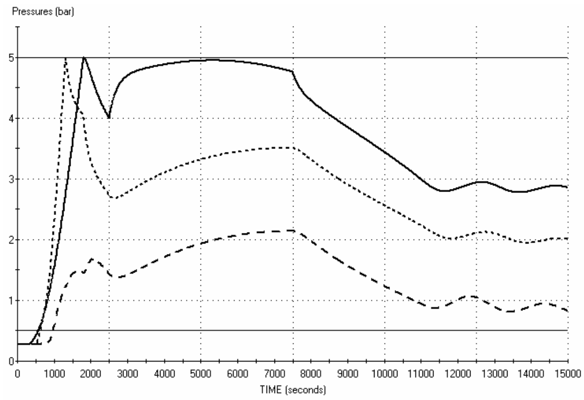

Fig. 10 Pressures in the evaporator juice chamber

If the other parameterization strategy for the decision variable, corresponding to Fig. 5, is used, then the optimal solution is **u** = [0.5, 1, 1, 0.75] with times of change t_1=3500, t_2=6500 and t_3=10000. In this case, a slight improvement is obtained J=612812, so that the total start-up time to reach the target region and the steam consumption were reduced to t_f=10835 seconds and F_v=71070, respectively. Fig. 15 shows the fresh steam opening profile. Using this optimal trajectory, the evolution of the levels, pressures and

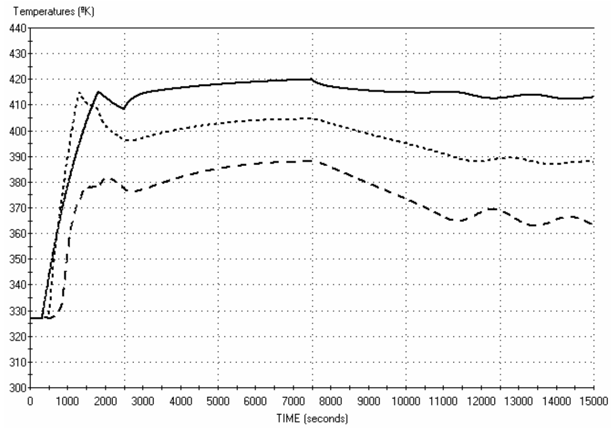

Fig. 11 Temperatures in the evaporator juice chamber

concentrations is similar to the previous strategy and for shortage of available space will not be represented.

The off-line optimization problem was also solved by an evolutionary strategy stochastic algorithm (SRES) using stochastic ranking as constraint handling technique but the results were worse.

4. MPC IMPLEMENTATION

In order to implement on-line the optimal start-up, the solution strategy was cast in the framework of NMPC. At each sampling time, the optimization problem (5)-(7) was solved in order to determine the optimum inputs **u** to reach the objective. The optimizer finds the future control input trajectory **u** by optimizing over a prediction horizon H_p that is an interval between actual time t and the final time T_p. The first sample u^* of this input trajectory is applied to the plant, and the optimization is repeated at the next sample using the new states of the plant. In the simulations it is assumed that the full state is available at time t, i.e. the initial conditions are known at every iteration. The sampling interval of the controller was T_s=120 seconds. The parameterization strategy used to calculate the future sequence of the control **u** corresponds to Fig.4, i.e. the prediction horizon is divided in N_u intervals with constant duration H_p/N_u.

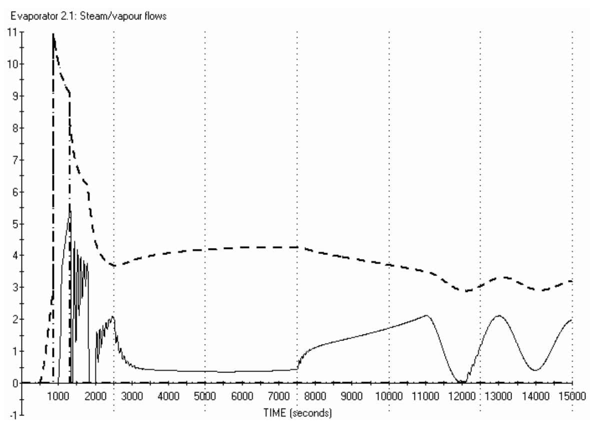

Fig. 12 Evaporator 2.1. Steam/vapour flows

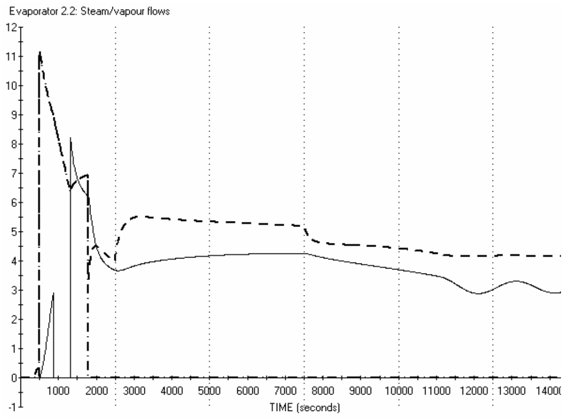

Fig.13 Evaporator 2.2. Steam/vapour flows

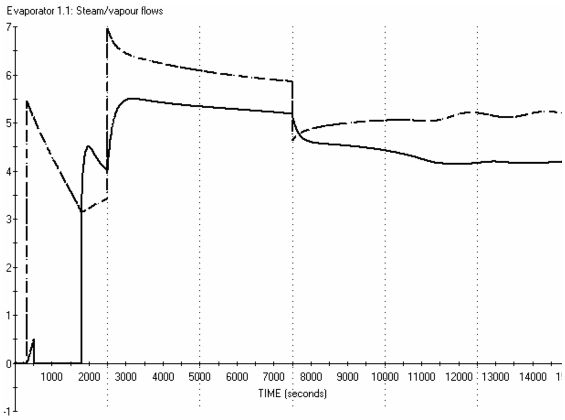

Fig.14 Evaporator 1.1. Steam/vapour flows

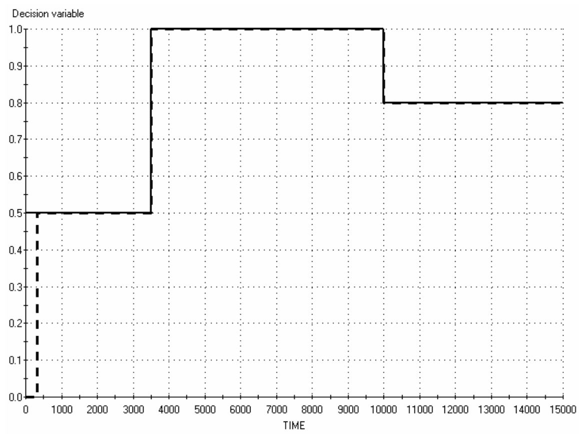

Fig. 15 Computed optimal trajectory of the control variable

Several dimensions for the vector **u** and the final time T_p have been considered and the performance obtained was similar. So, the results of the experiment using N_u=4 and T_p=10000 are presented. Figures 16, 17, 18 and 19 show simulation results with NMPC. As we can see, not only the levels and the temperatures in all evaporators and the product concentration in the last evaporator are kept between the allowed limitations but a faster start-up is possible: t_f=10700. As a consequence, the total cost is lower comparing with the open loop control J=607847 but the amount of fresh vapour required for the procedure is a little higher: F_v=72480.

The simulation was performed using the simulation language EcosimPro in a 1.83GHz computer with 1 GB of RAM and the simulation time of the whole experiment was almost 4 hours considering the parameter N_u=4. So, in this case the time required to solve the predictive control problem every sampling time is too high to implement the controller in real time. However, decreasing the number of the decision variables, for instance N_u=1 or 2, the computation time is reduced practically to one half and the process behaviour is very similar to the shown one above. So it could be possible to apply it in real time.

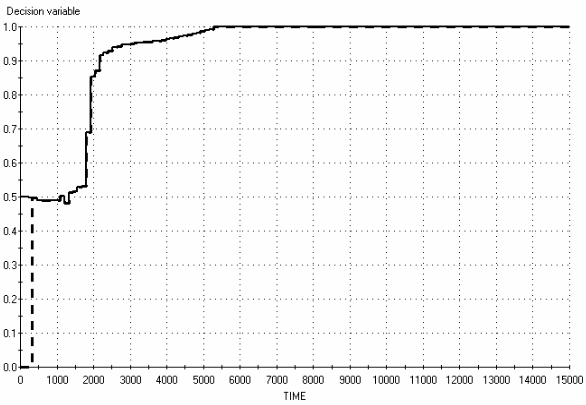

Fig.16 Evaporator 1.1 fresh steam valve opening

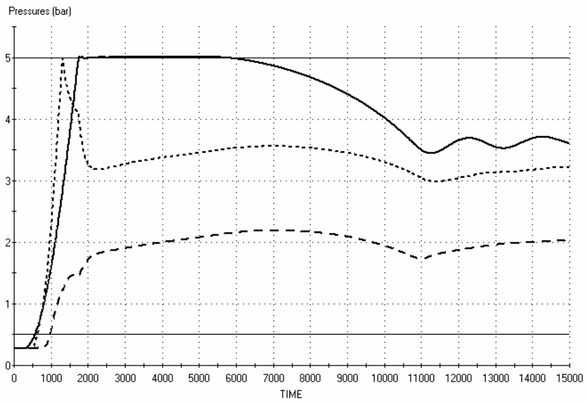

Fig. 17 Pressures in the juice space

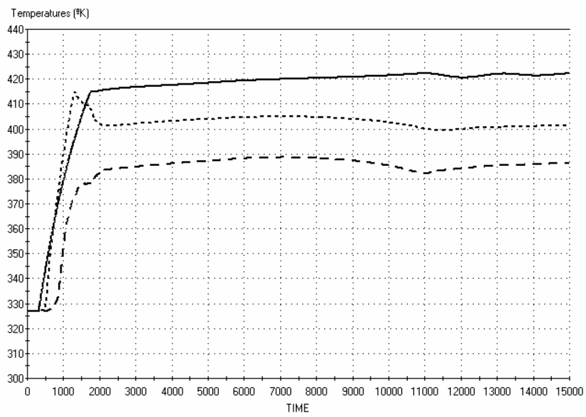

Fig. 18 Temperatures in the juice space

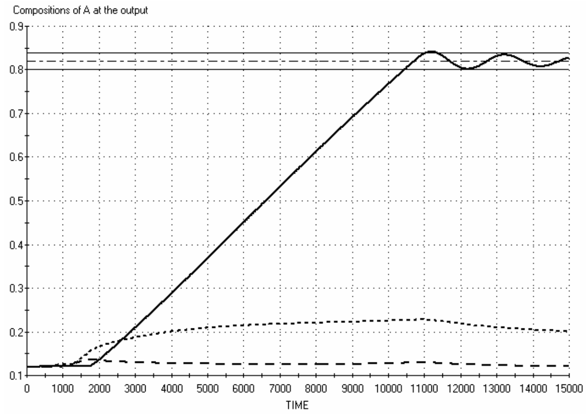

Fig. 19 Concentrations of A at the output of the evaporators

5. CONCLUSIONS

In this paper the optimal start-up of a multiple-effect evaporation station has been studied. The proposed system consists of a two layered control structure. The lower level uses PID controllers and incorporates logic elements that implement a predefined sequence of operations as required by the process. The upper level includes a NMPC that uses as internal model, the one of the process with its basic control and logic included. This approach allows embedding the logical decisions in the internal model so that a real optimization technique can be used. Simulation results have been provided, both in open and closed loop that show the optimal trajectories and the applicability of the approach.

ACKNOWLEDGEMENT

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