Chapter 7

Case studies

7.1 Polymer manufacturing

This industrial case study was carried out during 1998-99. The main objective was to provide a methodology supported by an appropriate tool which for the detailed scheduling of a polymer plant located in Tarragona. The plant is divided in four sub-plants that produce different intermediate materials and a fifth one which produces the final products. Figure 7.1 shows the summarized process material network of the whole complex.

The main characteristics of this case are:

- More than 1500 processes to consider.

- More than 2000 materials present (raw materials + intermediates + final products).

- Alternative processes to produce the same intermediate or final product.

- 21 processing units.

- 82 constrained shared resources (dosing and pumping equipment, cleaning equipment, etc).

- Cleaning constraints, considering different policies to control sequence and frequence of cleaning.

- 15 days scheduling period (about 160-180 batches).

- Off-line rescheduling preformed once a day from real data coming from the plant.

The steps performed to carry out the project can be summarized as follows.

1. Problem analysis: During this first step, several visits to the factory followed by discussions were carried out in order to fully understand the production processes. Preliminary recipe models were presented and discussed with the plant responsibles. Production plant policies were also examined as well as the constraints present in the plant.
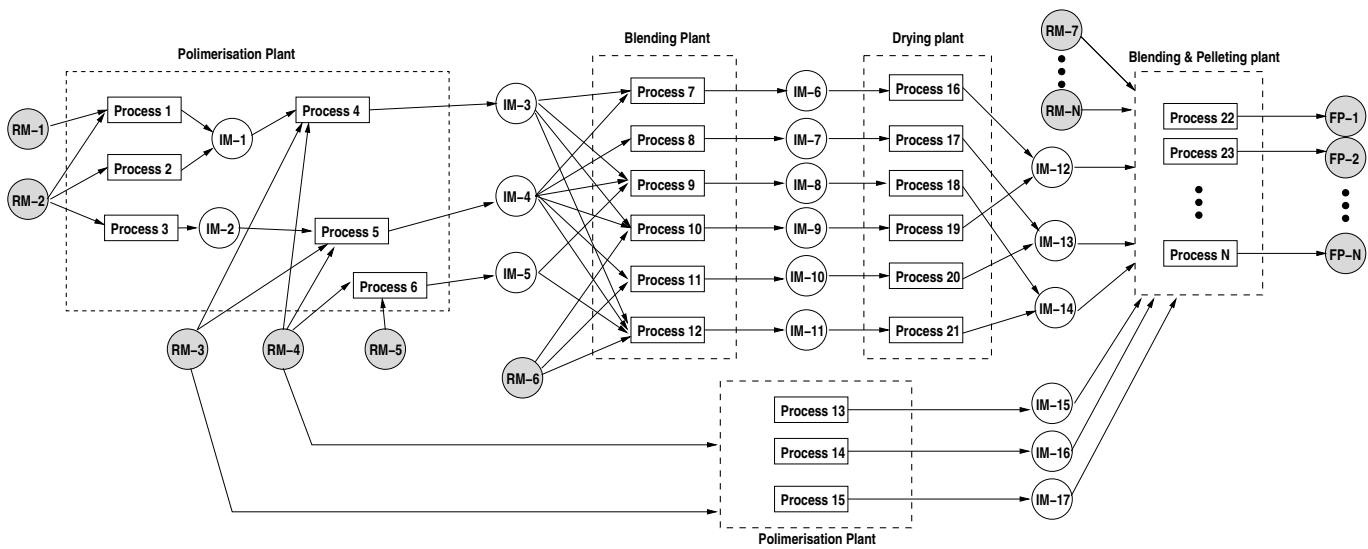
Polimerisation Plant

Blending Plant

Drying plant

Blending & Pelleting plant

RM–1

RM–2

Process 1

Process 2

Process 3

IM–1

IM–2

Process 4

Process 5

Process 6

IM–3

IM–4

IM–5

RM–3

RM–4

RM–5

RM–6

Process 7

Process 8

Process 9

Process 10

Process 11

Process 12

IM–6

IM–7

IM–8

IM–9

IM–10

IM–11

Process 16

Process 17

Process 18

Process 19

Process 20

Process 21

RM–7

RM–N

IM–12

IM–13

IM–14

Process 22

Process 23

Process N

FP–1

FP–2

FP–N

Process 13

Process 14

Process 15

IM–15

IM–16

IM–17

Polimerisation Plant

Figure 7.1: Process Material Network for the Polymer industry studied

2. Data acquisition: Real and detailed plant data was provided. With this data the database of recipes and constraints was built and first prototypes were presented. Critical data (as optimal coloring sequence) was identified as missing and a methodology was developed in order to acquire this data.

3. Development of specific sequencing and optimization algorithms: Specific sequencing and optimization algorithms were developed taking into account the precise know-how of the plant and the production policies present. Several prototypes were presented and discussed with the plant managers.

4. Off-line rescheduling development: A re-scheduling interface and methodology was developed and provided. The information came into the system through ASCII ".csv" files generated by the existing ERP system.

5. Final testing: testing and fine tuning was performed in the site.

This was the first industrial-sized case where a first version of the EON model (chapter 4) and data structure (chapter 3) was applied. The FCEON calculation algorithm (section 4.6.2) and the shared resources de-overlapping algorithm (section 4.4) were used to calculate the starting and ending times of all the operations involved in the process.
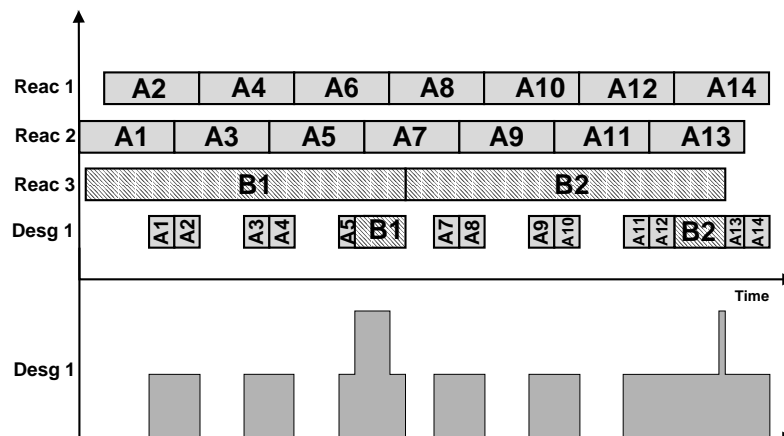

Figure 7.2: Polymer A and B production without de-overlapping constraint for Desg-1

As an example of the sequencing algorithms used in the scheduling tool, figures 7.2 and 7.3 illustrate the algorithm used for choosing the best recipe for the production of polymer IM-1 (shown in figure 7.1). This polymer can be produced using two different recipes. The first and preferred one has two stages using one of the two first reactors and a desgassification equipment to get rid off the remaining monomer. The second recipe uses a longer reaction in order to consume all the monomer.

The first step of the algorithm (represented in figure 7.2) generates an schedule using the preferred recipes for polymers A and B without the de-overlapping constraint for the degassification unit.

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In a second step, the batches coming through the degassification unit at the same time are identified, and the corresponding recipes (recipe A) are changed to use the recipe A' which is the one that does not require the use of the degasifier.
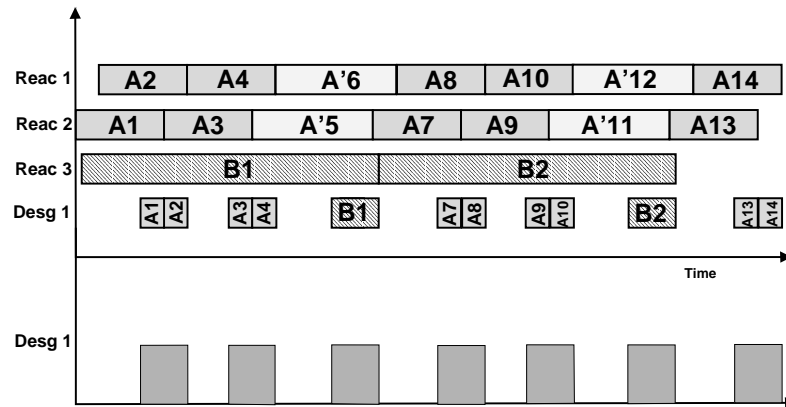

Figure 7.3: Changes in batches of recipe A to A' in order to avoid overlapping

The combination of different sequencing algorithms as the one just described allows to build the complete schedule taking into account all the plant policies. The aspect of the resultant application is shown in figure 7.4.

7.2 Sugar manufacturing

Two sugar manufacturing industries were examined using the scheduling approach described in this Thesis: Compañia Azucarera Concepción S.A. (CACSA) located in the surroundings of Tucuman, Argentina (figure 7.5) and "Camilo Cienfuegos" which is located nearby La Habana, Cuba (figure 7.6) within the framework of project WATERMAN (European Community funded project IC18-CT98-0271). The work carried out was the development of scheduling and planning methods and tools for the optimum resource management, leading to enhanced water (steam) and energy savings. This work was developed primarily in three steps:

- Building the models and development of tools for this specific application (sugar manufacturing).

- Analysis of the production process and generation of the data structures and definitions needed to represent different scenarios with the models and tools developed.

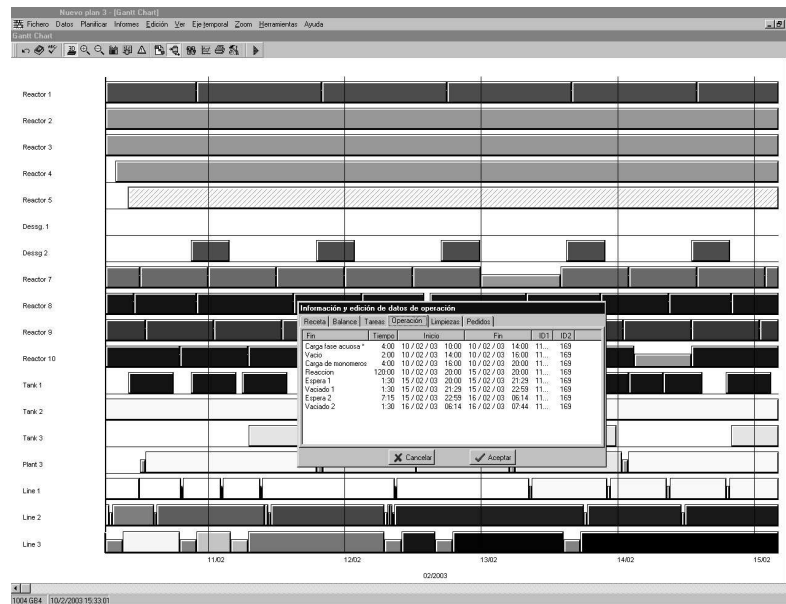- Utilization of real production data to evaluate the current production scenario.

Figure 7.4: Aspect of the scheduling application running

7.2.1 Case analysis

The preliminary analysis of the sugar industry batch scheduling problem shows a very high degree of complexity in the recipe structure and production processes. Up to this point, it was clear that the conventional MILP formulations for scheduling and planning were useless basically because of the complexity and specially, the size of the problem to solve. On the other hand, commercially available software usually works with oversimplified models, which become also useless in this case. The EON model (chapter 4) and data structure (chapter 3) developed in this Thesis was able to handle effectively, both the size and complexity of the problem.

Analysis of the production processes in the sugar plant CACSA and Camilo Cienfuegos was carried out using the developed tools. The scheduling model was applied to each one of the two sections of the plants, which operate in discontinuous mode and where most of the steam consumption is required. A key aspect to be considered in these plants in order to get an important reduction of the water and energy consumption is to obtain a detailed simulation of the temporary steam requirements which depend on the units assignment and the time of assignment.

The two processes are very similar, but CACSA is much bigger sugar mill than "Camilo Cienfuegos". On the one hand, in "Camilo Cienfuegos" the main equipment pans (tachos), are more flexible in the sense that one unit can be used to process more than one product.

The sugar manufacturing process is basically a refining process. The first step is the "Trapiche" where raw sugar cane is crushed obtaining the raw sugar cane juice. The raw sugar

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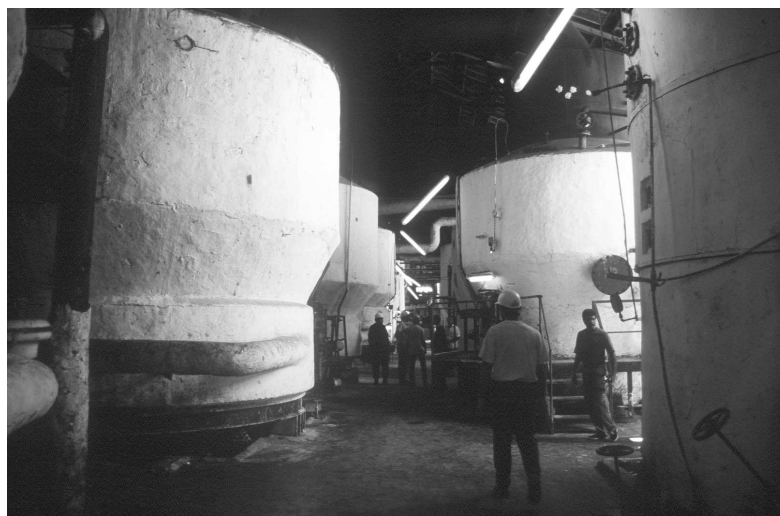

Figure 7.5: CACSA view of raw material reception

Figure 7.6: Camilo Cienfuegos view. "Tachos" section

cane juice is filtered and clarified an then concentrated in a multi-stage evaporator obtaining the concentrated sugar juice or "miel". The concentrated juice is then send to the sugar pans "tachos" where the sugar begin to cristalize. This is the bottleneck stage. Finally, the mix of remaining concentrated sugar juice and sugar crystals is separated using centrifuges.

The main problem in both cases is the same. The key objective function is to avoid the presence of peaks in the demand of steam, not only to avoid excessive consumption of energy and water, but also to increase the quality of the final product.

The conclusions to be drawn from this analysis can be summarized as follows:

- All intermediate storage should be taken into account in order to improve the management of the intermediate processes between different intermediate storage sites.

- The cristalizers perform the function of intermediate storage as they are used to link two batch trains of a very different capacity and cycle time.

- A detailed scheduling of all the centrifuges is not necessary as the limiting resources and the most important water consumption is carried out at the "tachos". In addition, the cycle time of the discontinuous centrifuges is very short when compared with the time required in the operation of the "tachos".

- Therefore, in order to carry out the scheduling, the centrifuges are grouped and simulated as a semi-continuous train.

- The unit assignment is not critical in this case, as all the critical equipment units (tachos) are used only to produce one specific product or intermediate. This situation makes much more easier the automatic scheduling. In any case, it will be very useful if specific plant policies are defined. This point is mainly applicable to CACSA facility, since Camilo Cienfuegos is much more flexible.

- In order to minimize the energy and water consumption in the "tachos", an appropriate scheduling is needed to avoid high demand peaks. These peaks usually mean that there are low demand situations, which imply a vent of steam to the atmosphere, with an obvious waste of resources.

- The actual recipes used in Camilo Cienfuegos plant can be significantly improved using in a more extensive way the intermediate storages, which allows the use of smaller recipes thus providing more flexibility to the system.

7.2.2 Utilization of real production data

Real data corresponding to a few days of production have been provided by CACSA as well as by Camilo Cienfuegos. In order to proceed to an evaluation of this data, an Excel Worksheet has been designed to be able to interact with the scheduling and Planning Software. In both cases, an specific MACRO in Excel (figure 7.7) was developed because of the different nature of the data provided by the companies.

CACSA provided 5-day real production data for the Refinery part of the plant. This data represents the production of 408 batches performing 2448 operations (figure 7.8). Otherwise, Camilo Cienfuegos, provided data from the crude sugar section for one day production time. In this case the number of the different batches was 21, but the recipes were much more complex than in the previous case, so the total number of operations involved was 171. As a result of this simulation of the real plant, the Gantt chart shown in figure 7.9 was obtained.

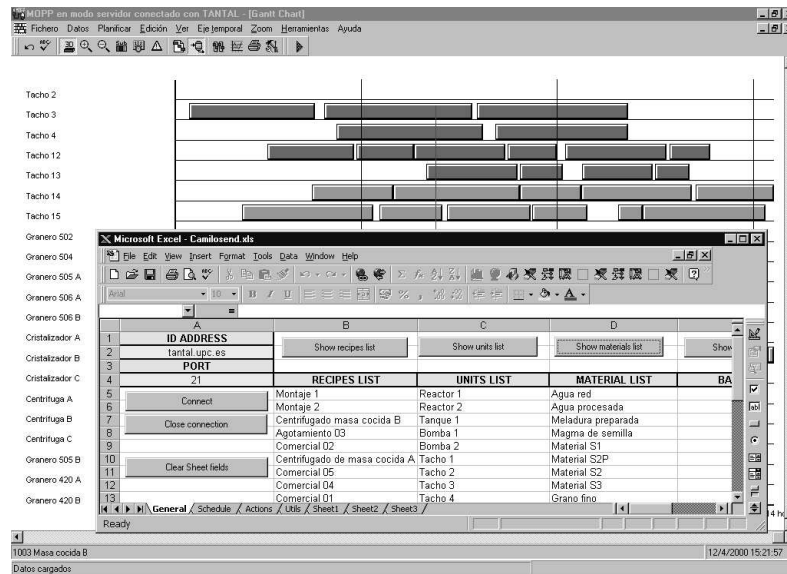**Chapter 7. Case studies**

Figure 7.7: Data input through Excel spreadsheet

This data allowed to perform an analysis of the real situation of both plants as well as setting the Excel spreadsheets that allow to communicate the data provided by the industry to the scheduling and planning package.

In both cases, the work done with the real production plans indicates that there is an extraordinarily high variability in the processing times (according to unpredictable factors) and a high complexity of the process itself. This high variability indicates that it could be useless to determine an optimal schedule without the knowledge of the real state of the plant at any instant. Otherwise, a significant improvement could be done if a scheduling and planning system could be implemented online, with the data flow of the plant. Therefore, the conclusions of this application were summarized in the following points.

- A scheduling and planning model appropriate for sugar plant factories was developed. Recipes for all the production processes for the studied two plants have been determined. In the case of "Camilo Cienfuegos", new recipes that provide more flexibility to the production process were developed.

- It has been demonstrated that it is possible to reduce the steam consumption applying the previously developed models and production recipes. The steam production can be reduced between 3% and 4%. This reduction can be achieved reducing the steam vents to the atmosfere by an appropriate scheduling of the operations carried out in the "tachos" section. Further work is needed to provide a more accurate steam requirement model for the crystallization sections thus obtaining a a fine adjustment of the steam consumption.
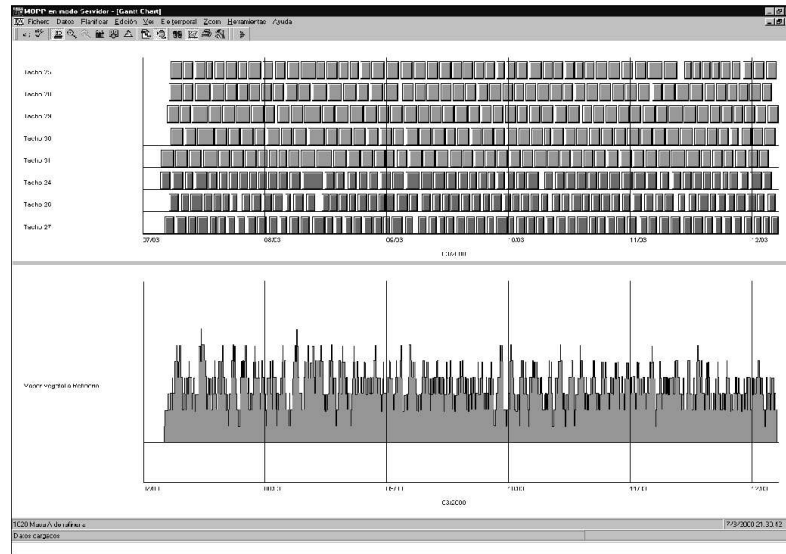
Figure 7.8: CACSA schedule & steam consumption view

- The high variability of the operation times requires that only an online scheduling system can really attain the objective of reducing the steam consumption. The operation times have a high variability so they cannot be predicted accurately in advance. Therefore the steam production reduction can only be achieved using a system that performs rescheduling continuously adapted to the changing conditions of the plant. Unfortunately, to develop such a system was out of the scope of this project.

7.3 Consumer products example

This case study, proposed in Honkomp et al. (2000), is based on an industrial scenario. All the data required for the description of the process is provided in the original reference, as well as a set of demands for several weeks of production. Additional constraints as work shifts are also provided. The process is illustrated in figure 7.10.

This process is a making and packing operation for more than 200 final products. These products are obtained as the result of almost 60 different bulk formulas, which in many cases are packed into more than one type of final container. The operation is made up of two main stages, making (figure 7.11), which are coupled by a limited number of intermediate storage tanks. The general recipe for this process is such that a premix (Mix) is produced, then transferred into a final mix tank where secondary materials are added and additional unit operations are performed (Mix2). The materials are transferred into intermediate storage tanks, where they are held for analysis and allowed to cure for a specified amount of time.
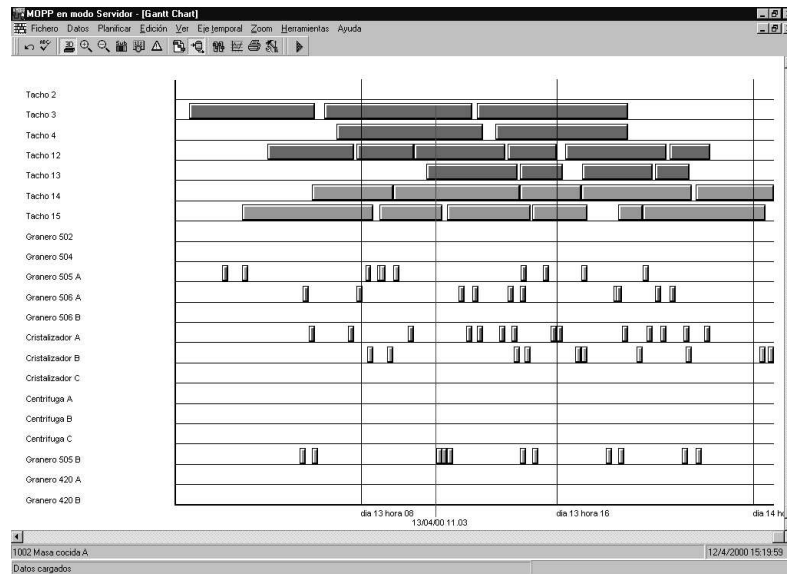
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Figure 7.9: Camilo Cienfuegos schedule

Finally, the approved bulk formula is sent to a packing line where it is placed into consumer packages, which are palletized and placed in a shipping warehouse.

There are 6 main mixing tanks, 3 shared premix tanks, and the 7 packing lines for converting bulk materials into the products consumers see on store shelves. All tanks are identical in size, and recipes and demands have been normalized to have a batch to be one unit of material.

The high level objective for this problem is to determine a feasible schedule to meet all production demands. Secondary objectives are to minimize the number of washouts and package size changeovers required, minimize the amount of final product on hand at any given time, and to complete operations with a minimal number of shifts.

The main challenging points of this case are:

- The size of the problem (200 recipes and 96 equipment units)

- Incorporation of shift constraints

- High number of alternative units (storage tanks) for the same task

As shown in chapters 5 and 6 this case study has been chosen to test the sequencing and assignment strategies as well as the optimization methods used. The incorporation of shift constraints has been also used to test the de-overlapping method used to take into account the availability of resources (section 4.4). One example of the last point is shown in figure 7.12.
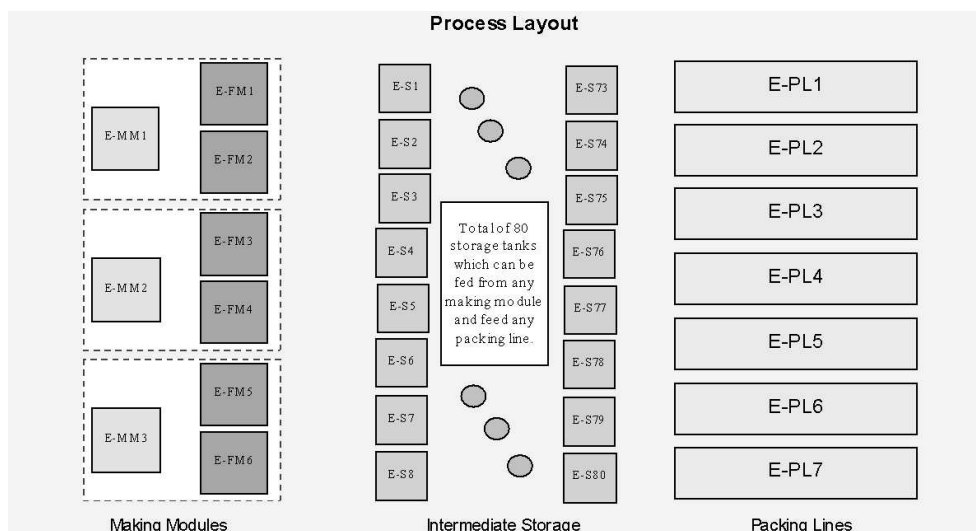
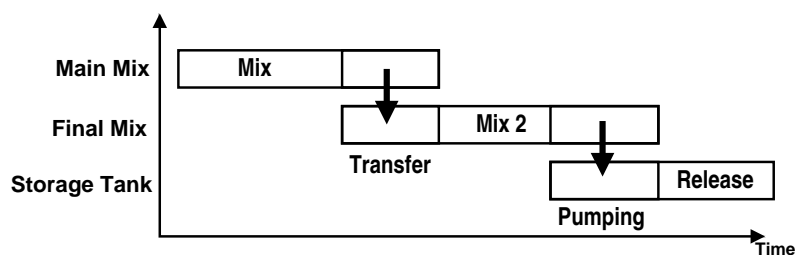Figure 7.10: Process Layout for Honkomp et al. (2000) industrial case

Figure 7.11: Making process for Consumer products example

7.4 Procel

PROCEL is a pilot plant located at the laboratory facilities at the UPC Chemical Engineering Department. It is constituted by three tank reactors, three heat exchangers and the necessary pumps and valves to allow changes in the configuration. Equipment of the PROCEL plant is fully connected and the associated instrumentation allows the change of configuration by software. The flowsheet of PROCEL plant is represented in figure 7.13.

PROCEL is fully controlled by a commercial Distributed Control System (DCS) and is designed to work in different operation modes. This flexibility allows making experiments in batch, continuous and batch-continuous mode simply configuring the control software. It also allows the TCP/IP communication with the LAN computer network. This communication permits performing real time applications like model predictive control, data reconciliation
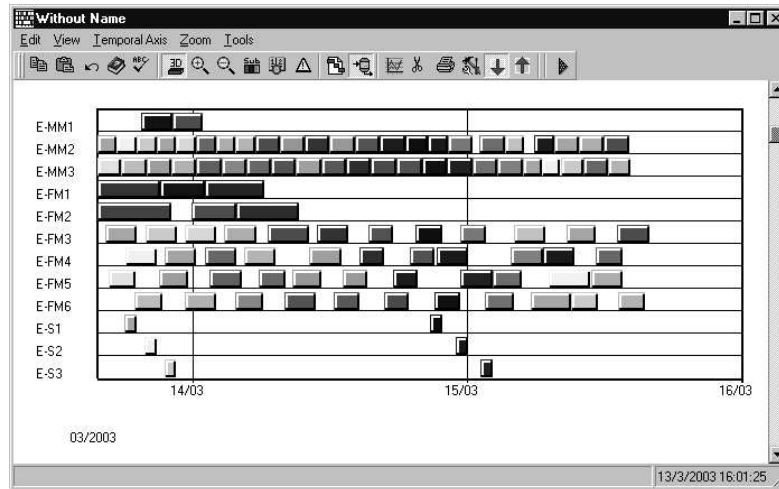
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Figure 7.12: Gantt chart of the consumer products example

and reactive scheduling.

This case study does not have the complexity of the previous examples, but it has an advantage of the availability. The availability of the pilot plant as well as the availability of additional software (coordination control, fault diagnosis system, communication system) also developed at the UPC makes it the ideal choice to test the on-line scheduling approach explained in chapter 5 in a real scenario.

In order to test the on-line scheduling features two different recipes were prepared. Table 7.1 shows the structure and the data concerning the recipes used in Procel. Unit Procedure 1 of both recipes can only be executed in Tank equipment (EQ2). Unit Procedure 2 can only be executed in pump B2. Unit Procedure 3 can be executed in one of the two reactors available (EQ1 and EQ3). The cycle time of recipe 1 is 10.55 minutes and for Recipe 2 is 13.89 minutes. These cycle times are short enough to make tests in the real environment.

The recipes were introduced in the scheduling software developed as well as in the coordination control system. The goal was to execute an schedule in the plant having on-line feedback of the deviations from the predicted schedule and, eventually, generate a new schedule taking into account the real data coming from the plant. A relational database (MySQL) was used as the media to connect the scheduling tool with the plant. Two database tables were built, one containing the predicted schedule (generated with the scheduling tool) and the other one containing the real schedule (all the batches "frozen" due to the control time window as shown in chapter 5). The on-line methodology was programmed and tested using this case study (fig. 7.14).

Several tests were carried out using this framework allowing the demonstration of the time windows approach for the on-line scheduling procedures. An specific Ph.D thesis dealing specifically with the on-line scheduling aspects is currently going in depth through this approach.
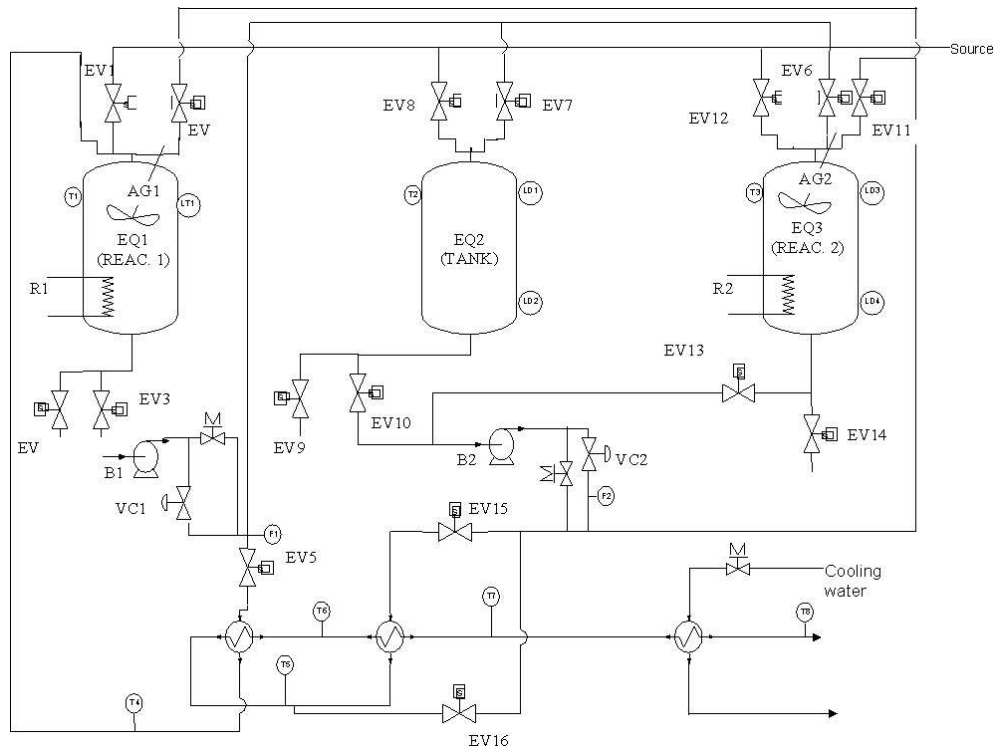
Figure 7.13: PROCEL flowsheet

7.5 Conclusions

The scheduling framework developed in this Ph.D. Thesis has been used to deal with several industrial scenarios proving that the approach used can handle the complexity of the real environments.

The industrial scenarios have been and excellent test bed to check out the different solutions shown in this thesis as:

- Modeling framework: The modeling framework presented in chapter 3 was able to represent the complexity of all the industrial scenarios shown.

- Timing Model: The EON model presented in chapter 4 was able to handle all the resource, storage, calendar and recipe constraints present in the different case studies used.

- Sequencing algorithms: The generic sequencing algorithms described in chapter 5 has been applied to the two last case studies presented. The on-line scheduling approach has been successfully tested on PROCEL validating the whole framework.

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Table 7.1: Recipes used in Procel

Recipe	Stage	Operation	Op. Time (min)
Recipe 1			
	Unit Procedure 1		
		Load Tank	2.6
		Hold	1
		Discharge tank	2
	Unit Procedure 2		
		Transfer	2
	Unit Procedure 3		
		Load Reactor	2
		Process of reactor	2.63
		Discharge final product	4.42
		Clean	1.5
Recipe 2			
	Unit Procedure 1		
		Load Tank	2.63
		Hold	1
		Discharge tank	2
	Unit Procedure 2		
		Transfer	2
	Unit Procedure 3		
		Load Reactor	2
		Process of reactor	4.33
		Discharge final product	5.56
		Clean	2

- Optimization algorithms: As shown in the previous chapter, the case study proposed in Honkomp et al. (2000) has been used to perform the comparison between the different optimization methods presented in this thesis. The results regarding to this case study have been resented previously.
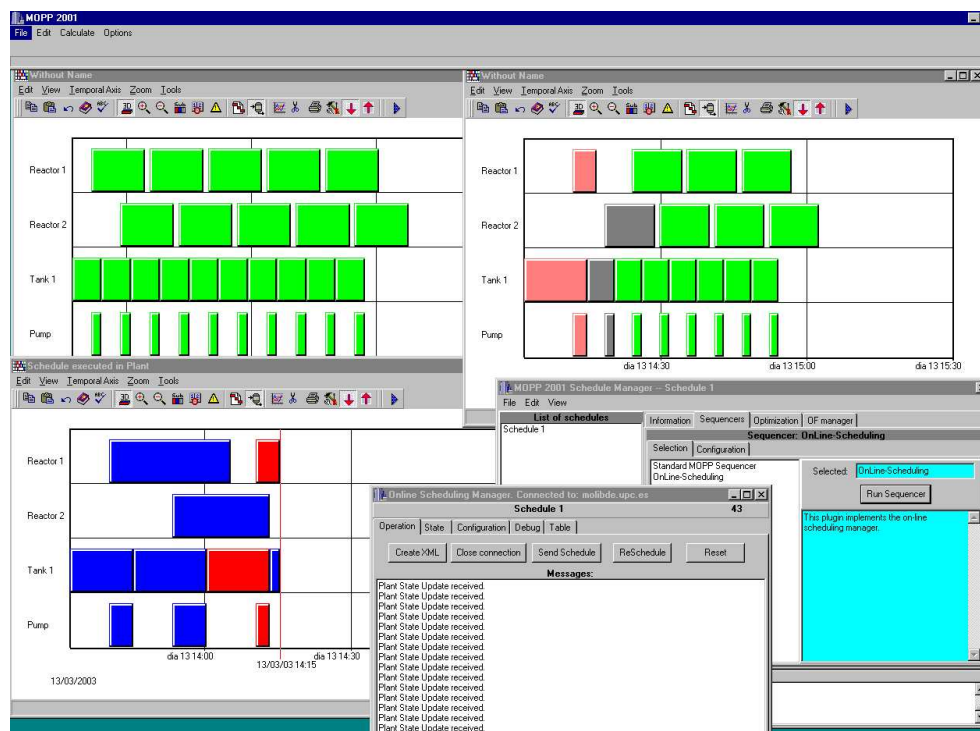
Figure 7.14: On-line scheduling methodology running using the PROCEL case study. Top left original schedule, bottom left schedule currentlly executed in the plant, top rigth result of the rescheduling.

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