# Proactive/Reactive Approach for Maintenance Tasks in Time Critical Systems

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## Abstract

*The maintenance of systems involved in production processes must be carried out with maximum efficiency and minimum downtime, especially on time-critical systems (operation times are included between a minimum and a maximum value). This paper presents a proactive/reactive control to fit preventive maintenance into a busy production schedule. As preventive maintenance is regarded as a non-preemptive task, P-time Petri Net is used as modelling tool to generate temporal and logical constraints to be considered. To update the tasks scheduling, flexibility on time and on task order is obtained by permitting negative instants in the used firing instant approach. The illustration of the method is made on a graphite ceramic cell.*

## 1. Introduction

Maintenance technicians have generally to choose between various alternatives when they develop preventive maintenance programs. The choices between different maintenance tasks and their related frequencies are carried out qualitatively, thanks to experts opinion, or quantitatively, by comparing various options [2, 3, 10, 14].

This paper focuses on the implementation of a preventive maintenance program on time critical systems (their operation times are represented by time intervals). To avoid down time, we propose to fit preventive maintenance into the production schedule by using a proactive-reactive approach.

The context is the following one:

As the system is operating in a repetitive mode, the maintenance plan is started only if the resource is unoccupied, and the policy to perform this plan is known (for example, to maintain a specific resource, the production rate must be diminished). This leads to a decreasing of the available resources to continue the production and causes a transient functioning during the maintenance phase.

The preventive maintenance is considered here as the occurrence of a planned disturbance reducing the number of available resources. So, the robust proactive/reactive approach presented in [6], initially developed to treat the starting phase of a production system can be extended to this problem. It is the purpose of this paper. This extension necessitates three steps:

- The first one consists of modeling the process flow, the needed resources and the unavailability of these resources due to the preventive maintenance. As the operation times are specified here by time intervals and as the preventive maintenance is performed when the resources are non operative, p-time Petri nets (p-time PN) [7, 11] offer an efficient tool. Their firing rules impose a firing compulsion whatever the activities considered are. This modeling tool provides the set of temporal and logical constraints that the transient scheduling and the repetitive one must ensure.
- The second step aims at computing a static reference schedule. When the system is described by a p-time PN, the scheduling problem consists in setting the firing instant of each transition of the model in order to obtain a desired specification as a definite cycle time, makespan, ... A firing instant approach [1, 4, 5] can be used if the admissible firing sequences have been previously determined by the enumeration phase. So, in the proposed approach, the logical functioning of the model is considered to build the temporal constraints. Via linear programming techniques, these constraints are used to evaluate the performances of the modeled system as well as to determine the exact firing order and instant of each transition for a chosen resource allocation.
- The third step consists in actualizing the static scheduling computed in the second step, to take into account an uncertainty on task duration, the drift of the process parameters due to the deterioration of the production equipment, ... The firing instants must be actualized to inhibit as quickly as possible the effect of disturbances [1].

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Section two covers the modeling of time critical systems by using p-time Petri Net. Firing instant approach and the method to obtain a static periodic schedule is recalled in section three. The proposed extension to integrate preventive maintenance program into a production schedule is given in section four. Some conclusions are given in the last one. An illustration is made on a graphite ceramic cell.

## 2. Modeling step

The distinctive feature of time critical systems is that their operation times are represented by time intervals. Time is essential in these systems because an acceptable behavior depends not only on the logical correctness of the sequence of the tasks, but also on the time of their completion.

Such systems can be found in computer systems as supervision applications requiring consistency of data, in manufacturing systems of the chemical industry where the chemical reagents are efficient during a time interval or in food industry where handling and delivery of the products are subjected to requirements of freshness.

To represent these systems, p-time Petri Net is a convenient tool [7, 11]. As their firing rules impose a firing compulsion whatever the activities considered are, the provided p-time model is more concise than the t-time one.

### 2.1. P-time Petri net

The formal definition of a p-time Petri Net [11] is given by a pair $< N ; I >$ where:

$N$ is a marked Petri Net [8, 9] (1)

$I : \boldsymbol{P} \rightarrow (\boldsymbol{Q}^+ \cup 0) \times (\boldsymbol{Q}^+ \cup +\infty)$

$p_i \rightarrow I_i = [a_i, b_i]$ with $0 \leq a_i \leq b_i$

where $\boldsymbol{P}$ is the set of places of net $N$, $\boldsymbol{Q}^+$ the set of positive rational numbers.

$I_i$ defines the static interval of the operation duration of a token in a place $p_i$. A token in place $p_i$ will be considered in the enabledness of the output transitions of this place if it has stayed for $a_i$ time units at least and $b_i$ at the most. Consequently, the token must leave $p_i$, at the latest, when its operation duration becomes $b_i$. After this duration $b_i$, the token will be "dead" and will no longer be considered in the enabledness of the transitions. A dead token is not removed from the place; this token state indicates that a temporal violation has occurred.

The particularity of this model requires analysis techniques, allowing taking account efficiently of the various functionalities associated with the modeled system, as well as its temporal features. It leads ineluctably to the need for having formal methods ensuring the system control. Indeed, the policy consisting in firing a transition as soon as it becomes enabled is not always feasible and usually leads to a potential constraint violation.

### 2.2. Illustrative example

The line described here (see figure 1) is a workshop manufacturing graphite ceramic electrodes. It is composed of six mixing tanks, two conveyors, two conditioners and one press.

The raw materials (primarily coke and binder pitch) are first mixed together at an elevated temperature in order to obtain an homogeneous mass. The obtained paste is then conditioned (the paste is refreshed to bring down its temperature). Finally, the paste is extruded into the shape and size of end-products. A time interval is associated to each of these operations. This interval represents an uncertainty on the duration (for example, the duration of the conditioning depends on the temperature of the ambient air, of the paste and of the conditioner). This interval may also correspond to the duration in which the good properties of the pitch are preserved (transfer, extrusion…).

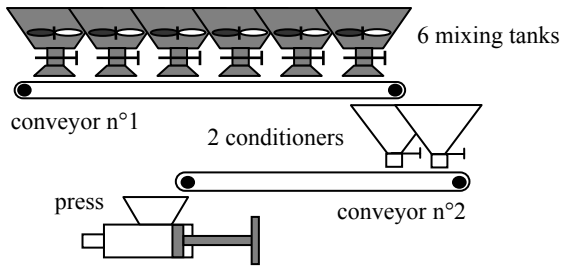



**Figure 1.The graphite ceramic cell considered**

The modeling is made in two steps (figure 2). First, the precedence constraints provided by the process flow (linear part of the graph) are modeled, considering that in a p-time PN, the places are representing the tasks and the transitions are associated with beginning and ending events. Then, the model is completed with the resources needed for the execution of the tasks. For instance, the synchronization structure associated with $t_2$ describes synchronization in a constrained time: it implies that the conveyor n°1 (place $p_9$) and one of the two conditioners (place $p_7$) must be available in a time compatible with the completion of the heating and mixing operation (place $p_1$).

The initial marking corresponds to the inactive workshop, where all resources are available. The marking of place $p_6$ (6) represents the number of mixers, the one of place $p_7$ (2) is the number of conditioners and the one of $p_8$ (1) corresponds to the single press. Notice that only the conditioners need a set-up time before re-using.

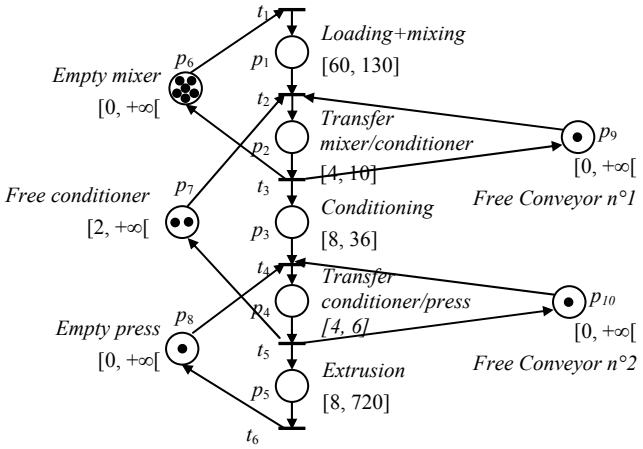



**Figure 2. p-time PN model of the considered cell**

All the constraints of the associated scheduling problem can be extracted from the model. This is the purpose of the following section.

## 3. Static scheduling

### 3.1. Firing instant approach

Enumerative analysis (or exhaustive simulation) aims at exhibiting all the admissible functioning of the modeled system. The selection of one of them is not evoked here, only the constraints extraction is developed. This one is based on the evaluation of the firing conditions for the first, the second, …, and $q^{th}$ firing instant [4].

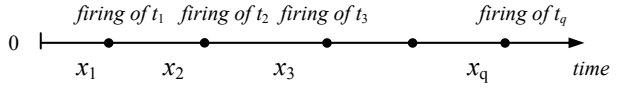



**Figure 3. Firing instants**

*Definition 3.1:* a fired transition denoted by $t_j$ will be associated with the $j^{th}$ firing instant (i.e. the firing sequence considered is $t_1t_2t_3...t_q$). A variable $x_i$ represents the elapsed time between the $(i - 1)^{th}$ and the $i^{th}$ firing instant.

For instance (see figure 3), $(x_2 + x_3)$ is the time elapsed between the first firing instant and the third one.

In a p-time PN, the sojourn time (*i.e. the amount of time that a token has been waiting in a place*) is counted up as soon as the token has been dropped in the place as seen previously. Thus, quantitative (*i.e. performance*) considerations take precedence over qualitative (*i.e. logical*) ones, in opposition to Merlin's time PN model [13]. To compute the firing instants, this approach requires that a token is identified by three parameters: the place that contains it, the information of its creation instant and the information of its consumption one. When a place contains several tokens, they are differentiated by their creation instant values and their consumption one. So, it is possible to impose any token management, but in the sequel a FIFO mode will be considered.

For each token in its place, the minimal and maximal effective sojourn times are evaluated. So, a sequence of transitions $\sigma = t_1, t_2, ..., t_q$ may be fired respectively at firing instants 1, 2,…, $q$ if and only if there exist $x_1 \geq 0$, $x_2 \geq 0$, ..., $x_q \geq 0$ that verify a pyramidal inequalities system $S_\sigma(q)$ (see [4] for more details).

Each left inequality member of this system $S_\sigma(q)$ can be interpreted as the availability of the tokens taking part in the firing of the transition considered, and the right one can be viewed as the "no token(s) death" constraint.

### 3.2. Periodic reference schedule and performance evaluation

*Theorem 3.2* [12]: The behavior of the periodic mode is fully determined by:

$\forall k \geq 1$, $s_i(k) = s_i(k\text{-}1) + \pi$, where $s_i(k)$ is the $k^{th}$ firing date of the transition $t_i$ and $\pi$ the functioning period. (2)

The benefit of this functioning mode [7] is that it suffices to compute the firing instants of the transitions on one cycle and the functioning period to build a repetitive static schedule.

Let us consider a firing sequence $\sigma = (\sigma_t\ \sigma_r)$ where $\sigma_t$ represents the transient functioning leading to a particular repetitive one (represented by $\sigma_r$) and such that the last transition of $\sigma_t$ is the same as the last one of the repetitive sequence $\sigma_r$. Let us denote by $|\sigma_t|$ (resp. $|\sigma_r|$) the length of $\sigma_t$ (resp $\sigma_r$). The lower (resp. upper) bound denoted by $\mu_{\sigma_r}^{min}$ (resp. $\mu_{\sigma_r}^{max}$) of the cycle time of $\sigma_r$ can be computed with the linear programs stated as follows:

$$\mu_{\sigma_r}^{min} = min(\pi) \,/\, \mu_{\sigma_r}^{max} = max(\pi), \quad (3)$$

$$\text{subject to} \quad \pi = \sum_{i=|\sigma_t|+1}^{|\sigma_t|+|\sigma_r|} x_i ,$$

the set of constraints $S_\sigma(|\sigma_t|+|\sigma_r|)$.

And the transient mode duration $\mu_{\sigma_t}$ is given by:

$$\mu_{\sigma_t} = \sum_{i=1}^{|\sigma_t|} x_i \quad (4)$$

A reference periodic schedule of period $\pi_{obj}$, with $\pi_{obj} \in [\mu_{\sigma_r}^{min}, \mu_{\sigma_r}^{max}]$ and the associated transient schedule $\sigma_t$ are obtained via the resolution of the following linear system if there exist $x_1 \geq 0$, $x_2 \geq 0$, ..., $x_i \geq 0$ ..., such that:

$\sum_{i=|\sigma_t|+1}^{|\sigma_t|+|\sigma_r|} x_i = \pi_{obj}$, subject to the set of constraints $S_\sigma(|\sigma_t|+|\sigma_r|)$ (5)

To introduce partial order on the reference sequence, negative firing instants are permitted [6]. New constraints must be added to the set of constraints $S_\sigma(|\sigma_t|+|\sigma_r|)$ to preserve the following properties:

i) all of the firing absolute dates must be non negatives

ii) the semantic of the expression of the cycle time $\pi=\sum_{i=|\sigma_t|+1}^{|\sigma_t|+|\sigma_r|} x_i$ for the repetitive sequence $\sigma_r$. As the firing instants are expressed as relative quantities, and as a cycle time is a positive value, this amounts imposing that the last fired transition must be the last transition of $\sigma_r$, and consequently of $\sigma_t$.

iii) maintaining the same firing occurrences of each transition in the repetitive reference sequence $\sigma_r$, because the generated schedule must be a repetitive one. In others words, the firing instants of the repetitive reference sequence $\sigma_r$ are relevant if they are greater than the transient mode duration.

So, the quantities $x_i$ with $x_i \in \boldsymbol{Q}$ must verify:

$$\begin{cases} \forall\, j \in \{1,...,|\sigma_t|+|\sigma_r|\},\ \sum_{i=1}^{j} x_i \geq 0 \\ \forall\, j \in \{1,...,|\sigma_t|-1\},\ \sum_{i=1}^{j} x_i \leq \sum_{i=1}^{|\sigma_t|} x_i \\ \forall\, j \in \{|\sigma_t|+1,...,|\sigma_t|+|\sigma_r|-1\},\ \sum_{i=1}^{j} x_i \leq \sum_{i=1}^{|\sigma_t|+|\sigma_r|} x_i \\ \sum_{i=1}^{|\sigma_t|} x_i \leq \sum_{i=1}^{j} x_i,\ \forall\, j \in \{|\sigma_t|+1,...,|\sigma_t|+|\sigma_r|\} \end{cases} \quad (6)$$

### 3.3. Application

Using the logical behavior of the model of figure 2, to obtain a steady state using all the mixers, the reference firing sequence $\sigma=(\sigma_t\ \sigma_r)$ is the following one: $\sigma_t=(t_1\,t_1\,t_1\ t_1\ t_1\ t_1\ t_2\ t_3\ t_1)$ and $\sigma_r=(t_2\ t_3\ t_4\ t_5\ t_6\ t_1\ )$, and the associated firing instant vector is: $(x_1\ x_2\ \ x_3\ x_4\ x_5\ x_6\ x_7\ x_8\ x_9\ x_{10}\ x_{11}\ x_{12}\ x_{13}\ x_{14}\ x_{15})$.

The system $S_\sigma(|\sigma_t|+|\sigma_r|)$ completed by the added constraints allowing the negative instants is given by (7).

So, the linear programs to evaluate performance are:

$\mu_{\sigma_r}^{\min} = \min(\pi)$, $(\mu_{\sigma_r}^{max} = \max(\pi))$, with $\pi = \sum_{i=10}^{15} x_i$, subject to the constraints (7).

Performance evaluation gives $[\mu_{\sigma_r}^{min}, \mu_{\sigma_r}^{max}]=[12, 26]$ and the associated selected orders are the following ones:

for $\mu_{\sigma_r}^{min}$ : $\sigma_t=(t_1\ t_1\ t_1\ t_1\ t_1\ t_1\ t_2\ t_3\ t_1)$ $\sigma_r=(\ t_2\ t_4\ t_3\ t_5\ t_6\ t_1\ )$

for $\mu_{\sigma_r}^{max}$ : $\sigma_t=(t_1\ t_1\ t_1\ t_1\ t_2\ t_3\ t_1\ t_1\ t_1)$ $\sigma_r=(t_2\ t_3\ t_4\ t_5\ t_6\ t_1)$

These results illustrate the benefits of the firing instant approach. Permutations in the reference sequence established on the associated underlying un-timed net are observable in the transient mode as well as in the repetitive one.

$$\begin{cases} 0 \leq x_1 \leq +\infty \\ 0 \leq x_1+x_2 \leq +\infty \\ 0 \leq x_1+x_2+x_3 \leq +\infty \\ 0 \leq x_1+x_2+x_3+x_4 \leq +\infty \\ 0 \leq x_1+x_2+x_3+x_4+x_5 \leq +\infty \\ 0 \leq x_1+x_2+x_3+x_4+x_5+x_6 \leq +\infty \\ 60 \leq x_2+x_3+x_4+x_5+x_6+x_7 \leq 130 \\ 4 \leq x_8 \leq 10 \\ 0 \leq x_9 \leq +\infty \\ 4 \leq x_{11} \leq 10 \\ 4 \leq x_{13} \leq 6 \\ 8 \leq x_{14} \leq 720 \\ 0 \leq x_{15}+x_{10}+x_{11}+x_{12} \leq +\infty \\ 0 \leq x_{12}+x_{13}+x_{14}+x_{15} \leq +\infty \\ 60 \leq 5\cdot(x_{10}+x_{11}+x_{12}+x_{13}+x_{14}+x_{15})+x_{10} \leq 130 \\ 2 \leq x_{14}+x_{15}+x_{10} \leq +\infty \\ 8 \leq x_{12}+x_{13}+x_{14}+x_{15}+x_{10}+x_{11}+x_{12} \leq 36 \\ \pi = \sum_{i=10}^{15} x_i \\ 60 \leq x_3+x_4+x_5+x_6+x_7+x_8+x_9+x_{10} \leq 130 \\ 60 \leq x_4+x_5+x_6+x_7+x_8+x_9+\pi+x_{10} \leq 130 \\ 60 \leq x_5+x_6+x_7+x_8+x_9+2.\pi+x_{10} \leq 130 \\ 60 \leq x_6+x_7+x_8+x_9+3.\pi+x_{10} \leq 130 \\ 60 \leq x_7+x_8+x_9+4.\pi+x_{10} \leq 130 \\ 8 \leq x_9+x_{10}+x_{11}+x_{12} \leq 36 \end{cases} \quad (7)$$

$$\cup \begin{cases} \sum_{i=1}^{j} x_i \geq 0,\ \forall\, j \in \{1,...,15\} \\ \sum_{i=1}^{j} x_i \leq \sum_{i=1}^{9} x_i,\ \forall\, j \in \{1,...,8\} \\ \sum_{i=1}^{j} x_i \leq \sum_{i=1}^{15} x_i\ \forall\, j \in \{10,...,14\} \\ \sum_{i=1}^{9} x_i \leq \sum_{i=1}^{j} x_i\ \forall\, j \in \{10,...,15\} \end{cases}$$

## 4. Preventive Maintenance Program

### 4.1. Modeling preventive maintenance state

According to the considered context, p-time Petri Net tool remains efficient to represent the maintenance state of a piece of equipment. Indeed, preventive maintenance is seen here as the temporary loss of some unoccupied resources and is regarded as a non-preemptive task. Moreover, as our problem is not to find the best maintenance strategy but to fit it into the production schedule, it requires a deterministic model. The possible states of a resource are (free, operating or maintenance), the failure states or others are not taken into consideration. Consequently, to model the unavailability state due to preventive maintenance, places and choice structures must be added. For instance, for the illustrative example, the model (Figure 2) becomes:

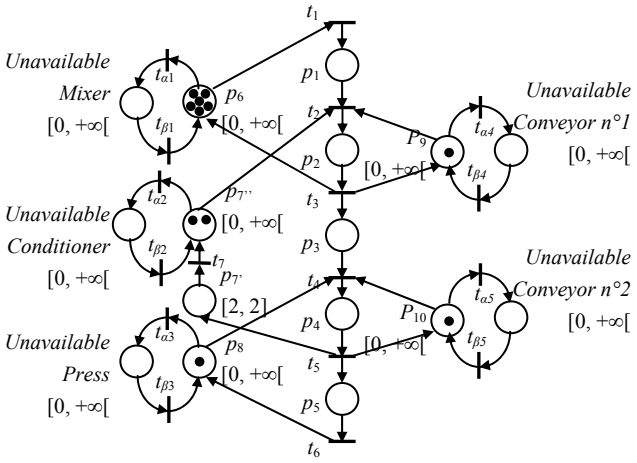



**Figure 4. p-time PN model of the considered maintenance**

The time interval associated to the added places can be used to specify the maintenance down time if they are known.

### 4.2. Control integrating preventive maintenance plan

As the firing instants method does not require strongly properties on the model net, the introduced choice structures do not generate particular problem. To extend this method to implement preventive maintenance plan, it is necessary to take into account the work-in process. The maintenance of systems involved in production processes must be carried out with maximum efficiency and with minimum downtime.

Consequently, fitting preventive maintenance plan into a busy production schedule will be tantamount to determining the firing instant of the following sequence $\sigma = (\sigma_r\ \sigma_t\ \sigma_{r'})$ where:

- $\sigma_r$ : reference periodic sequence of the current functioning
- $\sigma_t$ : sequence associated to the preventive maintenance phase
- $\sigma_{r'}$ : reference periodic sequence of the new functioning with possibly less resources.

For the illustrative cell, assume that the reference periodic sequence of the current functioning is given by $\sigma_r = (\ t_1\ t_2\ t_3\ t_4\ t_5\ t_7\ t_6\ )$. This sequence is firable for the following marking M=(5,0,1,0,0,1,1,0,1) corresponding to one of the states of this steady state. This busy production schedule uses all the resources of the cell.

To make maintenance on the press which is unique, the logical behavior of the model of figure 4 allows writing $\sigma = (\sigma_r\ \sigma_t\ \sigma_{r'})$ with:

$\sigma_r = (\ t_1\ t_2\ t_3\ t_4\ t_5\ t_7\ t_6\ )$,

$\sigma_t = (t_{\alpha 3}\ t_{\beta 3}\ t_1\ t_2\ t_3\ t_4\ t_5\ t_7\ t_6)$,

$\sigma_{r'} = (\ t_1\ t_2\ t_3\ t_4\ t_5\ t_7\ t_6\ )$,

and the transitions considered for the sequence order revision are only the ones following transition $t_{\alpha 3}$ . So, from this sequencing based on the logical constraints, a system of inequalities is built. Some constraints are added in order to ensure the good management of the work-in process. Via linear programming, the schedule corresponding to this scenario is given on a Gantt Diagram (see figure 5).

To make maintenance on a mixer, which is non unique, $\sigma = (\sigma_r\ \sigma_{t\alpha}\ \sigma_{r'})$ becomes:

$\sigma_r = (\ t_1\ t_2\ t_3\ t_4\ t_5\ t_7\ t_6\ )$,

$\sigma_{t\alpha} = (\ t_{\alpha 1}\ t_2\ t_3\ t_4\ t_5\ t_7\ t_6)$,

$\sigma_{r'} = (\ t_1\ t_2\ t_3\ t_4\ t_5\ t_7\ t_6\ )$.

Notice that in $\sigma_r$ , all the mixers are in use while in $\sigma_{r'}$ only five mixers are available. When the mixer in maintenance is available again, its insertion requires studying the sequence $\sigma = (\sigma_{r'}\ \sigma_{t\beta}\ \sigma_r\ )$ with $\sigma_{t\beta} = (\ t_{\beta 1}\ t_2\ t_3\ t_4\ t_5\ t_7\ t_6)$.

This strategy is very interesting when the maintenance duration is unknown because it is possible to use the periodic functioning mode properties to preserve production flow.

The schedule corresponding to the suspension of a mixer due to maintenance is given on a Gantt Diagram (see figure 6), and its restarting on figure 7.

If the preventive maintenance strategy requires a lower production rate in order to adapt it to the set of the available resources, the sequence $\sigma_t$ must be established by mean of enumerative approach [5] because the logical behavior of the underlying un-timed net is not sufficient. It is the case to achieve maintenance on a conditioner in the illustrative example.

## 5. Conclusion

In this paper, the implementation of a preventive maintenance program into a busy production schedule on time critical systems was proposed. This problem is viewed as the occurrence of a planned disturbance reducing the number of available resources. So, the proposed method is based on a proactive/reactive approach. It uses p-time Petri Net as modeling tool because preventive maintenance is regarded as a non-preemptive task. So, from a sequencing based on the logical constraints including the preventive maintenance phase, a system of temporal inequalities is built. The firing instants approach allows a possible re-ordering of the firing instants to guarantee the good management of work-in-process. Via linear programming, schedule in transient and repetitive mode are evaluated. One of the prospects of this work is to use firing instants approach to build robust temporal control in case of breakdown of a piece of equipment.

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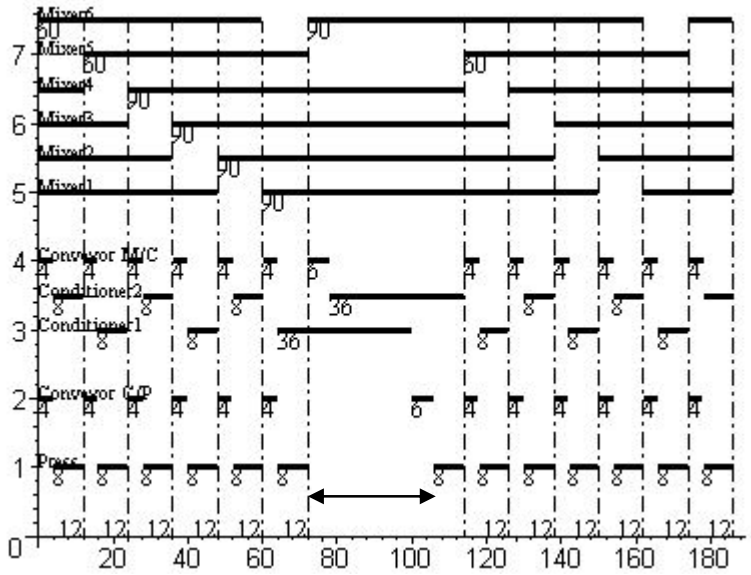




**Figure 5. press maintenance ( ⟷ )**

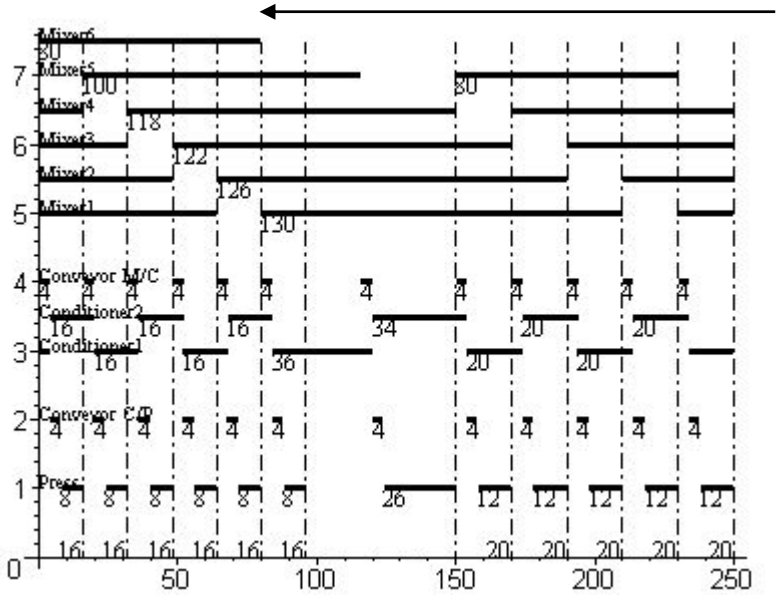



**Figure 6. maintenance of mixer 6**

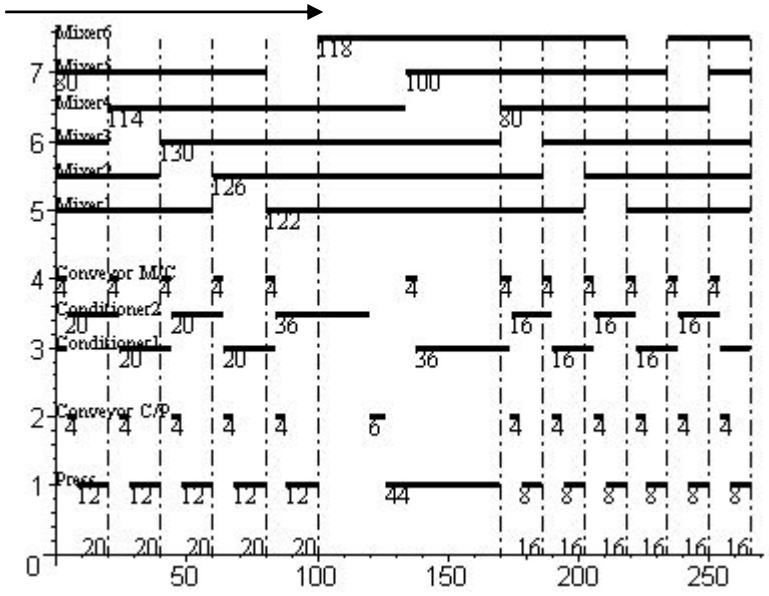



**Figure 7. restarting of mixer 6**