

Chapter 5

Sequencing and assignment Strategies

5.1 Overview

This chapter is dedicated to the methodologies used in this work to build schedules. The following aspects will be addressed: dispatching and assignment rules and rescheduling.

The EON model is very suitable to be used in combination with classical dispatching rules for assignment and sequencing purposes. Typical rules found in commercial packages and published works as well as novel rules are applied to the generic framework, using the capabilities of the basic EON model. Resource and storage constraints are also applied in combination of priority-based rules as a way to build quick sub-optimal schedules. The dispatching and assignment heuristics applied to the EON model are explained.

Finally, the approach used in this work to perform on-line rescheduling is also explained.

5.2 Assignment and sequencing

The EON model approach allows at this point to calculate the timing of the operations taking into account complex storage constraints as well as resource constraints. However, the problem that we want to solve is to find a schedule that accomplishes a set of demands on a given due-dates. The EON model with all the constraints explained up to this point needs an additional step to solve this problem: the generation of the batches that accomplishes a specific set of demands.

The EON model as explained in chapter 4 is very suitable to be used in combination with classical dispatching rules for assignment and sequencing. Unfortunately, the scheduling problem in the chemical industry has additional constraints. Classical rules based on a prioritacion of waiting jobs can be classified in two main blocks: rules based on due dates and rules based on processing time.

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Due date priority rules are those based on the due-dates of the different jobs. Some of these rules are:: ERD (earliest release date), EDD (earliest due-date) and MS (minimum slack time first).

Processing time priority rules are those based in the processing time of the jobs. Some of these rules are: LPT (longest processing time), SPT (shortest processing time) and WSPT (weighted shortest processing time first).

The advantages of such kind of rules are that they are fast to implement, fast to calculate and it is demonstrated that in some kind of specific problems they end up with the optimal solution (Baker, 1974). The main problem in the application of those rules in our case is that all of them are job-based, therefore some adaptation is needed to use them in connection with the modeling framework presented, which is batch oriented. A preliminary approach is shown in figure 5.1 that allows the use of dispatching rules within the framework presented in this thesis.

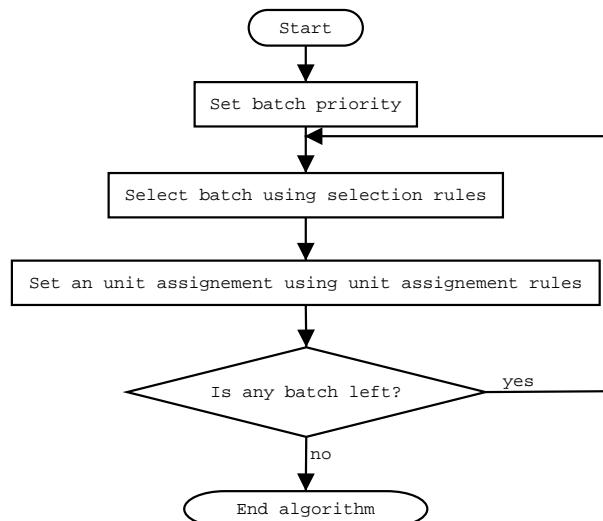


Figure 5.1: Generic sequencing algorithm

Nevertheless, since the primary source of information is the demand and not the complete list of batches to be sequenced, three aspects must be taken into account: the material balance, the unit assignment and the sequencing itself. These three aspects should be combined as shown in figure 5.2 in order to obtain a full functional model which allows the generation of the complete sequence and assignment of a set of batches trying to fulfill a set of demands.

5.2.1 Material balance

The first aspect to be considered is the material balance. The start point is the process and material network presented in chapter 3, like the one shown in figure 5.3. From this information

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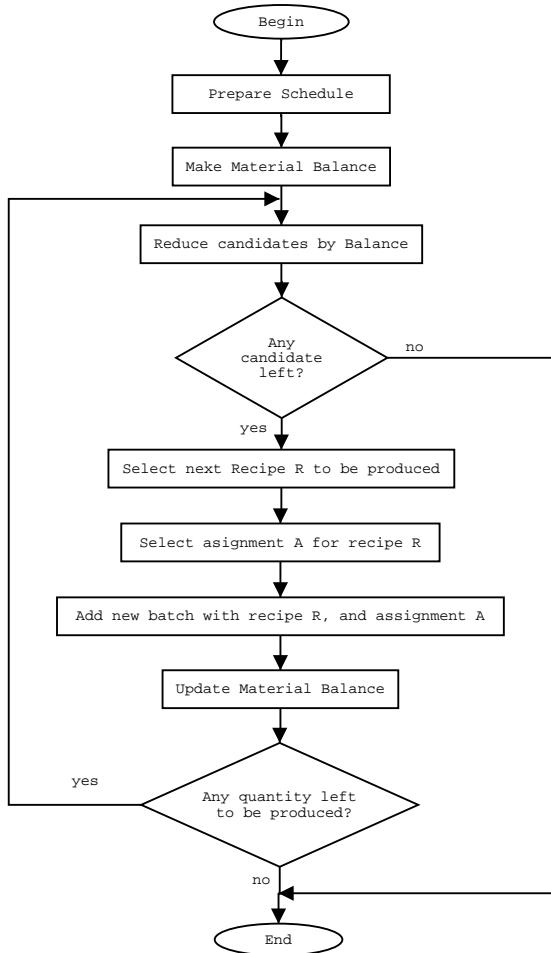


Figure 5.2: Complete flowchart for material balance, sequence and assignment

the following material balances are extracted:

$$\begin{aligned}
 3 \cdot RM1 + 6 \cdot RM2 &\longrightarrow BP1 + IM1 \\
 IM1 + 2 \cdot RM3 &\longrightarrow 5 \cdot FP1 \\
 2 \cdot RM4 &\longrightarrow FP2
 \end{aligned}$$

Solution to this kind of balances is quite trivial, for example, to produce 100 units of the final product $FP1$, batches of Process 1 and Process 2 should be executed. Solving the balances it is found that 60 units of $RM1$, 120 units of $RM2$ and 40 units of $RM3$ are needed. Process 1 will produce 20 units of byproduct $BP1$ and 20 units of the intermediate $IM1$.

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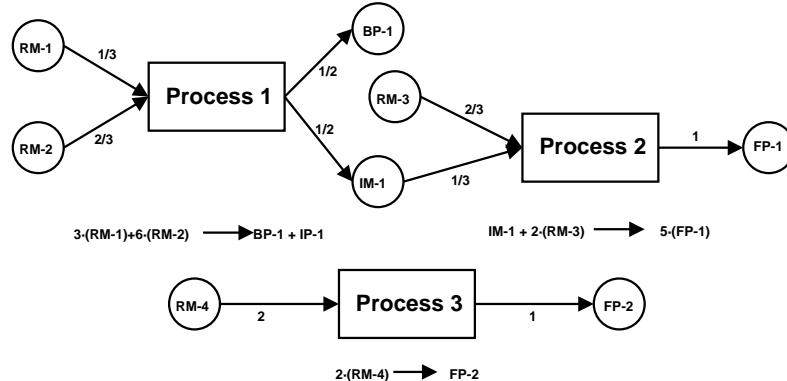


Figure 5.3: Process network for calculation of material balance

Unfortunately, not all the scenarios have this kind of linear situation. It is possible to find scenarios where two or more processes are capable to produce the same product (or intermediate). In this situation it would be possible to use an LP formulation to find out how much to produce with each process (Peschaud, 1997). Despite of the strict LP formulation, still the difficulty to obtain reasonable weights that allows the finding the “optimal” solution¹ makes unreasonable to use this method in a dispatching-like approach as the one presented here. Therefore, in this work a more simple approach has been followed. For the initial material balance, a priority-based rule has been used to choose between different alternative processes. Different rules can be chosen:

- HPP (highest priority process): the process with the highest priority is used.
- FP (first process): The process that has been included first in the system (has the lowest ID) is chosen.
- RP (random process): One of the alternative processes is chosen with the same probability.
- AUP (already used process): The process already used (because is also needed for other intermediate) is used again. This rule has to be activated with one of the other rules.

These rules allow to easily determine which processes are necessary to run in order to produce an specific material. The algorithm used is shown in figure 5.4.

The use of this algorithm ends up with a list of processes to be sequenced and assigned to specific units. The assignment and sequencing procedure is carried out at the same time, since the assignment is done when a process is selected for being sequenced as a batch in the future schedule. The assignment and sequencing are explained in sections 5.2.3 and 5.2.4.

¹In the work referenced (Peschaud, 1997) it is shown that the “optimal solution” always consists in processing all the intermediates with the cheapest process. This kind of solution its quite trivial as only the material balance is considered. So, the solution always consists in choosing the cheapest or the process with more priority.

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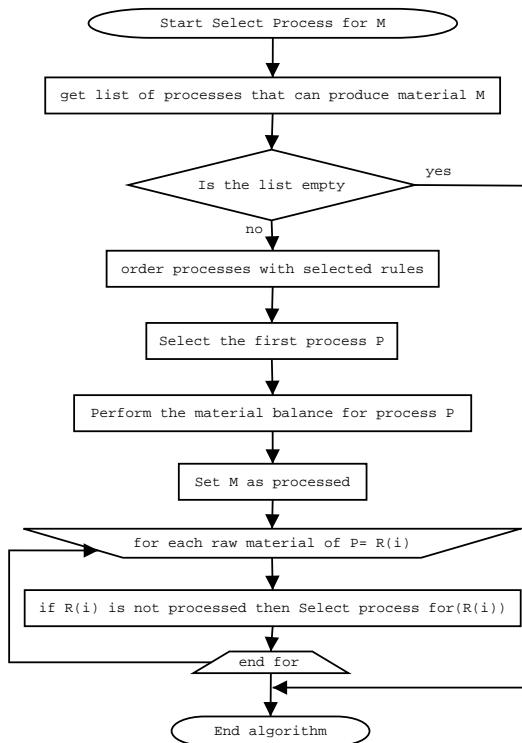


Figure 5.4: Recursive algorithm used for the selection of processes

5.2.2 Reduction of candidates by material balance

The material balance algorithm delivers a list of recipes and quantities to be produced like this:

Recipe	Quantity to be produced	List of demands
R_1	Q_1	D_1^1, \dots, D_n^1
\vdots	\vdots	\vdots
R_m	Q_m	$D_1^m, \dots, D_{n'}^m$

Obviously it is not possible to introduce a batch of any of these recipes at any instant. Additional aspects should be considered :

- The partial material balance
- The storage constraints

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- Dedicated storage constraints
- Shared storage constraints
- Shared exclusive storage constraints

5.2.2.1 Partial material balance

A batch of a recipe cannot be produced if the intermediate material needed to execute that batch is not available. The intermediate materials should be produced first. Different additional constraints should be checked to maintain an specified recipe as a candidate for the next batch. Any partial schedule SC has associated to each material m a set of ordered (in the same sequence as the batches) set of $N_m(SC)$ level variations $V_{m,i}$. Each material has also an initial stock associated (I_m) and a maximum and minimum capacity for storing this material (MAX_m and MIN_m). In this situations the sum of all the contributions of an specific material should be between the minimum and maximum capacity for this material (equations 5.1 and 5.2)

$$I_m + \sum_{i=0}^n V_{m,i} \leq MAX_m \quad \forall n, m; 0 \leq n \leq N_m(SC) \quad (5.1)$$

$$I_m + \sum_{i=0}^n V_{m,i} \geq MIN_m \quad \forall n, m; 0 \leq n \leq N_m(SC) \quad (5.2)$$

Applying these constraints to the initial set of candidates, all the recipes requiring the use of an intermediate that has not been provided by a previous batch will be discarded as possible candidates for the next batch to be launched. These two constraints must be satisfied for all the materials involved in the production. Additional constraints should be also checked if an specific storage policy has been defined.

5.2.2.2 Dedicated Storage

If a dedicated storage constraint is present, the given storage can only be used with one material. In this case, for a given partial schedule (SC), every storage S has associated a set of $N_s(SC)$ level variations and an initial level I_S . At any instant the level of the storage should be within the limits of the storage (MAX_S and MIN_S), that can be expressed as:

$$I_S + \sum_{i=0}^n V_{S,i} \leq MAX_S \quad \forall n; 0 \leq n \leq N_S(SC) \quad (5.3)$$

$$I_S + \sum_{i=0}^n V_{S,i} \geq MIN_S \quad \forall n; 0 \leq n \leq N_S(SC) \quad (5.4)$$

5.2.2.3 Shared Storage

In this kind of storage, several materials can be assigned to a single storage, and several different materials can be in the same storage at the same time.

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In this case there are different initial levels $I_{S,m}$ for each of the M materials stored. It is also defined $\alpha_{S,i,m}$ as a binary variable, which equals to 1 if the variation of level $V_{S,i}$ refers to material m and is 0 otherwise (eq. 5.5)

$$\sum_{m=1}^M \alpha_{S,i,m} = 1 \quad \forall i \quad 1 \leq i \leq N_S(SC) \quad (5.5)$$

In this case there are also general constraints to insure that the level of the storage will always keep between the limits:

$$\sum_{m=1}^M I_{S,m} + \sum_{i=0}^n V_{S,i} \leq MAX_S \quad \forall n; 0 \leq n \leq N_S(SC) \quad (5.6)$$

$$\sum_{m=1}^M I_{S,m} + \sum_{i=0}^n V_{S,i} \geq MIN_S \quad \forall n; 0 \leq n \leq N_S(SC) \quad (5.7)$$

An additional constraint is that none of the materials will be below 0 at the end of the partial schedule. This condition can be expressed as:

$$I_{S,m} + \sum_{i=0}^{N_S(SC)} \alpha_{S,i,m} V_{S,i} \geq 0 \quad \forall m \quad 1 \leq m \leq M \quad (5.8)$$

5.2.2.4 Shared exclusive storage

This storage can store different materials, but only one of the materials can be in the storage at any time. In this case there are also different initial levels $I_{S,m}$ for each of the M materials stored (only one of them can be greater than 0). It is also defined $\alpha_{S,i,m}$ as a binary variable according to the equation 5.5.

The minimum storage level in this case should be always 0 ($MIN_S = 0$), so that 5.6 and 5.7 become:

$$\sum_{m=1}^M I_{S,m} + \sum_{i=0}^n V_{S,i} \leq MAX_S \quad \forall n; 0 \leq n \leq N_S(SC) \quad (5.9)$$

$$\sum_{m=1}^M I_{S,m} + \sum_{i=0}^n V_{S,i} \geq 0 \quad \forall n; 0 \leq n \leq N_S(SC) \quad (5.10)$$

As in the previous case, none of the materials can go below zero, so constraint 5.8 is also applied.

Finally, an additional constraint must be met to insure the exclusivity of the storage for one material at any time. The total contributions at any time should be the same as the total contribution of the last material added (eq. 5.11).

$$I_{S,m} + \sum_{i=0}^n \alpha_{S,i,m} V_{S,i} = \alpha_{S,n,m} \left(\sum_{m=1}^M I_{S,m} + \sum_{i=0}^n V_{S,i} \right) \quad \forall m, n \quad 1 \leq m \leq M, 0 \leq n \leq N_S(SC) \quad (5.11)$$

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All the constraints must be satisfied in order to keep an specific recipe in the candidates list. If a Recipe does not meet the constraints of the partial material balance and storage used, the recipe is not maintained in the candidates list for sequence and assignment.

5.2.3 Assignment

The assignment is the procedure to determine which equipment unit should be used for each batch. The data model described in chapter 3 allows the specification of different alternative units for each stage. The assignment procedure should conclude with at least one unit used by each stage.

The approach used in this thesis for the unit assignment is also a priority-rule based approach. Different rules have been defined to determine which unit should be used:

- HPU (highest priority unit): The unit with the highest priority is used.
- FU (first unit): The first alternative unit defined in the recipe (lowest ID) is used.
- LUU (less used unit): The unit that has been chosen less times by the precedent batches is used.
- MAU (more available unit): The unit with the most available time is chosen.
- SPTU (shortest processing time unit): the unit that is capable to perform the stage in less time is used.
- AUA (Already used assignment): If some assignment has been used with the same recipe, it is given the highest priority.
- RU (Random unit): One of the available units is chosen randomly.

Some of these rules (SPTU and MAU) require information of the preceding batches in the sequence. This last aspect means that the assignment process is performed while the sequencing process is carried out. These rules also interact with the information about the connectivity between units. In fact, this last information is a hard constraint that decreases the size of the assignment problem.

5.2.4 Sequencing

Sequencing is the procedure to determine the sequence of batches (and consequently the sequence of operations for each unit) to be executed in the plant. As in the case of the material balance and the unit assignment a priority dispatching approach has been used. In this case the following rules are used:

- LSL (Lowest storage level) : A batch is performed if there is enough intermediate to process it, otherwise a batch to generate the intermediate is processed.
- HSL (highest storage level): The batches of intermediate products have the maximum priority.

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- EDD (Earliest Due Date): Highest priority is given to the batch with the earliest due date.
- SPT (Shortest processing time): Highest priority is given to the batch with the shortest processing time.
- SCT (Shortest cycle time): Highest priority is given to the batch with the shortest cycle time.
- LPT (Longest processing time) : Highest priority is given to the batch with the longest processing time.
- LCT (Longest cycle time): Highest priority is given to the batch with the longest cycle time.
- RANDOM (random): One of the possible batches to be added to the sequence is chosen randomly.

5.3 On-line scheduling

One of the advantages of the detailed model used for the representation of the recipes is that it makes easier the communication with other systems that use the ISA S88 standard to describe their data, specially the control systems. This way the interaction of the control system with the scheduling and planning tool is facilitated in order to react on-line to the incidences that may arise in the plant.

This section deals with the different aspects to be considered in order to integrate effectively a scheduling system to a control system.

5.3.1 Communication sequence

The first point to consider is to know which is the sequence of steps involved in the on-line scheduling procedure. The sequence diagram shown in figure 5.5 shows the main aspects involved in this communication.

The communication process starts usually in the user, who sets-up the scheduler, and accepts one specific schedule to be produced. The accepted schedule is sent to the control system, which executes it by expanding the schedule information in control recipes and executing control actions in the plant. The control system monitorizes the plant state and send the real schedule back to the scheduler. The scheduler compares the proposed and the real schedules and generates a new schedule to be executed. If the new schedule is approved by the user then it is sent to the control system to substitute the previous one.

5.3.2 The control time window

The starting point of the on-line re-scheduling procedure is an initial schedule as is represented in figure 5.6. The information that the scheduler provides once it is accepted by the user is the schedule to be executed in the plant.

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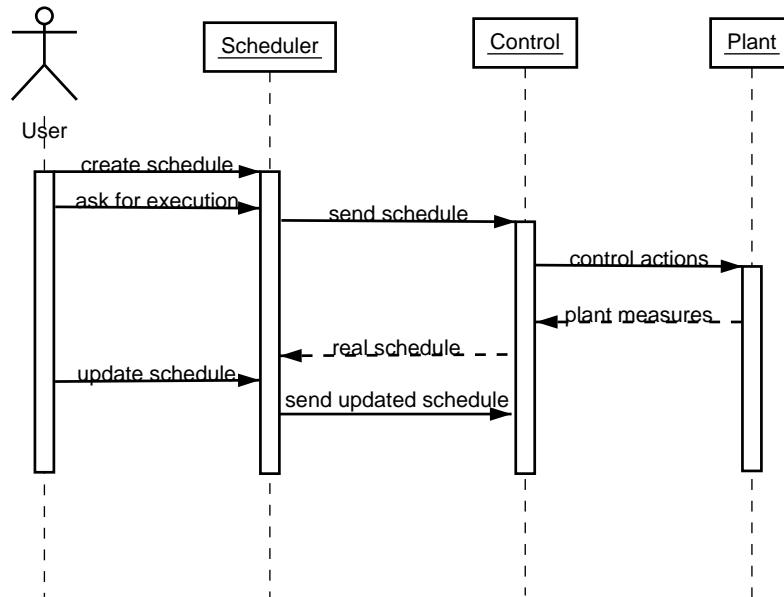


Figure 5.5: on-line Scheduling sequence diagram

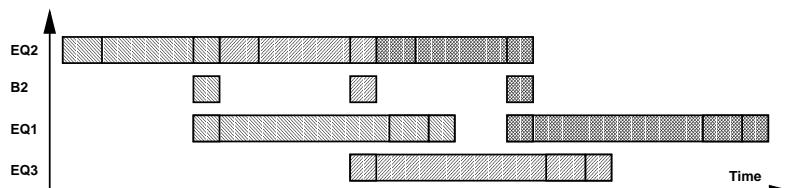


Figure 5.6: Initial schedule

This on-line scheduling approach is based in the existence of two time windows, one used by the control system and the other one used by the scheduling system (maximum time needed to perform all the calculations of the new schedule and approve it). The time window in the control system is used to activate an instance of the corresponding control recipe. For example, when the control time window is in the position shown in figure 5.7 the control system has only one control recipe active as is shown in figure 5.8

On the other hand, when two batches are affected (figure 5.9) there are two control recipes active (figure 5.10). It is important to note that once the control system has started/activated a control recipe, the scheduling system cannot make changes on the corresponding batch. It is the responsibility of the control system to make the corresponding changes if it is necessary. The logic involved in these changes is included in the detailed explosion of the recipe.

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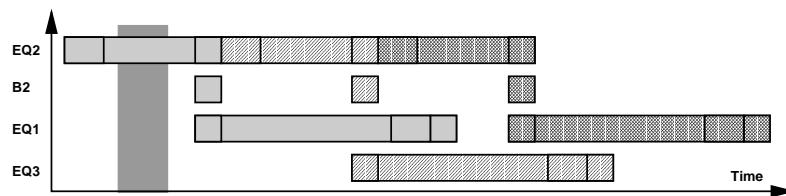


Figure 5.7: The time window affects one batch

Figure 5.10 shows the relationship between the first two unit procedures of both batches with a solid line, but has also included a dashed reference between the last unit procedure of the two batches even if according to the schedule provided, the two unit procedures are scheduled to be executed in different units. The reason for indicating this relationship is because that unit procedure can be executed also in the EQ1, thus it is important that the unit procedure has also available this information that will be used if the control system reassigns the unit procedure to the alternate unit.

It is important to note that the relationships shown in figure 5.10 are basically logical conditions that should be created and associated to the firsts transitions of the second batch. In other words, the transition is true if the first unit procedure of the first batch is finished.

5.3.3 The scheduling time window

As was shown in figure 5.5 the full on-line scheduling system involves several steps:

1. Schedule calculations.
2. Acceptance of the proposed schedule by the user.
3. Transmission of information to the control system.
4. Execution of the schedule in the plant.
5. Transmission of the executed schedule back to the scheduler.
6. Return to point 1

The on-line scheduling environment should take into consideration all the aspects involved in the whole cycle in order to insure the synchronization between the real execution of the schedule in the plant and the new proposed schedule. Figure 5.11 illustrates the timing involved in the whole process.

The process starts at time point 1. At time point 2 the current schedule has reached the scheduler and has been compared with the proposed schedule. The computation of the new schedule takes some time until time point 3. Then, the user acceptance of the new schedule is required until time point 4. The transmission of the new schedule to the control ends at time point 5. In other words, all the procedure requires a time window that goes from point 1 to point 5.

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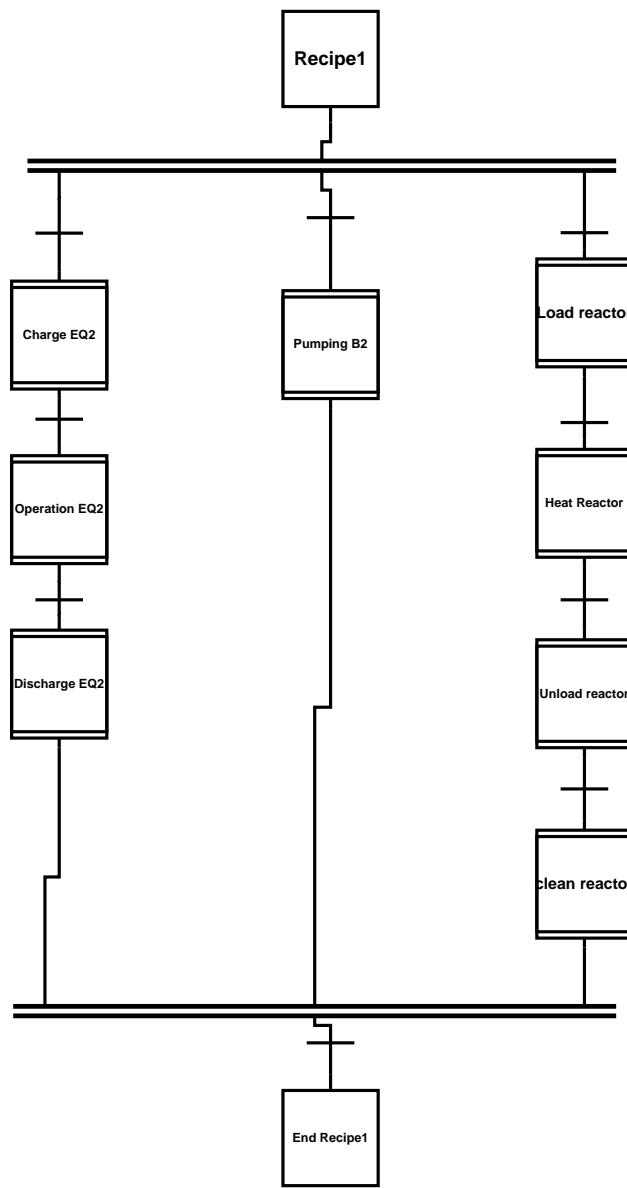


Figure 5.8: Control recipe of the batch affected in figure 5.7

Unfortunately, during this process the plant is also running so, when the updated schedule reaches the control system, the active control window has changed to the position shown in

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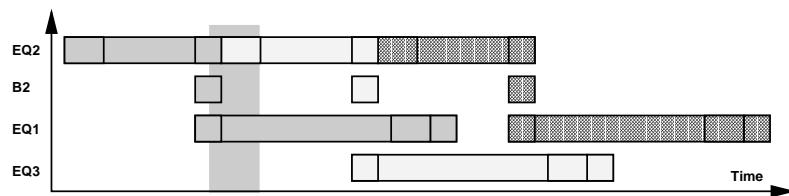


Figure 5.9: Control time window affecting two batches

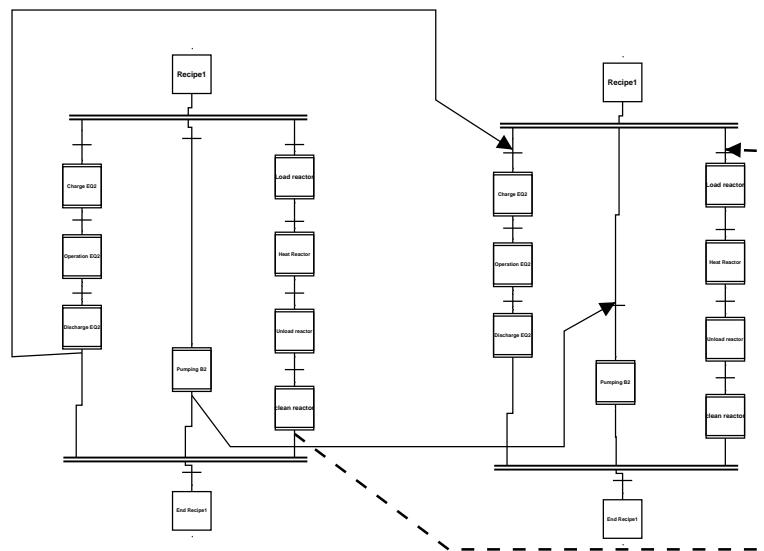


Figure 5.10: Control recipes of the batches affected in figure 5.9. The relationship between the two batches is shown

figure 5.12. Therefore, the consideration of the processing and transmission times involved in the on-line scheduling procedure requires that all the batches within the points 1 and 6 must be executed using the old schedule information, therefore those batches should be considered “frozen” in the calculations of the new schedule.

5.3.4 Schedule pre-processing

As shown previously in figure 5.2 on page 77 there is an “schedule preparation” phase before performing the material balance. There are two main information sources for this pre-processing:

- The schedule previously been sent to the plant

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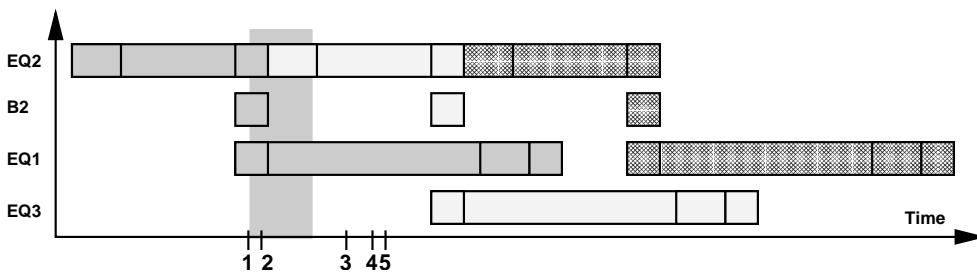


Figure 5.11: Timing of the steps involved in the on-line scheduling

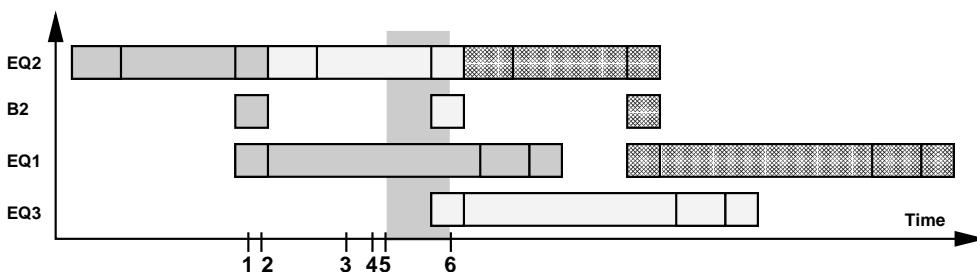


Figure 5.12: Position of the time window after the scheduling procedure

- The information about the execution of that schedule in the real plant

Working with the same example, figure 5.13 shows the initial situation. The upper gantt chart shows the actual predicted schedule and the two time windows. At T_0 the two time windows involve the batches which cover the demands $D1$ and $D2$. The other gantt chart shows the operations actually carried out in the plant and the unavailability of the equipment EQ3. Note that the operation times corresponding to the real operations differs from the planned ones.

The first thing to take into account is the constraint imposed by the time windows. Because of the behavior of control system, all the planned batches between T_0 and T_S will be under the responsibility of the control system at the end of the rescheduling procedure. This means that the batches that cover demands $D1$ and $D2$ are *frozen*, and cannot be scheduled again. Additionally, all the new operations should be scheduled after T_S . Additionally, the information related to the unavailability of the equipment EQ3 indicates the scheduler that some changes will be necessary in the execution of the batch that covers the demand $D2$. Having into account all these aspects, the scheduler should build first the expected schedule for the frozen batches as shown in figure 5.14. New batches should be added afterwards following the same or a different set of rules than the ones used for the generation of the first schedule. It is important to note that the needed demand to cover is only $D3$ as $D1$ and $D2$ are already covered by the *frozen* batches.

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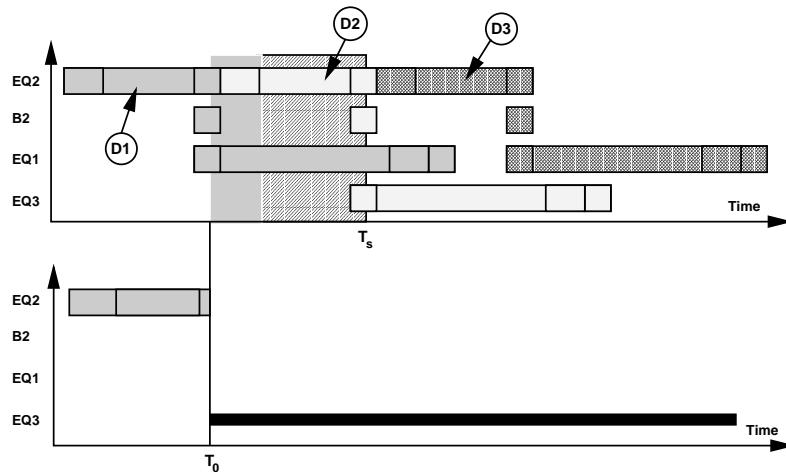


Figure 5.13: Plant situation and initial schedule with the control and schedule windows shown

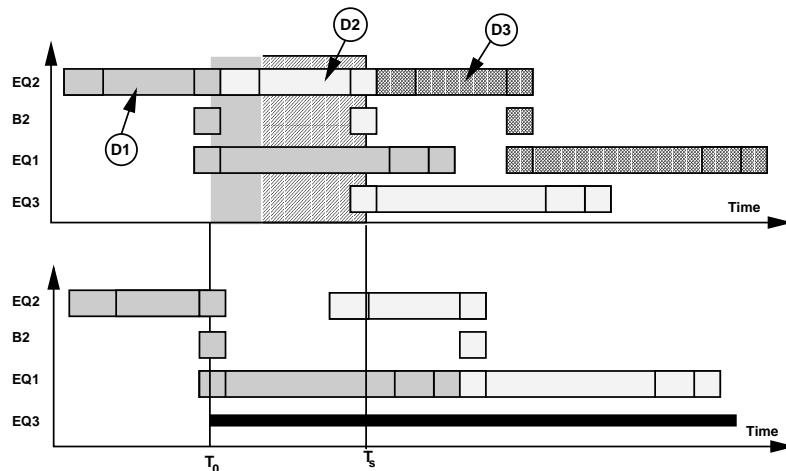


Figure 5.14: Schedule pre-processing performed. Initial schedule and pre-processed new schedule

Once finished the whole process, the new schedule which results is shown in figure 5.15 and the batches which are not frozen are sent back to the control system.

This procedure can be repeated every time that an incidence in the plant occurs. Using the same example, let us assume that the equipment becomes again available and a new rescheduling is started at T_0' . The initial situation for the scheduler will be the one represented in figure 5.16 and after the rescheduling procedure, the new schedule send back to the control

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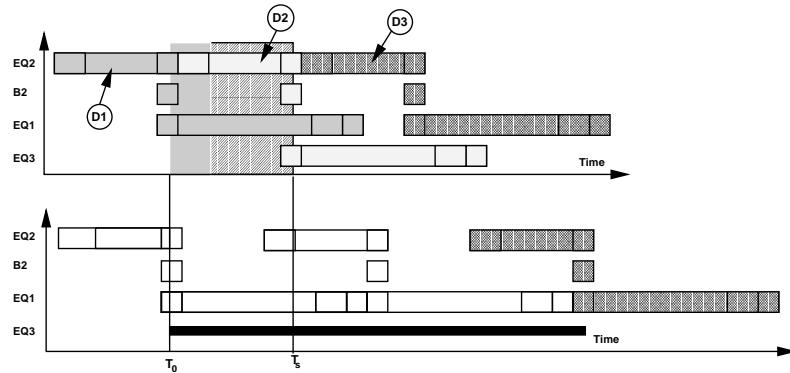


Figure 5.15: Final schedule sent back to the control system. Only filled batch is sent.

system will be the one shown in figure 5.17. Note that the batch which is rescheduled is performed after $T_{S'}$, which is the minimum time for the rescheduled batches due to the time windows used. This approach assures the synchronization between the control system and the scheduling system thus making possible the on-line schedule.

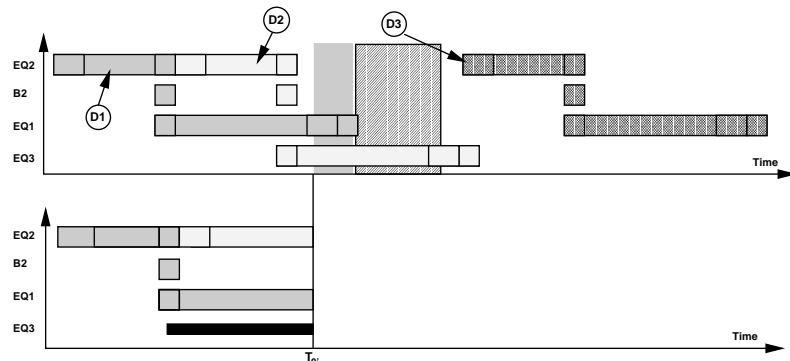


Figure 5.16: Initial situation for the second reschedule. Predicted and real schedule.

5.4. Conclusions

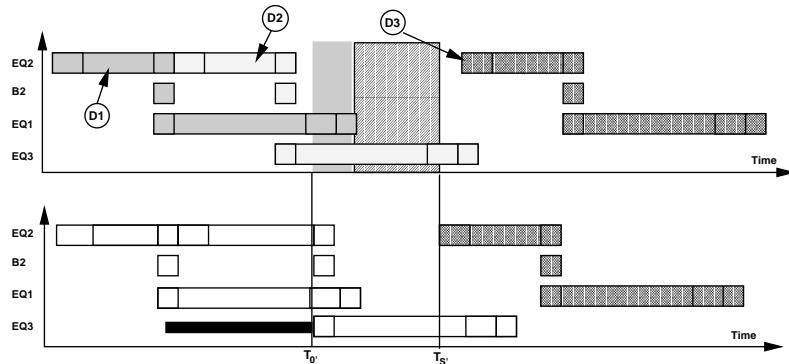


Figure 5.17: End situation for the second reschedule with the schedule send back to the control system shown.

5.4 Conclusions

This chapter has shown the approaches used in this thesis regarding the sequencing assignment and online scheduling.

Dispatching-like rules have been used for the calculation of the material balance, the unit assignment and the batch sequencing. The strength of this approach is based in the easy implementation and adaptation to a batch oriented framework. Additionally, the application of these rules can end up with near optimal schedules as it will be shown in the next chapter where a comparison between the optimization techniques and the sequencing rules will be shown.

These rules can be applied to empty schedules or to schedules that already contain *frozen* batches which represents the actual state of the plant.

The aspects regarding to the use of online information coming from the plant have also been presented as well as the aspects concerning the pre-processing of the schedule.

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Nomenclature

I_m : Initial stock level of material m

I_S : Initial level associated to storage S

$I_{S,m}$: Initial level associated to storage S and material m

MAX_m : Maximum storage capacity for material m

MAX_S : Maximum storage capacity for storage S

MIN_m : Minimum storage capacity for material m

MIN_S : Minimum storage capacity for storage S

$N_m(SC)$: number of level variations of material m in the partial schedule

$N_s(SC)$: Number of level variations associated to storage s

SC : Partial schedule

$V_{m,i}$: Level variations for material m

$V_{S,i}$: Level variations for storage S

$\alpha_{S,i,m}$: Binary variable equal to 1 if the variation $V_{S,i}$ refers to material m