Hycon 2 Network Show Case: Sugar Factory

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Abstract— **The paper describes a dynamic simulator of a scaled sugar factory to use as a reference, or benchmark, to design and test complex systems control strategies. The process is a subset of a general sugar production process that contains both continuous and batch process units and is closely linked to the factory energy consumption and the quality of the produced sugar. The control problem and the indexes to measure the process performance are set up and the simulation scenarios, or study cases, are given. Finally, different ways to use the simulator from the software point of view are outlined.**

Keywords-process-industry; benchmarking; hybrid systems control

I. INTRODUCTION

HYCON2 Network of excellence [1], supported by the European Union Seventh Framework Programme, has as aims stimulating and establishing the long-term integration of the European research community, leading institutions and industry in the strategic field of control of complex, large-scale, and networked dynamical systems. It has identified several applications domains: transportation, energy, and biological and medical systems.

HYCON2 organizes in ten Work Packages (WP), the WP V is related to benchmarking for testing and evaluating the technologies developed in the network. In particular, two show-case applications corresponding to real-world problems have been selected: the freeway network around the Grenoble area and the high-level operation of two coupled sections of a sugar factory.

In the field of process control, different benchmarks can be found. Some of them are used to controller design [2][3]; others are process-identification oriented (for instance de Wiener-Hammerstein benchmark); control plant-wide is another subject for some of them [4].

In our proposal, a system oriented to design high level controllers, which includes plant scheduling, operation and economic optimization, has been thought. The sugar factory show case considers significant problems and elements of a real sugar plant combining sections with continuous and batch process units. The low level regulatory control system is given and the researchers must concentrate on designing methods and algorithms to operate the plant optimally, according to a set of economic targets and observing a set of constraints. Four performance indexes, to compare the solutions, are given. They measure the energy cost, the economic profit and the productive capacity of the system.

The simulation model has been implemented in EcosimPro [5][6], that is an Object Oriented Modeling and Simulation Tool with similar characteristics of any language that implements Modelica [7][8][9], reusing model components from sugar process model libraries [10][11][12]. The simulation model cannot be validated versus real data, because the real system doesn’t exist. However, the library of models has been used to develop a simulator to train plant operators of sugar factories. This training simulator has been partially quantitative validated with real data and totally qualitative validated by managers and control plant operators [13][14][15].

The simulator is available from EcosimPro or MATLAB-SIMULINK environment and, additionally, a standalone version with a Supervisory Control and Data Acquisition (SCADA) interface is available too. The standalone version can communicate with any software tool that works as an OLE for Process Control (OPC) server [16].

The paper is organized as follows: in Section 2, a description of the simulated process and the control problem is outlined; Section 3 explains the show case performance indexes and study cases; Section 4 deals with the computer subjects and, finally, some conclusions are given.

II. PROCESS DESCRIPTION

A. Sugar Production Process

A typical beet sugar factory (Fig. 1) is divided in two great sections: the Beet End and the Sugar End [17][18]. The Beet End contains the diffusion, purification and evaporation stages. The sucrose is extracted from beets by using a diffusion process, the removal of as many impurities as possible is carried out in the purification section and the concentration of the resulting sucrose solution is achieved in the evaporation section, which uses live steam. In the Sugar End is where the crystallization of the dissolved sucrose is carried out to deliver the white sugar grains with commercial value. The crystallization is performed in batch and continuous crystallizers that are heavy consumers of the steam, which is served by the evaporation. Other parts of a standard sugar factory are the boilers and turbo generators, where fuel or gas is used to obtain electric energy and live steam, and the pulp dryer, where the exhausted beets are dried to obtain food for the cattle.

For the show case, only a subset of the real process has been selected: the evaporation and crystallization sections. Although the proposed process is smaller than a real factory, the control problem is very significant, because of the great interaction between sections, the continuous mode operation of the evaporation section and the semi-batch operation in the crystallization one.

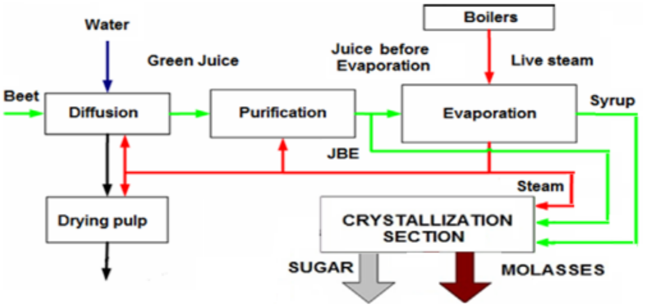

Figure 1. Schematic of a sugar factory

B. *Evaporation Section*

The aim of this section is to increase the Brix (matter content in sugar solution) of the juice (sugar solution), by evaporating the water to obtain syrup. The required heat is provided by a flow of fresh steam that comes from the boilers after passing by electricity generating turbines. Usually, the evaporators are grouped in four or more effects. An effect is a cascade of evaporators, in which the juice flows from one to other one, but using the same source of steam.

In the show case, each effect contains only one evaporator and it's a three effect arrangement (Fig. 2), in which the juice circulates in series increasing its Brix up to a certain value. The first evaporator receives its heating steam from the boilers, but the heating of the other evaporators is provided by the steam produced in the previous one. The scheme is energy efficient in the sense that allows the multiple reuse of the live steam that comes from the factory boilers. It is important to mention that part of the steam produced in each evaporator is redistributed in the factory to fulfill other technological duties. In particular, the most important consumers of the steam generated by the evaporation section (steam I and II) are the crystallizers of the Sugar End.

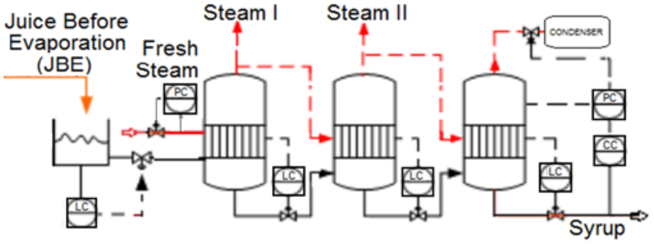

Figure 2. The show case Evaporation Section

With respect to the low level control structure, the Brix of the syrup at the output is controlled by a cascade arrangement of two Proportional Integral and Derivative (PID) controllers; the outer loop (CC) gives the reference of the inner loop (PC), which controls the vacuum pressure in the last effect chamber. Besides, the juice level in the evaporators and in the feeding tank is maintained by level controllers (LC). Additionally, there is a controller to set the value of the fresh steam pressure (PC).

C. *Crystallization Section*

In modern factories, the Sugar End, usually, has an architecture consisting of three stages: the first, or A stage, is dedicated to the production of commercial white sugar crystals and the rest to the exhaustion of the remaining syrup.

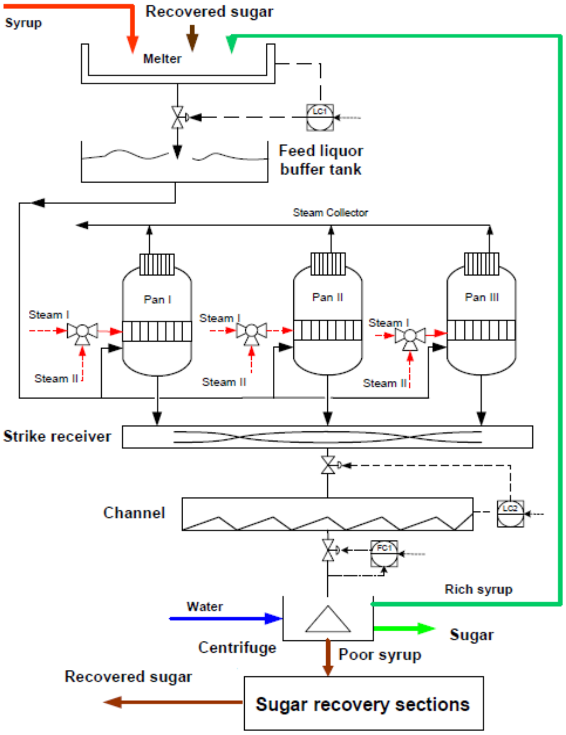

Figure 3. The show case Sugar End (Crystallization Section)

The show case, exclusively, considers A stage (Fig. 3). The syrup from the evaporation stage is sent to the melter plus a flow of recycled rich syrup and another one of low-quality sugar from the B and C stages, with the purpose of obtaining the so called standard liquor. The latter is discharged in a storage tank, which serves the feed syrup to the crystallizers or pans (it should accommodate the peaks in demands from the crystallizers with the continuous supply of standard liquor from the melter). These vacuum pans (Fig. 4) operate in batches, following a recipe with a set of stages using steam from the evaporation section to further concentrate the syrup until over-saturation stage. After discharge, the mixture of crystals and non-crystallized syrup (mother liquor) is stored in an agitated tank called strike receiver that feeds to another tank that supplies the mother liquor to a set of centrifuges where white sugar crystals are separated from the syrup. The centrifuges, that are modeled as a continuous component, use a small amount of water in their operation and produce two types of syrups (honeys): a high purity one, that is recycled to the melter, and a low purity one that is processed further in other stages (B and C) and finally is partly recycled to the melter too as a flow of low quality sugars (B and C). The recipes of the crystallizers are automated with Programmable Logic Controllers (PLCs) and the inner control loops are implemented with PIDs (level and pressure). In manual mode, the operator only decides when then recipe is started and the type of heating steam. Thus, the consumed steam and syrup and produced mother liquor by each crystallizer are not homogeneous and they depend on the stage (Fig. 5).

At the Sugar End, another three PIDS control the flow of massecuite (mother liquor), to the centrifuges and the levels of the melter and the tank that feeds the centrifuges (Fig. 3). However, the storage tank and the strike receiver levels are not controlled. Then, the high level operation of the process must guarantee that are kept within certain limits.

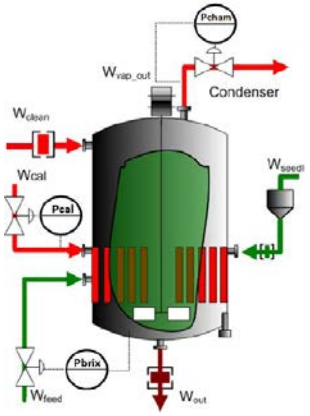

Figure 4. Sugar Batch Crystallizer

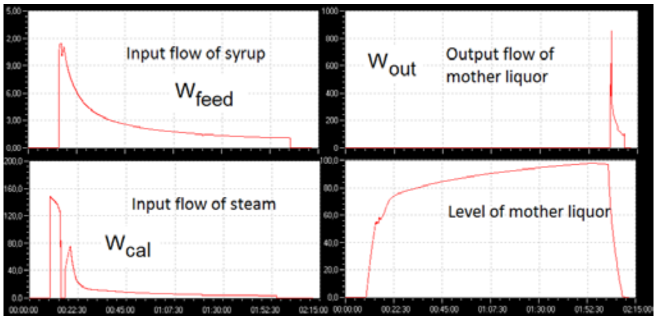

Figure 5. Flows (kg/s) and level (%) in a crystallizer cycle (time in hours: minutes: seconds)

D. *Operation*

The process operation is complex because both sections interact strongly in terms of mass flow and energy. For a given flow of juice before evaporation, the flow of produced syrup and the fresh steam demands depend on the set points for the fresh steam pressure and syrup concentration (Brix) controllers as well as on the steam demands from the crystallizers. On their side, each crystallizer's cycle time and its variable profiles depend on the concentration and purity of the evaporation syrup as well as on the pressure of the steam provided. Purity is defined as the % of sucrose of the solids dissolved in the syrup and affects also the % of crystals obtained in a batch. The cycle time determines the syrup processing capability of the Sugar End, which obviously limits the maximum allowable syrup flow from the evaporation. Other technical variable that affects the working of the Sugar End is the ratio water/massecuite in the centrifuge. Increasing it, the purity and flow of the rich syrup recycled are increased and it means that the cycle time of the crystallizers is decreased but, on the other hand, it decreases directly the white sugar crystals flow from the centrifuge. Thus, there are many choices of a set of key variables that determine the right operation of both sections, both from the point of view of the process working and its economy.

On the other hand, the crystallizers must be well sequenced. For instance, they mustn't start at the same time because it would imply a great initial demand of syrup and steam from the evaporation that it may not be supplied. Besides, the storage tank in the crystallization could empty and the strike receiver in the discharge stage could overflow. Fig. 5 shows the peaks in the steam and juice demand at the beginning of each cycle crystallizer and the peak in the discharge of mother liquor at the end of the same cycle).

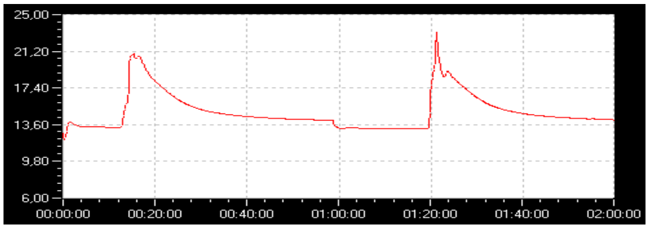

Figure 6. Fresh steam flow (kg/s)

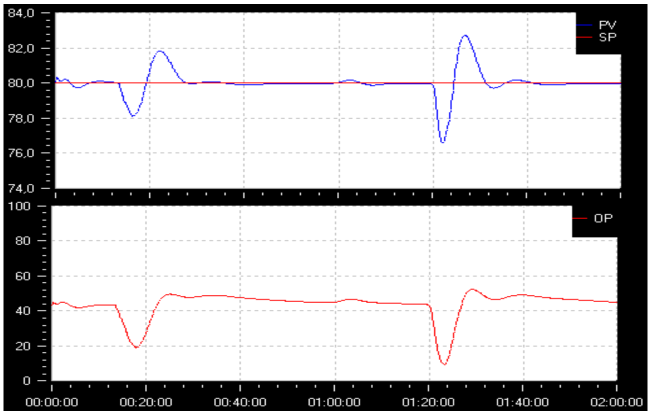

Figure 7. III effect level controller (PV: Process Variable (%), SP: Set Point, OP: Output to Process (%))

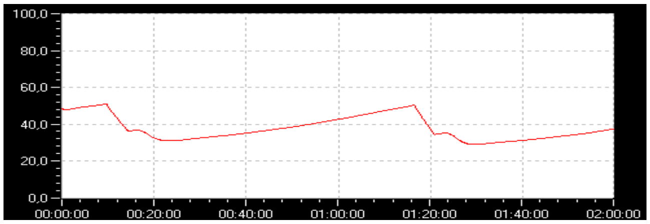

Figure 8. Storage tank level (%)

For instance, Fig. 6 shows the fresh steam demands when the crystallizers are well synchronized. The peaks, that are due to start a crystallizer, are homogeneously distributed along the time and their values are assumable by the boilers. Fig. 7 displays the level in the last evaporation effect and the control signal of the valve that govern the flow of syrup. This flow goes down when a crystallizer starts, because the increase of the steam demand of the crystallizer (see Fig. 5) affects to the Brix and pressure at the last effect that are controlled variables. Fig. 8 shows the level of the storage tank. When a crystallizer starts, it demands a great amount of syrup (see Fig. 5) and the produced syrup in the last effect decreases. Then, the level of this tank goes down. Later, this level recovers its value when the demand of syrup decreases and the produced syrup gets back its average value.

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Summarizing, although the process is automated using PID and PLC controllers, some variables must be handled by a high level controller (or qualified operators) to assure that:

1. All the juice before evaporation will be processed, ensuring that the levels of uncontrolled buffer tanks are kept within certain limits.
2. Additionally, the process operation must minimize the energy consumption, trying to obtain a smooth and homogeneous fresh steam demand to avoid problems in boilers and turbo generators.
3. And, if possible, maximize the produced sugar.

To obtain these aims, the main decision variables are:

1. A set of set point controllers: (a) the fresh steam pressure to the evaporation from the boilers, P_{fs}; (b) the syrup concentration from the last evaporator, B_s and (c) the massecuite flow to the centrifuges, W_m.
2. The ratio water/massecuite in the centrifuge ($R_{w/m}$).
3. And, for each crystallizers, the scheduling, that is, when the operation of each batch cycle starts; and the selection of the steam source (steam I or II).

Finally, the control objectives must be met in the presence of disturbances. The main ones are changes in the amount of juice before evaporation (W_j), or its composition (Brix, B_j, and purity, Pu_j).

III. STUDY CASES

In this section, the study cases to test the different control algorithms are described. Each study case is characterized by some unknown operating boundary conditions and a process performance criterion.

A. Process Performance Criteria

The following criteria or targets have been defined:

First: Operate the plant to assure that uncontrolled buffer tanks levels (storage tank and strike receiver) are kept within certain limits and to maintain the value of the Brix and purity of the standard liquor within a maximum and minimum value due to technological requirements of the crystallizers.

$$L_{st}^{Min} < L_{st} < L_{st}^{Max}; \qquad L_{sr}^{Min} < L_{sr} < L_{sr}^{Max} \qquad (1)$$
$$Pu_{sl}^{Min} < Pu_{sl} < Pu_{sl}^{Max}; \qquad B_{sl}^{Min} < B_{sl} < B_{sl}^{Max}$$

L_{st} and L_{sr} are the storage tank and strike receiver levels. Pu_{sl} and B_{sl} are the purity and Brix of the standard liquor.

Second: Minimize the energy to the system per kg of produced sugar (J_1, kJ/kg) and the variance of the normalized power to the system (J_2), respecting the first target.

$$J_1 = \frac{\int_0^T E(t)\,dt}{\int_0^T W_{sugar}(t)\,dt} \qquad (2) \qquad J_2 = \sigma^2 = \frac{1}{T}\int_0^T \left(\frac{E(t)}{\overline{E}(t)} - 1 \right)^2 dt \qquad (3)$$

T is the total simulation time. W_{sugar} is the produced sugar flow. E(t) is the instantaneous power or energy flow to the first evaporator, and, $\overline{E}(t)$ is the moving average of E(t).

$$\overline{E}(t) = \frac{1}{\Delta t} \int_{t-\Delta t}^{t} E(\tau)\,d\tau \qquad (4)$$

Being Δt, the time interval for the moving average and it's equal to the total cooked time in one batch crystallizer (normally 9.000 seconds).

Third: Maximize the average profit per kg of produced sugar (J_3 (€/Kg)), respecting the **first** criterion:

$$J_3 = \frac{\int_0^T \left(\delta \cdot W_{sugar}(t) - \beta \cdot E(t) - \gamma \cdot W_j(t) \right) dt}{\int_0^T W_{sugar}(t)\,dt} \qquad (5)$$

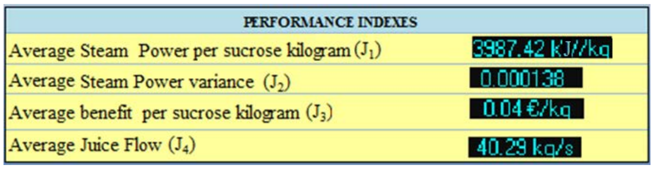
Where δ, β, γ are the prices of the produced white sugar in centrifuges (€/kg), consumed energy (€/kW) and juice before evaporation (€/kg), respectively.

Fourth: Maximize the average value of the flow of juice before evaporation (J_4 (Kg/s)), respecting the **first** criterion.

$$J_4 = \frac{1}{T}\int_0^T W_j(t)\,dt \qquad (6)$$

This target is oriented to maximize the production capacity of the process, respecting the constraints.

In the simulation, these four indexes are calculated and their values are available for the users (Fig. 9).



PERFORMANCE INDEXES	
Average Steam Power per sucrose kilogram (J_1)	3987.42 KJ//kg
Average Steam Power variance (J_2)	0.000138
Average benefit per sucrose kilogram (J_3)	0.04 €/kg
Average Juice Flow (J_4)	40.29 kg/s

Figure 9. Performance indexes at the simulator interface

B. Operation Conditions

Two days was selected as the total simulation time of each exercise. The cooked time in a crystallizer is about 2 hours and a half, thus, the total simulation time must be broad enough to consider several batches. Thus, when the boundary conditions are modified, changing of a stationary point to another one spends several hours.

Two different boundary conditions are specified. **Operation condition one (OP1)**:

a. The system remains in a stationary state 6 hours.
b. Then, during 36 hours, the process is disturbed with variations in the flow, Brix and purity of the juice before evaporation.
c. Here, the initial values of the boundary conditions are restored and the simulation continues during 6 hours more until the end of the exercise.

Operation condition two (OP2): it is similar to the OP1, but the flow of the juice before the evaporation is not disturbed. Now, it must be managed by the high level controller.

Fig. 10 shows the trend of the uncontrolled level of storage tank when the operation condition one is selected and no actions are made over the process (red line). It can be seen that the storage tank level will go through the limits (20-80%). However, the black line shows the same situation with some changes in the crystallizer scheduling to satisfy the first target. Now, the performance of the uncontrolled tank level is better than in the previous situation and the constraint is satisfied.

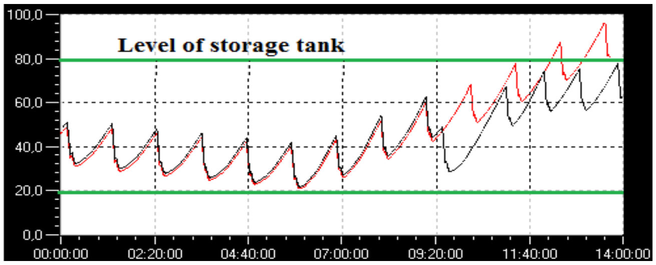


Figure 10. Red/black (without/with control actions

C. *Summary of Study Cases*

Thus, based on the operation conditions and the performance criteria, four benchmark study cases have been proposed (Table 1). Each study case is defined by one operation condition and one operation criterion or target.

TABLE I. *STUDY CASES*

	Operation		Variables	
Study Case	**Conditions**	**Criteria**	**Manipulated**	**Disturbance**
1	**OP1**	First	P_{sf}, B_s; $r_{w/m;}$ $W_{m;}$ Pans scheduling	W_j, B_j; $Pu_{j;}$
2	**OP1**	Second	Idem study case 1	Idem study case 1
3	**OP1**	Third	Idem study case 1	Idem study case 1
4	**OP2**	Fourth	Idem study case 1 plus W_j	B_j; Pu_j

The controller for the study cases number 1, 2 and 3, that isn't implemented in the software, should have the same data interface (Fig. 11). The disturbances are the same ones (flow, Brix and purity of the fresh juice) and the difference is the target function. The study case number 1 looks for a controller that operates the process subject to constraints in some variables without target function. The controller for the study case number 2 must operates the process subject to the same constraints and minimize the J_1 and J_2 indexes, that are related with the energy consumption. Finally, the controller for the study case number 3 must operates the process subject to such constraints and maximizes the J_3 index that is related with the greatest profit.

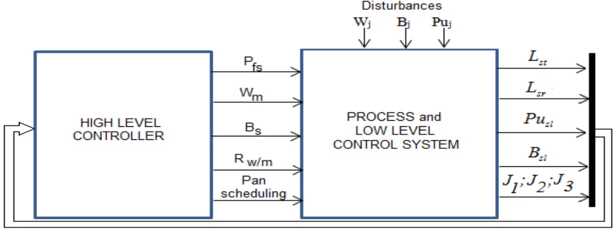


Figure 11. Control Structure for Operation Condition 1

For the study case number 4, the data structure of the high level controller changes, because the flow of the juice before evaporation is considered a manipulated variable, instead a disturbance. Now, the operation target to maximize is the number four (J_4). In this case, the controller must look for the maximum production capacity of the system with disturbance on the Brix and purity of the juice.

IV. SOFTWARE

The model and control system of the show case process is programmed in the simulation environment EcosimPro, which incorporates state-of-the-art simulation features. The model can be simulated, and the controller could be implemented, within the EcosimPro software environment but, for those that prefer to use other tools, and in order to facilitate the operation of the process from a graphic Human Machine Interface (HMI), a system with the architecture represented in Fig. 12 has been set up. It combines a real time execution of the simulation with a SCADA system to supervise and control the simulation. The communication between both elements is made by OPC. Additionally, using OPC, it's possible to connect the simulator and the SCADA with other external devices and software tools.

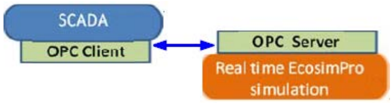


Figure 12. Show case software architecture

The SCADA system, called EDUSCA [19], was developed at the University of Valladolid and it's a not licensed tool that runs on PC over Windows OS. It has a friendly configuration environment and can work versus simulations or real process. It's used in a training simulator for control operators of sugar factories carried out by the Center of Sugar Technology and in some university labs. An example of the SCADA HMI is shown in Fig. 13.

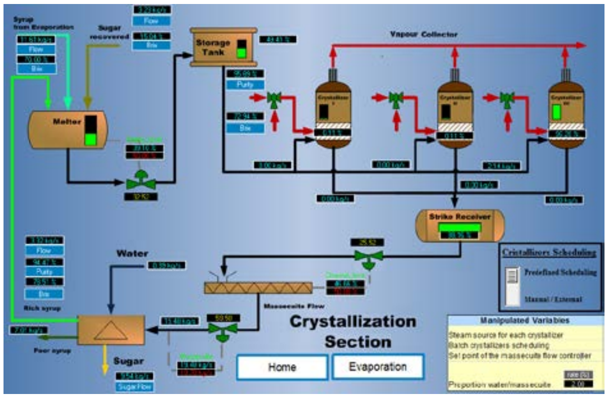


Figure 13. SCADA HMI, a synoptic of the Sugar End section

There are different display boxes associated to the process variables showing their values and units. Pushing on them, a graphic with the time evolution of the variable is displayed (some instances can be seen in Fig. 6-8). If the variable is a manipulated one of a control loop, full graphical information of the loop parameters and variables is provided. In order to facilitate the operation of the process, an alarm system is included, so if any variable goes beyond the allowed limits the process, the operator is warned with an alarm. An alarm register and historic data storage is maintained as well. The HMI includes the possibility of entering changes in previously defined modifiable process variables, set point controllers and scheduling of the crystallizers. By default, the simulator runs in real-time, the user can to speed-up its execution by a certain rate.

Besides, it is possible to interact with the simulator in different ways to the ones previously exposed (here, communication details are not given). In particular, it is possible to use the simulator from the MATLAB-SIMULINK environment. First, it is possible to connect the OPC server simulator to MATLAB-SIMULNK using the OPC toolbox, being MATLAB-SIMULNK a standard OPC client. Second, the EcosimPro simulation code, not the OPC server simulator, can be called directly from MATLAB using some functions provided for this purpose.

Summarizing, the user can access to the show case simulator using the next methods:

a) From the EcosimPro environment, if a program license is available.
b) EcosimPro simulation code can be used from MATLAB using a toolbox supported by EcosimPro.
c) It can be used the set formed by the OPC show case simulator and the SCADA system, that it is supplied by the developers.
d) The OPC show case simulator can be connected with any OPC client. It is possible to link it with several OPC clients simultaneously.
e) Especially, the OPC show case simulator can be connected with the OPC clients provided by MATLAB or SIMULINK.

The first two methods implies run the simulation as fast as possible, but in the last three methods it runs in real-time, being possible to speed-up its execution to a certain rate.

V. CONCLUSIONS AND FUTURE WORK

The paper has showed the result of one and a half year of work to develop a complex dynamic simulator of a standard industrial process. The simulator, that includes the low level control system, is thought to serve as a test bench of plant-wide control algorithms. The proposed control problem implies plant scheduling, operation and economic targets. Several scenarios and different performance indexes are defined. The combinations of these simulated scenarios with the targets constitute the so called study cases.

The simulation program can be used for different methods and tools. The MATLAB users can run the simulator easily. The simulator can run in real time or to a certain rate of real time, but in a standard PC, due to the model complexity, the acceleration rate is not greater than 20. In this way, a study case of 48 hours of real time can need about 2 hours of simulation time (the computational load of the high level plant controller is not considered).

The system can be used for the scientific community interested in the plant-wide control linked to economic requirements. Supplementary material and software of the sugar factory show case can be downloaded [20]. Researchers are invited to use this benchmark to test their control algorithms for hybrid complex systems.

As, strictly, benchmarking means comparing a solution to a reference, the exposed simulator cannot be still consider a benchmark, because a reference control system solution is not provided. Thus, the authors are working to supply a reference solution as soon as possible.

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