# PROCESS SYNTHESIS AND MANAGEMENT IN THE BOILING HOUSE OF SUGAR FACTORIES

By

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**KEYWORDS: Sugar, Boiling, Modelling, Scheduling, Synthesis.**

## Abstract

IN THE BOILING house of sugar factories, the process manager may conduct the process through different ways due to the batch mode of operation of vacuum pans, the need for cutting over materials among pans to achieve the required crystal sizes, and the different types of materials that must be handled, some of which are recycled. The process manager addresses most of his efforts to this area since he must try to reach the required standards of quality in end-products and the expected yields, but meanwhile he must also keep a stable steam demand and accumulation of intermediate materials in adequate quantities to maintain a steady operation. A new approach for synthesis and management (material and energy balances, scheduling) of the processes on the pan stage for sugar production from cane is presented and its advantages demonstrated in this paper. Detailed models and approaches for process synthesis and operations management on the pan stage of sugar factories are described. These models are the basis of the software tool PLANAZUCAR® dedicated to the scheduling of complex production systems in the sugar industry. Approaches include the use of HAZOP techniques and other software tools. Through actual case studies, the feasibility of using the software tool PLANAZUCAR for scheduling analysis in the sugar industry was demonstrated. Use of the software has allowed a thorough study of the utilisation rates of the equipment in a factory as well as an analysis of the influence of the production planning on the steam consumption profile, looking for stability in demand.

## Introduction

From the process operation point of view, the pan stage differs from other areas of the factory. Whereas most stations operate in a continuous way, most pans do not. The main task of the production manager is to ensure that this batch-wise part of the process operates as steadily as possible, since the efficiency of sugar recovery and maximum processing of raw materials depend on the co-ordination of operations, use of recycled materials, use of equipment, etc. A very important aspect for pan stage operation is the stabilisation of steam demand.

For years these management tasks have been accomplished by process managers using tools which they developed themselves through practice and heuristically. Modern approaches for process synthesis and management in this area have been studied.

Aguado (1973) published a paper proposing a discrete programming model for scheduling of operations in vacuum pans. De Armas and Rostgaard (1983) proposed another approach: that of representing this problem as an activity network with limited resources and the use of linear programming (LP) for solving the materials balances.

The Monte Carlo method was used to predict duration times of activities during simulation runs to establish the more probable way of conducting operations in the boiling house. Since then, simulation languages and dynamic programming methods have been used. All these jobs had limitations in representing the whole process.

In this paper, three case studies introducing new models for process synthesis in both raw and refined sugar production from cane are presented. Two of them are used for operations scheduling and another, at operations level, is proposed for material balances linked to the operations schedule.

**Case study 1: The EON approach**

This approach is based on the definition of recipes describing tasks being done for sugar production on the pan stage. These recipes include information about operations that should be carried on and resources (materials, utilities) used by them. Operations are then assigned to equipment to represent a strategy to be simulated. The structure of the activities to be performed within each process is represented through a general activity network called Event Operations Network or EON (Graells *et al.,* 1998). The rigorous modelling of the operation timing involved in the recipe is achieved by means of EON elements: events, operations and links.

Events designate time instants in which a change may occur. They are represented by nodes in EON graphs and should be linked also with other events. Each event is associated with a time value and a lower bound. The time values for each event will be the variables of the timing problem that must be solved. The lower bound can be used to force delays in a given solution or force a new solution fulfilling special constraints.

Operations designate those time intervals to be observed between the starting event (initial node) and the ending event (final node). Operations are expressed as equality links between nodes in terms of the operation time and the waiting time. The operation time is a pre-determined value as a function of the amount being processed, unit assigned, etc. The waiting time is a value below the maximum time a material could be stored in the vessel before discharge.

Finally, links designate event-event precedence constraints.

Thus the linear programming problem formulation may be defined by:

- Ending time of operation $i$ in stage $j$ in unit $k$ is equal to operation starting time plus operation duration time, plus waiting time.
- Starting time of operation $i+1$ in stage $j$ in unit $k$ is greater than or equal to the ending time of operation $i$ in the same stage and unit.
- If any two operations $i$ and $i^*$ corresponding to tasks $j$ and $j^*$ are done simultaneously in two $k$ and $k^*$ units and one depends on the other (such as transfer of material from one pan to another), then waiting time of operation $i$ in stage $j$ in unit $k$ is less than or equal to the maximum waiting time defined for that operation in that stage and unit.
- Duration time of operation $i$ in stage $j$ in unit $k$ is defined as a function of unit $k$ volume occupation during operation $i$ of task $j$.
- Consumption of material $l$ for each operation $i$ in every stage $j$ and unit $k$ is defined in the same way as the duration time.
- Lower and upper bounds for unit operating capacities.

An objective is needed to discriminate a good solution among the infinitely feasible solutions. A simple and practical one is minimising the total duration of the process which allows compressing the resulting schedules and improving capacity utilisation. This function takes into account durations of all operations done in the process.

The factory being studied produces 2000 tonnes per day of refined sugar, using a four massecuite processing system with double seed magma preparation in raw sugar production, producing 'A' sugar for the refinery and raw sugar for sales. In the refinery, a three massecuite processing system is used for the production of three qualities of refined sugar, while final molasses from the refinery is recycled to the raw sugar factory. In the raw sugar section of the factory, there are 23 vacuum pans, 14 vessels for intermediate and final materials, 52 crystallisers and 35 batch centrifugals. In the refined sugar section, there are eight vacuum pans, six vessels for intermediate materials, 11 crystallisers and 17 batch centrifugals. Seventeen different materials are processed. All the mentioned equipment, materials and areas were included in the analysis, so the dimensions of both the models for material balances and scheduling were large.

The material and energy balance calculations were done using the SIMFAD software package (Sabadí *et al.*, 1991). The mathematical model describing the process includes constraints for:

- Solids, total flows and pol balances;
- Mass fraction of sugar crystals contained in massecuites;
- Growth of sugar crystals from seed to commercial size;
- Steam and power demand in operations; and
- Other technological constraints based on operators' experience.

The main purpose was to study the best co-ordination between vacuum pans, crystallisers and centrifugals to achieve an optimal equipment utilisation and to avoid any instantaneous high steam demand. The objective function used was to minimise steam consumption, both for raw and refined sugar production. All results, including those for purities of intermediate materials are in close agreement to the actual values in the plant.

Different boiling strategies were defined and 10 basic recipes were developed for raw sugar and six for refined sugar production strategies. Data regarding resource information and recipe definitions were used to perform the calculations that end up into a desired production plan.

In sugar boiling, the duration of the operation depends on the crystal growth which is not a fixed value. A closer representation to reality is reached using the Monte Carlo simulation method based on the historical average values of task duration and their variance. These values are used in PLANAZUCAR© 2.0 for randomly generating values for duration in order to select the most probable makespan of the process.

Manual modifications in the proposed schedule were done to evaluate the consequences of the changes performed. Timing of operations, predicted evolution of the level profiles of intermediate storage, prediction of the use of resources such as steam, etc., were considered. The Gantt chart in Figure 1 shows operations done in six of the pans in the factory, as a prediction over 32 hours.

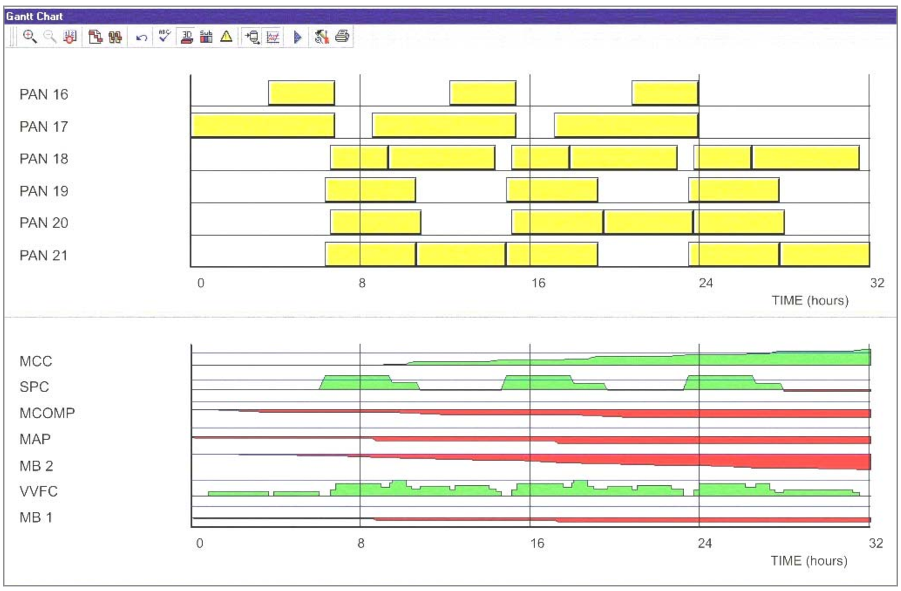


Fig. 1—Gantt chart for six pans showing materials generation and consumption.

It also includes the production consumption profiles for the final massecuites (MCC) as well as for the required and/or produced intermediate materials (first growth of seed crystals (SPC), syrup (MCOMP), A molasses (MAP), 1st purge, B molasses (MB1) and 2nd purge B molasses (MB2)) and vapour bleed from the evaporators (VVFC, also called 'vegetal' steam). These charts compare well with actual operations in the plant. The predicted number of batches is similar to those produced in the factory in the selected equipment for guaranteeing the final products demand.

The profiles of steam consumption for every stage of operation were determined. A highly variable steam demand was shown to exist, thus affecting the boilers and evaporator station in a negative way (Figure 2).

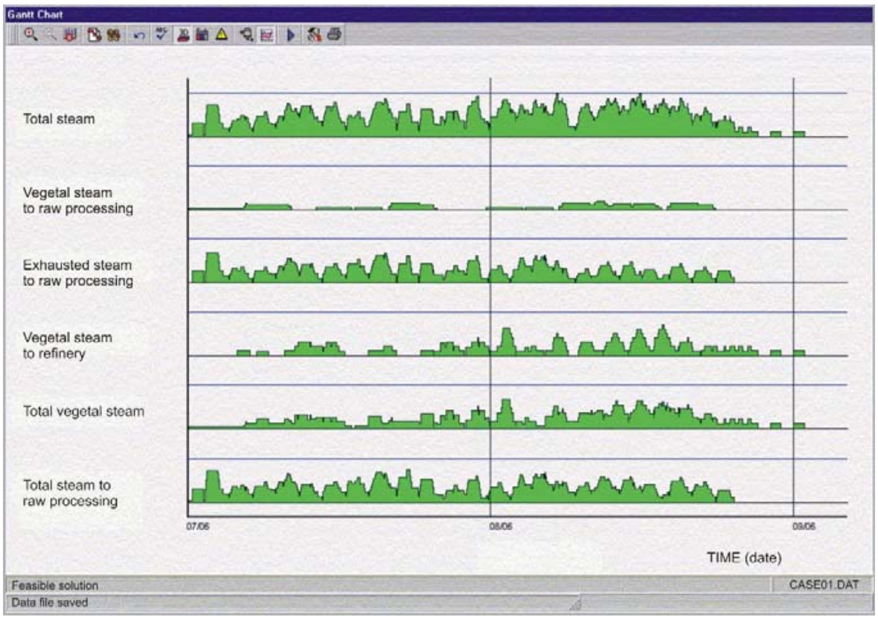


Fig. 2—Steam consumption profiles.

Despite this positive experience (Sabadí *et al.*, 2005), some further improvements in the software were identified and introduced in PLANAZUCAR© 3.0:

- Equations used for consumption of utilities such as steam were improved by using second or third degree polynomial expressions.
- Objective function is optional and flexible; in each case study, the user can select the criterion to be satisfied.

**Case study 2: The STN approach**

The objective of this case is to evaluate the state task network (STN) approach (Kondili *et al.*, 1993), which is a mixed integer linear programming model (MILP), in boiling schemes synthesis, through the software tools gBSS (Pantelides *et al.*, 1993) and PLANAZUCAR© 3.0 (Hurtado and Sabadí, 2005). Although it is an actual case, its representation is not so detailed because it is oriented to evaluate the new approach and software instead of supporting actual decisions in the factory. The fundamental constraints to be satisfied include:

(1) The resolution of conflicts when pans are allocated to tasks. At any given time *t*, a pan can only start at most one task. Of course, if a pan starts performing a given task, then it cannot start any other task until the current one is finished.

(2) Limitations on the capacities of pans and storage vessels:

– The amount of material *B* that starts undergoing task *i* in unit *j* at time *t* is bounded by the maximum and minimum capacities of that unit.

– The amount of material stored *S* must not at any time exceed the maximum storage capacity $C_s$ for this material.

(3) Material balances. This constraint simply states that the net increase in the amount of a material stored at time *t* is given by the difference of the amount produced and that used. The initial amount of each material is assumed to be known. All material inventories (including intermediate and final products) have to be specified for adjusting the model to the actual situation in the factory.

In a similar way, some other constraints may be included, extending the model:

1. Temporary unavailability of equipment.
2. Limited availability of utilities and materials.
3. Cleaning of equipment items.
4. Use of equipment items for storing task feeds.
5. Continuous feeds addition and products withdrawal.

As an objective function, the model is capable of accommodating a variety of either economic or system performance measures. The criterion mainly used in the present study is the maximisation of processed syrup.

Figure 3 represents the operation strategies in the production of massecuites. The circles represent the pans, identified by their number, and the other equipment (crystallisers and intermediate storage tanks for example) is represented by rectangles and other symbols. The arrows indicate the feeding and discharge of material. The high grade massecuites are boiled in seven pans while low grade massecuites are boiled in two pans.

Note that there is not a previous assignment of a particular equipment item to a task. Only the information on which tasks can be done in each equipment item is supplied. The solution includes the assignment of tasks to equipment items along horizon time.

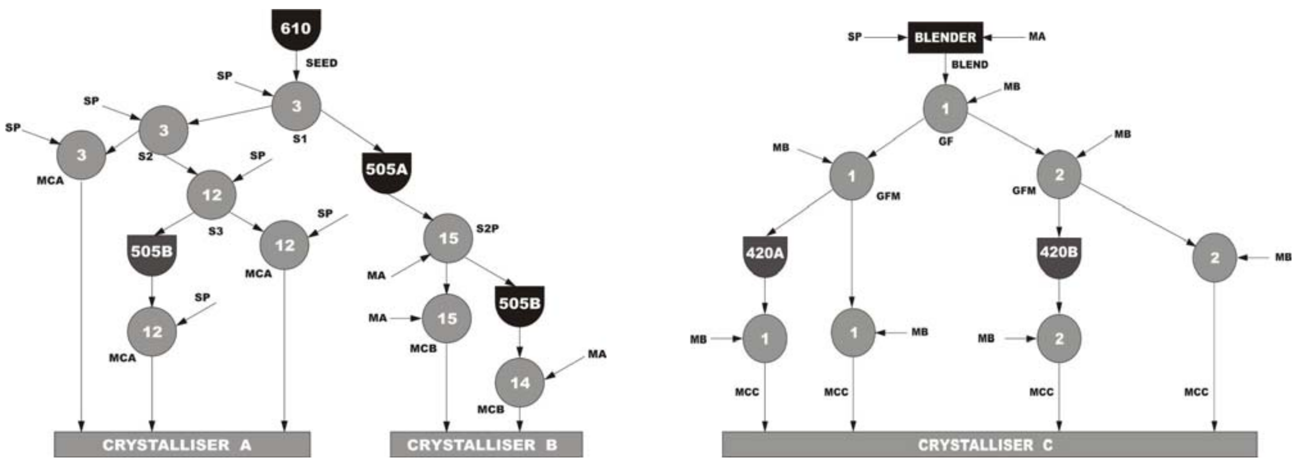


Fig. 3—Operation strategies in massecuites production.

Figures 4 and 5 show the results of the process synthesis for a 24 hours time horizon. In the Gantt chart, operations carried on in each equipment (pans, blender, centrifugals) are represented by blocks of different lengths according to their duration. Each operation is identified by a colour. Numbers inside the blocks identify batches and tasks.

Profiles of production and consumption of materials are shown in Figure 5. Massecuites are denoted by MCA, MCB and MCC, and molasses by MA, MB and MC. Intermediate materials in high grade massecuites are identified with an initial S and, in low grade massecuites, by an initial G. AA and AB are commercial raw sugars. Green colour in the profiles indicates no violation of volume constraints and enough material for operations. A red colour profile indicates an unfulfilled condition.

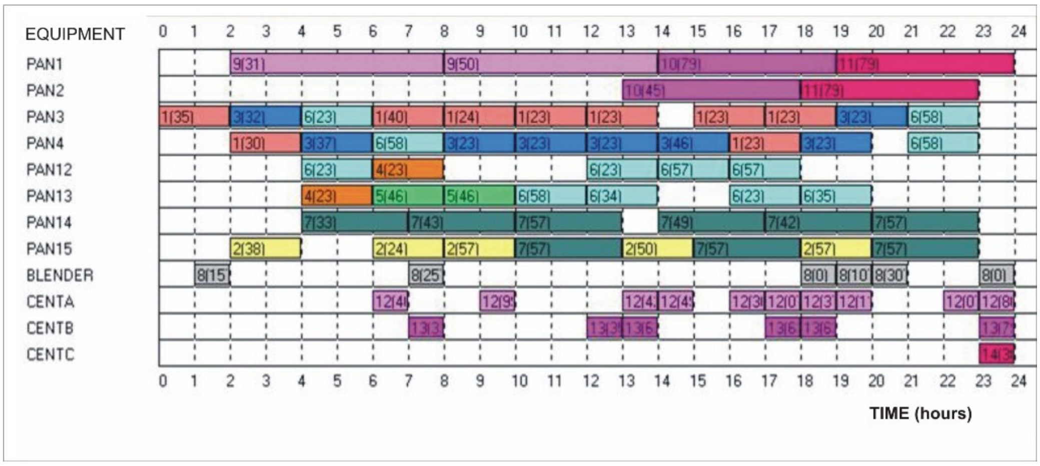


Fig. 4—Gantt chart showing assignment of tasks to equipment.

Although all details of operations corresponding to each task were not defined, it is demonstrated that the model determines the definition and use of each task in the analysis for an optimal solution. Such a solution allows a more effective use of installed capacities due to the fact that an initial feasible solution is not required. Any solution reached must take into account real equipment connectivity in the factory to avoid mathematically feasible, but practically infeasible, solutions. This condition could be included in the mathematical model which can also accommodate equations for defining new piping and pumping installations for a solution. These options were not tested in the actual case study.

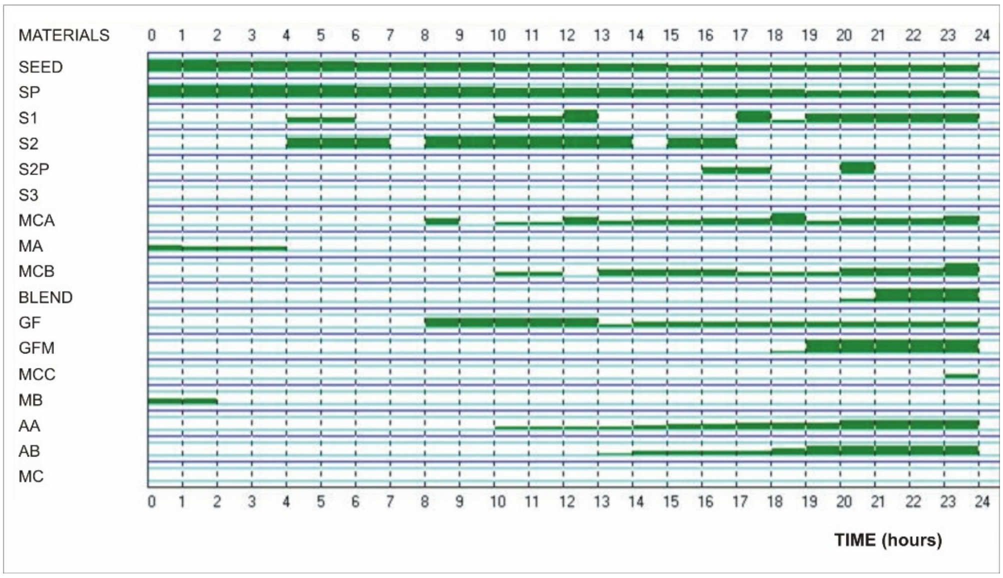


Fig. 5—Profiles of production and consumption of materials.

Using discrete variables in time representation (MILP) causes a bigger size of the problem, even for analysis of small cases. This case generated 593 equations for an 8 hour time span and 1905 equations for a 24 hour analysis. With gBSS and PLANAZUCAR 3.0, it is now possible to find solutions to these models.

**Case study 3: Balances at operations level**

The development of a non-linear mathematical model for material balance calculations in cane sugar production has been described (Ribas *et al.*, 2002) as well as the software CALIFA©

(Hurtado *et al.*, 2002), supported over such a model. The use of a LP model for the calculation of the material balance in sugar boiling for a specific configuration of pans has been described by De Armas and Sabadí (1993). That approach was used in a scheduling case study for a flow sheet of a three massecuite processing system for a sugar factory which also produced refined sugars based on an EON approach (Sabadí *et al.*, 2001). A similar case study is used to allow comparison. In order to use the results in operations scheduling at the operator's level, it is necessary to extend the balances to equipment at operations level.

In Figure 6, a non-detailed flow sheet corresponding to the operations level is shown. Nodes (geometric figures) represent the boiling operations, centrifugation, seed preparation and materials distribution; arrows represent flows among nodes and evaporated water. This representation is useful for balances in equipment at the operations level.

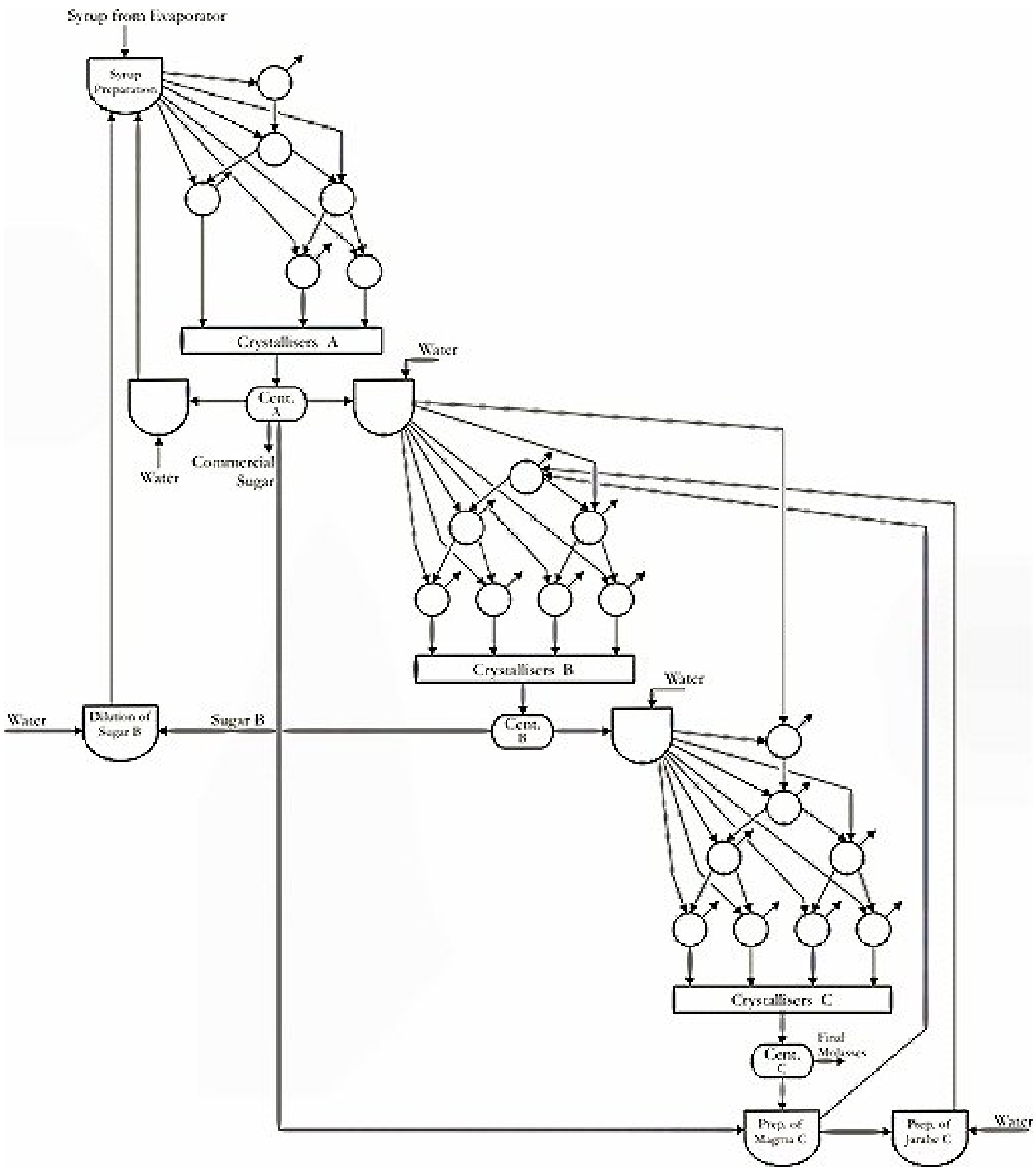


Fig. 6—Flow sheet at operations level.

Recipes at operational level were built for high and low grade massecuite production. These recipes describe the way in which operators conduct the operations in the selected equipment. All relevant tasks for producing the output material are included. Each task is described through its operations. The material balance for each recipe was usually introduced through coefficients related to one of the flows coming in or out of the recipe. In former exercises, those coefficients were calculated from an overall material balance for the process flow sheet and adjusted to the number of 'trees' required for a specified level of production of a certain material in a certain time interval (Sabadí *et al.*, 2001). In this approach the material balance is done considering every individual operation, so the results are actually fitted to the equipment configuration and production strategy.

In this case, only values for eight variables need to be fixed, including the syrup flow, brix and purity to be processed. The rest of the values for the brix and purity of each flow are lower and upper bounded, based on actual experience and describe the characteristics of final products.

The model includes:

- total flow, solids and purities balances in each node;
- lower and upper bounds corresponding to limiting operating capacities in pans; and
- lower and upper bounds for intermediate storage vessels.

For this exercise, the maximisation of commercial 'A' sugar production was used as the objective function.

The results of the material balance for the strategy of production of 'A' massecuites, when compared with actual values, show no significant differences. The maximum value for commercial sugar production was 871.5 tonnes, and the value reported by the factory is 864.0. While the calculated 'A' massecuites is 2022.4, the value reported by the factory is 2013.0.

Similar comparisons can be done with results for the balances in 'B' and 'C' massecuites. The main benefit of this methodology is that these results are now easily, and more realistically, associated with the operations when facing a scheduling problem.

It is now possible to know the values for each stream going in and out of the pans and other vessels in each operation. So it is possible to conduct the process provided that the balances include the technological constraints which must be followed during operation for guaranteeing production and quality.

These material balance results can be compared to the corresponding Gantt chart representation of the process obtained with PLANAZUCAR® software tool and shown in Figure 7.

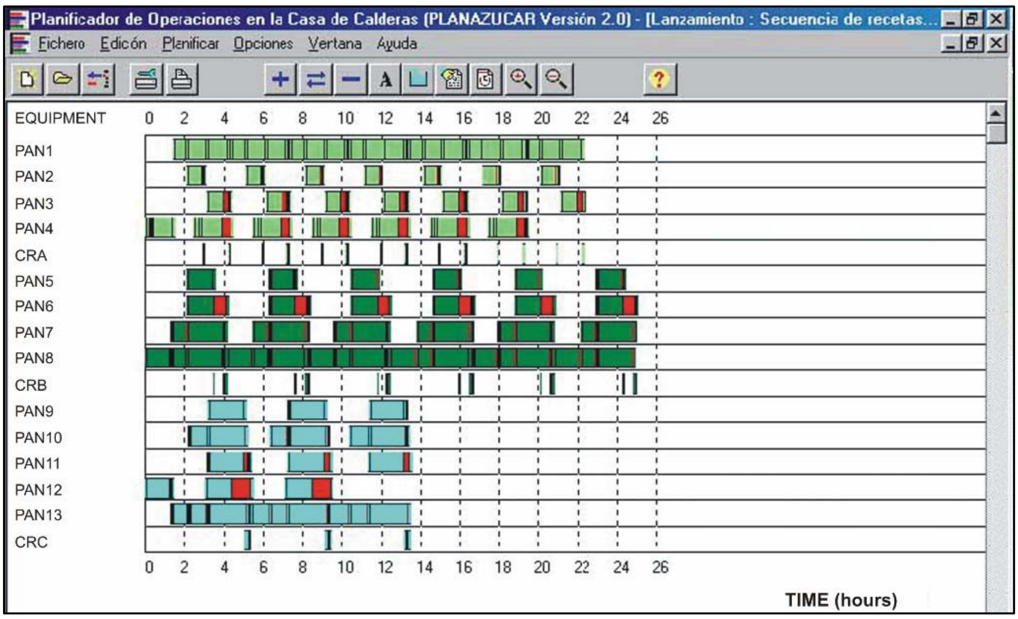


Fig. 7—Gantt chart of the process.

The operations for the 'A' massecuites are those in the first five lines of the chart (corresponding to pans 1, 2, 3 and 4 and the 'A' crystalliser called CRA). Operations for 'B' massecuites are done in pans 5, 6, 7 and 8, using crystalliser CRB. Operations for 'C' massecuites are done in pans 9, 10, 11, 12 and 13, using crystalliser CRC. Red colour in the blocks represents waiting time in operations.

With both results, the operator has a proposed schedule for the operations, including the values of the flows. He can guide the process knowing the time in which every operation must begin and the materials he should use to reach the expected results. In practice, it is very difficult to exactly follow the proposed schedule because of the possible occurrence of abnormal situations. So, operators must be well trained to face these problems. A hazard and operability (HAZOP) analysis would be a good basis for such training.

To represent the whole flow sheet of the process with this approach, a medium or large scale model must be built. Experiences with the SQP algorithm demonstrated that it is feasible to do it (Sabadí *et al.*, 2003). To improve user exploitation of the software, it is recommended to include the automatic generation of the initial solution. The Powell algorithm for simultaneous solution of non-linear equation sets can be used for this aim (Sabadí *et al.*, 1991). The lower and upper bounds for all streams could also be generated from this initial solution and improved, if necessary, based on estimates recommended by actual experience. Bounds such as lower and upper operating capacities of vessels and pans should always be provided by the user as well as the selected calculation basis.

## Conclusions

Two new approaches have been studied for process synthesis and management of the boiling house of sugar mills: the event oriented and the state task networks, based on LP and MILP models. Both of these models have proven to be useful and included in PLANAZUCAR® 3.0 software. The usefulness of doing material balances at operations level when undertaking scheduling studies has been demonstrated. A model for such an analysis has been included in CALIFA® software. The next step in our work will be the creation of a software suite including the above mentioned tools and another one for hazard and operability analysis (HAZOP) in the boiling house.

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## SYNTHESE ET ORGANISATION DE L'ATELIER DE CRISTALLISATION DE LA SUCRERIE

Par

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**MOTS CLEFS: Sucre, Cuites,**
**Modélisation, Programme, Synthèses.**

**Résume**

LES OPERATIONS de l'atelier de cristallisation peuvent être programmes de différentes façons, à cause des cuites discontinues, du coupage de massecuites, pour produire des cristaux de tailles voulus et pour manipuler des produits différents dont certains sont recycles. Le Gestionnaire de processus concentre ses efforts dans ce domaine car il doit essayer d'atteindre les normes requises de qualité et les rendements attendus; il doit également maintenir une demande stable de vapeur et une accumulation de matières intermédiaires en quantités suffisantes pour permettre un fonctionnement stable. Une nouvelle approche de synthèse et de gestion (matériel et énergie) des processus est présentée et ses avantages démontrés dans ce document. On donne des modèles détaillés et des approches pour la synthèse et les opérations de gestion de la cristallisation. Ces modèles sont à la base de l'outil logiciel PLANAZUCAR® dédié à la planification des systèmes de production complexes dans l'industrie sucrière. On présente aussi d'autres techniques (HAZOP) et outils logiciels. La faisabilité de l'outil logiciel PLANAZUCAR dans l'industrie du sucre a été démontrée. L'utilisation du logiciel a permis une étude approfondie sur le taux d'utilisation de l'équipement dans une usine ainsi qu'une analyse de l'influence de la planification sur la consommation de vapeur et la stabilité de sa demande.

# SÍNTESIS DE PROCESO Y GESTIÓN EN LA CASA DE COCIMIENTOS DE UN INGENIO

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**PALABRAS CLAVE: Azúcar, Cocimiento, Modelamiento, Programación, Síntesis.**

## Resumen

EN LA CASA de cocimientos de un ingenio azucarero, el jefe de elaboración puede conducir el proceso de diferentes formas debido al modo de operación de los tachos, la necesidad de repartir el material entre los tachos para obtener los tamaños de cristal requeridos, y los diferentes tipos de materiales que se deben manejar, algunos de ellos recirculados. El jefe de elaboración orienta la mayoría de sus esfuerzos en esta área dado que debe obtener las especificaciones requeridas de calidad en los productos finales y los rendimientos esperados, pero debe mantener una demanda estable de vapor y acumulación de materiales intermedios en cantidades adecuadas para mantener operación estable. Un nuevo enfoque para síntesis y gestión (balances de masa y energía, secuenciación) de procesos en la estación de tachos, se presenta en este trabajo junto con las ventajas de su adopción. Se describen modelos detallados y enfoques para síntesis de procesos y gestión de operaciones en la estación de tachos. Los modelos se basan en el programa PLANAZUCAR® dedicado a la programación de sistemas complejos de producción en la industria azucarera. Las aproximaciones incluyen el uso de técnicas HAZOP y otras herramientas informáticas. Se demuestra la aplicabilidad del programa PLANAZUCAR para análisis de programación en la industria azucarera usando el análisis de casos reales. Su uso ha permitido un completo estudio de las tasas de utilización del equipo en un ingenio así como un análisis de la influencia de la planeación de producción en el perfil de consumo de vapor, buscando estabilidad en la demanda.