International Journal of Industrial Engineering, 15(3), 266-277, 2008.

Electroplating Line Flexible Control Using P-Time Petri Nets Modeling and Hoist Waiting Times Calculation

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In automated electroplating lines, product quality depends on soak times in chemical tanks while line throughput depends on hoist moves cycle time. These parameters are antagonistic since on-line tuning of cycle time interferes with processing duration and thus quality, and vice versa. Furthermore, on-line tuning actions performed without exploiting process flexibility may affect hoist moves schedule feasibility and call for complex scheduling at the on-line level. In this paper a flexible control for electroplating lines (EPL) is proposed that allows quality and throughput tuning within calculated margins and with no need for hoist moves rescheduling. Firstly a P-time Petri Nets (P-time PNs) tool is used to model hoist move sequence. Afterwards, linear programs (LP) are proposed to determine cycle time and soak times tuning margins without the need to reschedule hoist moves. Flexibility will be achieved using empty-hoist wait times.

Significance: Electroplating lines are essential in the finishing of several products. On-line tuning of throughput and quality are often required given product shape, batch size, time delays and process variability. The significance of this control is to allow tuning actions without hoist moves rescheduling, particularly when hoist scheduling is known to be NP-Hard.

Keywords: Electroplating line, P-time Petri nets, Flexibility, Linear programming, Hoist, Cyclic, Scheduling.

(Received 7 April 2008; Accepted in revised form 11 October 2008)

1. INTRODUCTION AND BACKGROUND

Several semi-finished products require plating operations to protect, decorate, or enhance their surface properties (coloring, coating, etc…). Plating operations are carried out in automated electroplating lines. Typical treatment sequences in these processes start by loading parts into carriers to be transferred and immersed in chemical tanks using several computerised hoists. Tanks may contain corrosive baths such as sulphuric acid, metallic solutions such as gold, or simply rinsing water.

Considering the technological complexity and economical importance of electroplating lines control, several researchers devoted their efforts to the problem of finding efficient hoist move schedules. Products are usually treated in batches which lead to cyclic hoist moves. This problem is also known as the Cyclic Hoist Scheduling Problem (CHSP). A feasible solution of the CHSP depends on the respect of product treatment sequences (routings), soak time intervals in chemical tanks, tank capacities and hoist capacities. In addition, hoist loaded moves must be executed with no wait times to avoid product surface oxidation during transfer.

The CHSP has been proved NP-hard for a single hoist line in 1-carrier cycle functioning mode (Lei *et al*., 1989). Several quality contributions were made to the CHSP. The earliest solutions based on mathematical programming were proposed in (Phillips *et al*., 1976); (Shapiro *et al*., 1988). Since then, many studies were conducted on a multitude of aspects related to electroplating lines. These aspects involved on-line scheduling search (Chauvet *et al*., 2000); (Thesen *et al*., 1990); (Yih, 1994); multi-hoist lines (Che *et al.,* 2004); (Lei et al., 1991); (Leung *et al*., 2004); and lines with redundant or multi-function tanks (Che *et al*., 2005); (Liu et al., 2002); (Zhou *et al*., 2003).

Most of the existing approaches focus on searching an efficient hoist moves schedule (or a minimum cycle time hoist moves sequence), which is important given the bottleneck usually caused by slow chemical reactions. However, as explained in (Chetouane, *et al*., 2007), chemists and electroplating line operators are mostly interested by flexible control approaches which allow on-line tuning actions without affecting hoist schedule feasibility, particularly when faced with time delays, change in hoist speed, change in batch size or drifts in chemical bath concentrations. Such actions are unavoidable and necessary to keep up with quality requirements and changes in product demand: if a drift is recorded in a chemical bath concentration, product soak times need to be adjusted to maintain surface quality without causing additional delay. Also, if a delay is caused during carrier loading, hoist cycle time must be adjusted without affecting targeted soak times. Once an efficient hoist sequence is programmed on hoist controllers it will be complicated to search and program another sequence every time a tuning action is performed. In this paper an on-line control layer made of linear programming (LP) and Petri nets (PNs) models is proposed for addition to any off-line schedule to allow such flexibility. This idea is based on empty-hoist wait time calculation. The paper is organised as follows: in section 2, a brief example of a single hoist electroplating line in cyclic operating mode is illustrated to describe how these systems work, and also to introduce symbols and notations that will be used in the rest of the paper. Section 3 introduces the use of P-time Petri nets (P-time PNs) for modeling hoist moves sequence and time constraints characterising electroplating lines. A taxonomy of the P-time PN critical circuits is also proposed in this section. These critical circuits are then analysed in section 4 to obtain LPs which will be used for cycle time interval computation. This interval contains an infinite number of cycle time values at which the hoist could function without changing its moves sequence. This characterises the flexibility of our approach since other approaches propose only one hoist schedule with a unique cycle time value (usually the minimum). Based on the developed LP models, we show in sub-sections (4.1) and (4.2) how to exploit this flexibility to allow cycle time and soak times tuning without changing hoist moves sequence. An illustrative example is detailed in section 5 to show how to integrate the proposed approach in the electroplating line control system. Further discussions and conclusions are presented in section 6.

2. ELECTROPLATING LINES: CHARACTERISTICS AND NOTATIONS

Automated electroplating lines are fundamentally made of a set of chemical tanks and a set of computerized hoists moving on a shared or dedicated track suspended above the tanks. The usual length of a single hoist line can average 60 meters and may contain more than 50 different chemical baths. To save space several layouts shapes can be found in practice such as "I", "L", "O", and "U". Hoist are computerised and powered by embedded electric motors. Hoist speed may vary between 0.5 and 4 meters per second; it is mostly kept constant to ensure synchronisation with chemical tank durations. It is important to avoid retrieving a carrier from a tank before it finishes its treatment. It is also important not to allow the carrier to remain beyond a certain time inside a tank; otherwise product surfaces may be damaged. Thus, soak times are defined by an interval for each tank. In practice it is common to vary soak times within their interval to cope with changes in product size or in chemical bath concentration. A typical hoist may have a load capacity range between 200 and 5,000 kilograms, and it can lift a carrier containing more than 200 articles requiring treatment. When traveling loaded, to prevent product oxidation, a hoist is not allowed to wait in mid-air. Wait times are only permitted on empty-hoist moves. Processing sequences start by loading a carrier on the hoist usually by a human operator at a loading station. Small delays may be introduced at this stage due to lack of consistent repetitive operator behaviour. The carrier will be transferred between tanks according to its established routing. To avoid baths pollution, rinsing tanks are inserted between different chemical tanks. There is no maximum soak time limit in rinsing tanks. Processing sequences end by unloading the carrier from the hoist at an unloading station. For "L" and "U" shaped layouts, loading and unloading stations are usually separate and a group of hoists may be used for each straight track of the layout. In "O" shaped layout loading and unloading operations are done from the same station. An "I" shaped layout may have joint or separate loading and unloading stations and several hoists if the line is lengthy. This paper addresses the case of a single hoist "I" shaped line with a joint loading and unloading station (see Figure 1). The proposed control approach can be easily applied to other layouts.

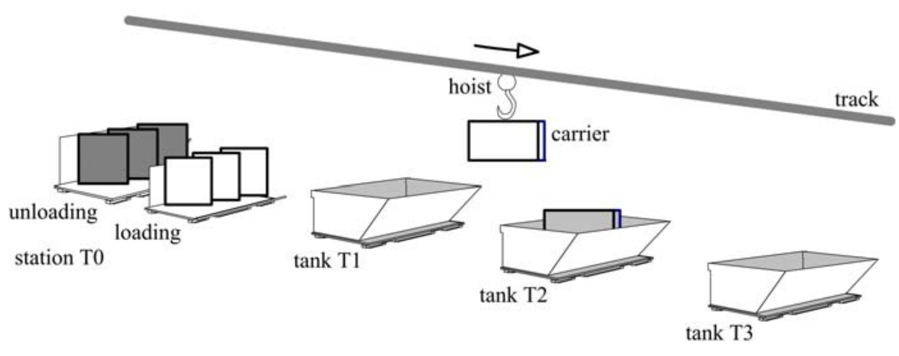


Figure 1: Single hoist electroplating line with three chemical tanks

Electroplating lines function in batch production mode thus hoist moves are usually performed in repetitive way (cyclic moves pattern). Cycle time is defined as the duration separating the launch of two successive carriers. As an example of a hoist moves sequence that may be performed on the line shown in Figure 1, a cycle may start by carrier number "j" being loaded at station T_0. Once loading is completed, the hoist moves carrier "j" and drops it in tank T_1. An empty-hoist move is then performed from tank T_1 to pickup a previously launched carrier numbered "j-1" from tank T_2 and to transfer it to tank T_3. At tank T_3, the hoist remains stationary and waits for carrier "j-1" to finish its treatment. This may be the case when soak time in a tank is short compared to hoist travel time causing the hoist to wait for the carrier to complete its treatment instead of using the time to perform other operations. Once its treatment in tank T_3 is completed, carrier “j-1” is transferred to station T_0. From there, hoist leaves empty to tank T_1 to pick up carrier “j” and to drop it in tank T_2. Afterwards, the hoist returns empty to station T_0 to start a new cycle by launching carrier number “j+1”.

Main characteristics of electroplating line models are: hoist travel times are not negligible, chemical treatment times are bounded, transfer must be performed with no-wait, a tank can treat only one carrier at time, a hoist can transfer only one carrier at time, a hoist may remain above a tank waiting for a carrier to complete its treatment or it may use that time to perform other operations on the line, hoist load has no effect on its speed or travel time, waiting times are allowed on free hoist moves, loading and unloading times are usually included in loaded move durations, and products must be processed according to their routing. Respect of these characteristics determines the feasibility of a hoist moves sequence (schedule) while cycle time length determines the efficiency of the schedule. In this paper we assume that product type doesn’t change over the production horizon, thus processing sequence is cyclic and identical for all carriers. To address the control problem in the rest of the paper, the following nomenclature will be used to designate electroplating line parameters:

- T_0 : loading / unloading station
- T_i : chemical tanks, $i = 1, 2\ldots n$
- a_i : minimum soak time in tank T_i
- b_i : maximum soak time in tank T_i. Rinsing tanks have no upper bounds (related b_i are set to large values, e.g. $+\infty$)
- d_i : effective time spent by a carrier in tank T_i. $a_i \le d_i \le b_i$ for $i = 0,1...n$
- $c_{i,j}$: minimum time for the hoist to move empty from T_i to T_j. $c_{i,i} = 0$, $c_{i,j} = c_{j,i}$
- $w_{i,j}$: additional waiting time above tank T_j since hoist arrives from T_i
- ℓ : time required for loading or unloading a carrier
- h_i : loaded hoist travel time from tank T_i to tank T_{i+1}, $h_i = c_{i,i+1} + \ell$
- C : hoist moves sequence cycle length.

3. P-TIME PETRI NETS AND HOIST MOVES SEQUENCE MODEL

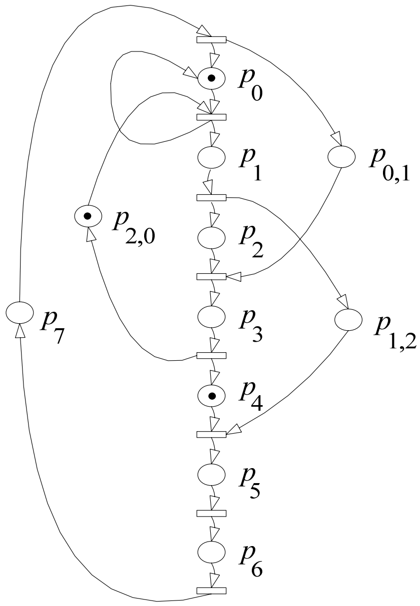
In a time PNs, a time interval is associated either with each transition or with each place, and accordingly the models will be called T-time or P-time PNs. P-time PNs were introduced by W. Khansa and co-workers (Khansa *et al*., 1996). The model was defined for time-constrained systems where the sojourn time in some state must have a value between a minimum and a maximum limit. This is the case for systems which may be found in various domains such as electroplating, thermic treatments, and perishable food distribution. P-time PN is appropriate to describe time constraints in electroplating lines (Chetouane et *al*., 2004). A P-time PN is a pair $\langle R, I_0 \rangle$, where R is a marked PN and I_0 a function defined from the set of the Petri net places P to the domain $Q^+ \cup \infty \otimes Q^+ \cup \infty$ as:

$$I_0 : P \to Q^+ \cup \infty \otimes Q^+ \cup \infty$$
$$p_i \mapsto [q_{i,min}, q_{i,max}] \text{ with } 0 \le q_{i,min} \le q_{i,max} \ \forall p_i \in P$$

Q^+ is the set of positive rational numbers, I_0 a function that assigns a stay time interval for every place p_i. A token in p_i is available for transition validations if and only if its stay time q_i falls within the interval $[q_{i,\,min}, q_{i,\,max}]$. Otherwise, the token is said to be unavailable ($q_i < q_{i,\,min}$) or dead ($q_i > q_{i,\,max}$). P-time PN tool allows powerful modeling characteristics of several PN classes, such as timed PNs ($q_{i,\,max} = \infty$) or fixed time PNs ($q_{i,\,min} = q_{i,\,max}$). In addition it has the unique capability of modeling time intervals on treatment operations in an electroplating process. This is not possible using timed PNs, because the later can only model minimum part soak times.

In this section we show how P-time PN tool can be used to model and analyse a given hoist moves sequence. As an example, Figure 2 presents the P-time PN model of the hoist moves sequence described in the previous section for the electroplating line of Figure 1.

The P-time PN model can be explained as follows: Tank T_i is represented by place p_{2i} for i = 0, 1, 2…n (here n=3). A loaded-hoist move from tank T_i to T_{i+1} is represented by place p_{2i+1} for i = 0, 1, 2…n-1. The loaded move from tank T_n to T_0 is represented by place p_{2n+1}. Forward empty-hoist moves are represented on the right side of the P-time PN while backward empty moves are represented on the left side. An empty move from tank T_i to T_j is represented by place $p_{i,j}$. After completing its empty move $p_{i,j}$ a hoist may need to wait an additional time $w_{i,j}$ before picking up a carrier from tank T_j. This is the case when a hoist arrives early and waits for a carrier to complete its treatment. Every time a hoist picks up a carrier it must transfer it immediately to the next tank with no additional waiting time; failure to do so could result in part surface oxidation. Therefore waiting times are allowed only when the hoist moves empty.



places	operations and associated time interval
p_0	loading/unloading at station T_0: $[a_0 , b_0]$
p_1	hoist moves carrier from T_0 to T_1: $[h_0 , h_0]$
p_2	carrier treatment in tank T_1: $[a_1 , b_1]$
p_3	hoist moves carrier from T_1 to T_2: $[h_1 , h_1]$
p_4	carrier treatment in tank T_2: $[a_2 , b_2]$
p_5	hoist moves carrier from T_2 to T_3: $[h_2 , h_2]$
p_6	carrier treatment in tank T_3: $[a_3 , b_3]$
p_7	hoist moves carrier from T_3 to T_0: $[h_3 , h_3]$
$p_{0,1}$	empty move from T_0 to T_1: $[c_{0,1}+w_{0,1} , c_{0,1}+w_{0,1}]$
$p_{1,2}$	empty move from T_1 to T_2: $[c_{1,2}+w_{1,2} , c_{1,2}+w_{1,2}]$
$p_{2,0}$	empty move from T_2 to T_0: $[c_{2,0}+w_{2,0} , c_{2,0}+w_{2,0}]$

Tokens are black dots inside active operations

Figure 2: P-time PN model for cyclic hoist moves sequence

A token can indicate a carrier inside a tank (place p_{2i}, on Figure 2), a hoist moving empty to a station or waiting on top of it (place $p_{i,j}$), or a hoist moving loaded between stations (place p_{2i+1}). The number of token in a place p represents its marking. One can assign a generalised notation $\mu(p)$ to the stay time duration for a token in a place p according to one of the following cases:

$$\mu(p) = d_i \text{, for } p = p_{2i} \text{, } i = 0,1...n \quad \text{(if p models a tank operation)} \quad \ldots \quad (1)$$

$$\mu(p) = h_i \text{, for } p = p_{2i+1} \text{, } i = 0,1...n \text{ (if p models a loaded hoist move)} \quad \ldots \quad (2)$$

$$\mu(p) = c_{i,j} + w_{i,j} \text{, for } p = p_{i,j} \text{, } i \neq j \text{, and } i, j = 0,1...n \text{ (if p models an empty hoist move)} \ldots \quad (3)$$

The P-time PN model for hoist moves sequence in electroplating lines can contain only four types of circuits which are defined using the following classification approach proposed in (Chetouane *et al.,* 2001):

- *Processing sequence circuit*: This circuit is unique for the single part type case (the model can contain only one) and is formed by the set of places $\{p_0, p_1, ...p_{2i}, p_{2i+1}, ...p_{2n+1}\}$. This circuit models part processing sequence consisting exclusively of loaded hoist moves and tank operations (including loading and unloading stations).
- *Hoist moves circuit*: This circuit is also unique. It contains places modeling all hoist movements: loaded ones (p_{2i+1}) and empty ones ($p_{i,j}$). It also contains places (p_{2i}) if the hoist waits for a carrier on top of tank T_i. In the single hoist case the circuit contains only one token. For multiple hoists sharing the same track, the total number of tokens in this circuit represents the total number of hoists in the electroplating line.
- *Single backward move circuits*: The number of these circuits is greater or equal to one ($n_b \geq 1$). A single backward move circuit contains a unique place ($p_{i+1,j}$, $j \prec i+1$) modeling a hoist backward empty move (located on the left side of the P-time PN) and the set of places $\{p_{2j+1}, p_{2j+2}, ...p_{2i}, p_{2i+1}\}$ modeling tank and loaded-hoist move operations.
- *Single forward move circuits*: The number of these circuits is greater or equal to one ($n_f \geq 1$). A single forward move circuit contains a unique place ($p_{j,i}$, $i \succ j$) modeling an empty-hoist forward move (located on the right side of the P-time PN) and all places modeling tank and loaded hoist operations except the set $\{p_{2j}, p_{2j+1}, ...p_{2i}\}$.

This classification can be helpful in the circuit search process, especially in the case where the P-time PN model contains a large number of places. In the next section an analysis approach of these circuits is proposed to compute cycle time interval and soak times margins. It will be shown how these margins can be used for on-line tuning actions without affecting the P-time PN structure, and thus, the hoist moves sequence.

4. PROCESSING SEQUENCE ANALYSIS AND FLEXIBLE CONTROL USING P-TIME PETRI NETS

Let Ω be the set of all elementary circuits of the P-time PN hoist sequence model. According to the previous classification the total number of circuits in a P-Time PN model of an electroplating line is "$n_b + n_f + 2$". The set Ω can be expressed as: $\Omega = \{\omega\langle j\rangle : j = 1, 2....n_b + n_f + 2\}$, where $\omega\langle j\rangle$ is a given elementary circuit. If $M(\omega\langle j\rangle)$ denotes the total number of tokens in a circuit $\omega\langle j\rangle$, the common mean cycle time value for all circuits in a cyclic functioning mode is given by equation (4):

$$C(\omega\langle j\rangle) = \frac{\sum_{p_i \in \omega<j>} \mu(p_i)}{M(\omega\langle j\rangle)} \quad \dots \quad (4)$$

System (4) contains "$n_b + n_f + 2$" equations. Based on equations (1) to (4) for circuits $\omega\langle j\rangle \in \Omega$, we can write the following LP model:

Goals: Minimise cycle time C, and then, Maximise cycle time C
Subject to:

$$M(\omega\langle j\rangle) \cdot C = \sum_{p_{2i} \in \omega\langle j\rangle} \mu(p_{2i}) + \sum_{p_{2i+1} \in \omega\langle j\rangle} \mu(p_{2i+1}) + \sum_{p_{g,k} \in \omega\langle j\rangle} (c_{g,k} + w_{g,k}), \text{ with } \begin{matrix} j = 1, 2..., n_b + n_f + 2 \\ i, g, k \in \{0, 1..., n\} \\ g \neq k \end{matrix} \quad \dots \quad (5)$$

$$a_i \le \mu(p_{2i}) \le b_i, \text{ with } p_{2i} \in \omega\langle j\rangle, \; j = 1, 2..., n_b + n_f + 2, \text{ and } i = 0, 1..., n \quad \dots \quad (6)$$

$$w_{g,k} \ge 0, \text{ with } \begin{matrix} p_{g,k} \in \omega\langle j\rangle, \text{ for } g, k \in \{0, 1..., n\} \text{ and } g \neq k \\ j = 1, 2..., n_f + n_b + 2 \end{matrix} \quad \dots \quad (7)$$

In equations (5) and (6), $\mu(p_{2i}), i = 0, 1, 2..., n$ represent soak times in chemical tanks. For each tank T_i, $i = 1, 2..., n$, soak time can be selected by a chemist according to surface quality requirements using equation (6). Minimum time duration d_0 is required to load/unload a carrier at station T_0. Because there is no chemical treatment at this station an upper bound b_0 is not defined or can be fixed to an infinite value.

By minimising and maximising cycle time the LP model allows determination of the interval $[C_{min}, C_{max}]$ in which the cycle value C may be adjusted without changing the hoist moves sequence. The cycle time interval allows characterisation of the intrinsic flexibility of the cyclic hoist moves sequence. It also gives a wide selection of possible cycle time values for throughput control or load balancing between several connected electroplating lines in the case of U, L, or H configurations.

4.1 Set-point and disturbances

A set-point can be defined by a desired cycle value $C \in [C_{min}, C_{max}]$ and a set of soak time values $\{d_i, i = 1...n\}$ at which the electroplating line may be programmed to operate for a particular cyclic hoist moves sequence. The concept of set-point is necessary to ensure repeatability of surface quality and to maintain the electroplating line's throughput at specified value. A target set-point will be designated by $(C, \{d_i\})$.

In the vicinity of a target set-point, the electroplating line is continuously subject to disturbances that may occur inside or outside its process. These disturbances require tuning actions to keep the desired cycle or soak time values. For instance, if a part with a similar processing sequence but of a different size is launched, it becomes necessary to adjust soak time durations by a value $\pm\Delta d_i, i = 1,..., n$ due to the difference in surface size. It is also required to adjust soak time durations in the case of a drift in bath concentration due to ambient temperature variations or to pollutants. A flexible control system must be able to allow tuning actions $\pm\Delta d_i, i = 1,..., n$ without affecting the set-point cycle time value (throughput) and hoist moves sequence feasibility. We refer to this ability as *processing durations flexibility*.

Likewise, the cycle time value can be disturbed by voluntary or involuntary events. For instance, if line balancing or throughput control is required, it becomes necessary to tune cycle time by a value $\pm\Delta C$. A similar situation where tuning of cycle time may be required is when a time delay is introduced by an operator during loading a carrier on the hoist, or by the hoist slipping on the track. A flexible control system must be able to allow tuning actions $\pm\Delta C$ without affecting set-point soak time values (quality) and hoist moves sequence feasibility. We refer to this ability as cycle time flexibility.

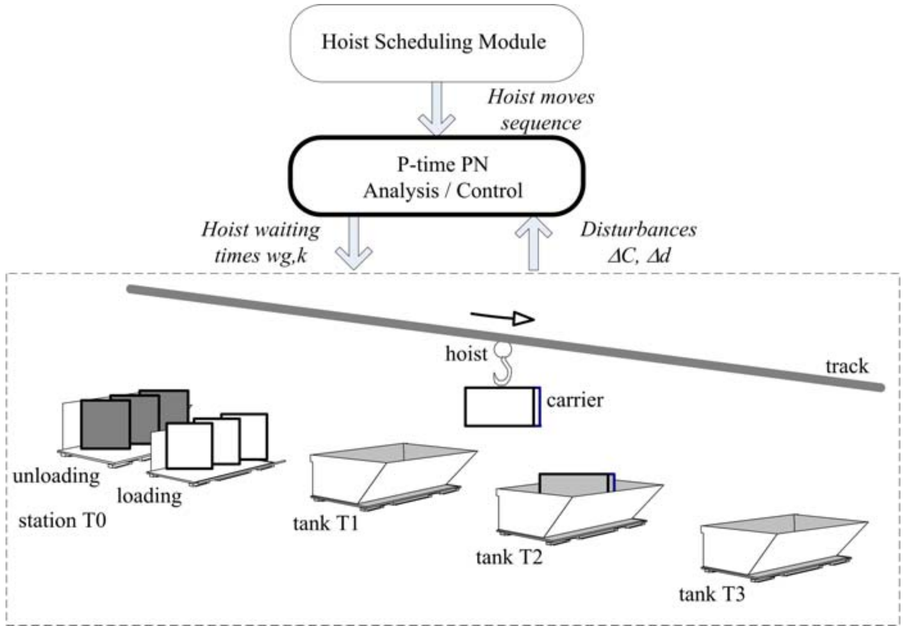


Figure 3: Single hoist electroplating line with three chemical tanks

Figure 3 shows the integration of these flexibility types by adding a P-time PNs control level to the control architecture. The hoist sequence is programmed using P-time PN and analysed based on LP models (5), (6) and (7). If tuning actions $\pm\Delta d_i, i = 1,...,n$ or $\pm\Delta C$ are required due to disturbances, the control level re-computes, in real time, new values for empty-hoist waiting times to maintain the desired set-point and hoist moves sequence feasibility. In the following sections, the computation of empty-hoist waiting times will be detailed for each type of flexibility.

4.2 Cycle time flexibility model

Let us consider a cyclic functioning mode defined by the set-point $(C, \{d_i\})$, where $C_{min} \le C \le C_{max}$ and $a_i \le d_i \le b_i, i = 0,1...n$. Hoist waiting time values for this set-point are $w_{g,k}$. If cycle time is adjusted to a new target value $C^* : C^* = C \pm \Delta C$, new waiting time values $w^*_{g,k}$ must be determined by the control system to maintain prescribed soak times $\{d_i, i = 0,1...n\}$ and hoist moves feasibility. Introducing the new cycle time target value in the previous LP model constraints (5) leads to the following equation (8):

$$M(\omega\langle j\rangle)\cdot C^* = \sum_{p_{2i}\in\omega\langle j\rangle} d_i + \sum_{p_{2i+1}\in\omega\langle j\rangle} h_i + \sum_{p_{g,k}\in\omega\langle j\rangle} (c_{g,k} + w_{g,k}) \pm M(\omega\langle j\rangle)\cdot \Delta C \text{, with } \begin{matrix} j = 1, 2..., n_b + n_f + 2 \\ i, g, k \in \{0, 1..., n\} \\ g \ne k \end{matrix} \quad \ldots \quad (8)$$

One of the equations (8) is linked to the processing sequence circuit. This circuit does not contain places $p_{g,k}$. Thus, new empty-hoist move waiting times $w^*_{g,k}$ can be calculated using the remaining equations (10) and (11) defined below:

$$\sum_{p_{g,k}\in\omega\langle j\rangle} w^*_{g,k} = \sum_{p_{g,k}\in\omega\langle j\rangle} w_{g,k} \pm M(\omega\langle j\rangle)\cdot \Delta C \text{, with } \begin{matrix} j = 1, 2..., n_b + n_f + 1 \\ g, k \in \{0, 1..., n\} \\ g \ne k \end{matrix} \quad \ldots \quad (10)$$

$$w^*_{g,k} \ge 0 \text{, with } \begin{matrix} p_{g,k} \in \omega\langle j\rangle, \text{for } g, k \in \{0, 1..., n\} \text{ and } g \ne k \\ j = 1, 2..., n_f + n_b + 1 \end{matrix} \quad \ldots \quad (11)$$

4.2 Processing durations flexibility model

A similar analysis is used for processing durations flexibility. When fine-tuning actions $\pm\Delta d_i, i = 1,...,n$ are introduced, the new soak time values d^*_i : $\{d^*_i = d_i \pm \Delta d_i, i = 1...n\}$ require computation of new waiting time values $w^*_{g,k}$ to maintain prescribed cycle time value C, and hoist moves feasibility. The previous LP model constraint (5) leads to the following expression (12):

$$M(\omega\langle j\rangle)\cdot C = \sum_{p_{2i}\in\omega\langle j\rangle} d_i^* + \sum_{p_{2i+1}\in\omega\langle j\rangle} h_i + \sum_{p_{g,k}\in\omega\langle j\rangle}(c_{g,k}+w_{g,k}) \mp \sum_{p_{2i}\in\omega\langle j\rangle}\Delta d_i \text{ , with } \begin{array}{c} j=1,2...,n_b+n_f+2 \\ i,g,k\in\{0,1...,n\} \\ g\neq k \end{array} \quad \ldots \quad (12)$$

Empty-hoist move waiting times $w^*_{g,k}$ can be calculated using the "$n_b + n_f + 1$" equations defined by (13).

$$\sum_{p_{g,k}\in\omega\langle j\rangle} w^*_{g,k} = \sum_{p_{g,k}\in\omega\langle j\rangle} w_{g,k} \mp \sum_{p_{2i}\in\omega\langle j\rangle}\Delta d_i \text{ , with } \begin{array}{c} j=1,2...,n_b+n_f+1 \\ g,k\in\{0,1...,n\} \\ g\neq k \end{array} \quad \ldots \quad (13)$$

$$w^*_{g,k} \geq 0 \text{ , with } \begin{array}{c} p_{g,k}\in\omega\langle j\rangle, \text{for } g,k\in\{0,1...,n\} \text{ and } g\neq k \\ j=1,2...,n_f+n_b+1 \end{array} \quad \ldots \quad (14)$$

System (10) and (13) contain "$n_b + n_f + 1$"linear equations with "$n_b + n_f$" unknowns $w^*_{g,k}$. These over-determined systems can be solved by minimizing the sum of error-squares (errors *2*-norm) affecting each unknown. In our case, we use the least-squares method.

5. ILLUSTRATIVE EXAMPLE

Let us consider the electroplating line shown previously in Figure 1. The P-time PN model for the retained hoist moves sequence is represented by Figure 4. The classification approach given in section 3 allows us to determine the following five circuits $\omega\langle j\rangle$ with their respective marking $M(\omega\langle j\rangle)$:

- Processing sequence circuit: $\omega\langle 1\rangle = \{p_0, p_1, p_2, p_3, p_4, p_5, p_6, p_7\}$ with $M(\omega\langle 1\rangle) = 2$
- Hoist moves circuit: $\omega\langle 2\rangle = \{p_{0,1}, p_3, p_{2,0}, p_1, p_{1,2}, p_5, p_6, p_7\}$ with $M(\omega\langle 2\rangle) = 1$
- Single backward move circuit: $\omega\langle 3\rangle = \{p_1, p_2, p_3, p_{2,0}\}$ with $M(\omega\langle 3\rangle) = 1$
- Single Forward move circuits: $\omega\langle 4\rangle = \{p_0, p_1, p_{1,2}, p_5, p_6, p_7\}$ with $M(\omega\langle 4\rangle) = 1$, and $\omega\langle 5\rangle = \{p_{0,1}, p_3, p_4, p_5, p_6, p_7\}$, with $M(\omega\langle 5\rangle) = 1$.

For this example, hoist travel times and soak time intervals are specified in Table 1. The duration for loading and unloading a carrier is ℓ =20 (all time durations are in seconds).

Table 1: Hoist travel times and soak time intervals

$c_{0,1}$	$c_{0,2}$	$c_{0,3}$	$c_{1,2}$	$c_{1,3}$	$c_{2,3}$	$[a_0, b_0]$	$[a_1, b_1]$	$[a_2, b_2]$	$[a_3, b_3]$
11	14	19	5	8	9	$[90,\infty[$	[120, 225]	[85, 117]	[45, 75]

Using equations (5), (6) and (7) given in section 4, the LP model from can be formulated as follows:

Goal: Minimise C, then, Maximise C
Subject to:

$2\cdot C = d_0 + d_1 + d_2 + d_3 + 124$

$C = d_3 + w_{0,1} + w_{1,2} + w_{2,0} + 154$

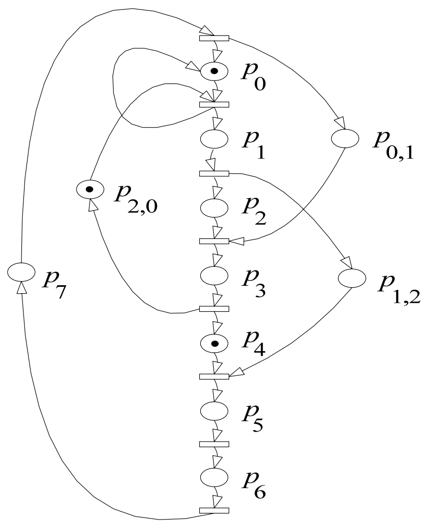
$C = d_1 + w_{2,0} + 70$

$C = d_0 + d_3 + w_{1,2} + 104$

$C = d_2 + d_3 + w_{0,1} + 104$

$d_0 \geq 90\,;120 \leq d_1 \leq 225\,;85 \leq d_2 \leq 117\,;45 \leq d_3 \leq 75$

$w_{0,1}, w_{1,2}, w_{2,0} \geq 0$



places	operations and associated time interval
p_0	loading/unloading at station T_0: $[90,\infty[$
p_1	hoist moves carrier from T_0 to T_1: [31,31]
p_2	carrier treatment in tank T_1: [120,225]
p_3	hoist moves carrier from T_1 to T_2: [25,25]
p_4	carrier treatment in tank T_2: [85 ,117]
p_5	hoist moves carrier from T_2 to T_3: [29,29]
p_6	carrier treatment in tank T_3: [45,75]
p_7	hoist moves carrier from T_3 to T_0: [39,39]
$p_{0,1}$	empty move from T_0 to T_1: $[11+w_{0,1}$, $11+w_{0,1}]$
$p_{1,2}$	empty move from T_1 to T_2: $[5+w_{1,2}$, $5+w_{1,2}]$
$p_{2,0}$	empty move from T_2 to T_0: $[14+w_{2,0}$, $14+w_{2,0}]$

Figure 4: P-time PN model for a cyclic hoist moves sequence

Solving the LP model yields the two extreme cycle time values supported by the considered hoist moves sequence: C_{min} and C_{max}. Hoist waiting times and soak time values for each cycle are given by:

- $C_{min} = 239$, $(d_0, d_1, d_2, d_3) = (90, 134, 85, 45)$ and $(w_{0,1}, w_{1,2}, w_{2,0}) = (5, 0, 35)$
- $C_{max} = 362$, $(d_0, d_1, d_2, d_3) = (213, 225, 117, 45)$ and $(w_{0,1}, w_{1,2}, w_{2,0}) = (96, 0, 67)$.

The cycle time interval $[C_{min}, C_{max}] = [239, 362]$ contains all possible cycle values which ensure hoist moves sequence feasibility. For this case, a functioning mode (solution) is composed of an octuplet formed by cycle time, waiting time and soak time values. In the following sections of the example we will condense the soak times set into a variable "u" and the hoist waiting times set into a variable "v" using the *2*-norm measure such as: $u = \sqrt{\sum_{i=0,\dots,n} d_i^2}$, and $v = \sqrt{\sum_{p_{g,k} \in \omega\langle j \rangle} w_{g,k}^2}$. Thus, the octuplet $(C, d_i, w_{g,k}) = (260, 103, 140, 100, 53, 3, 0, 50)$ will be written under a simpler form as a triplet $(C, u, v) = (260, 207.41, 50.09)$. This data aggregation will help in the graphical representation of electroplating line functioning modes.

5.1. Cycle time flexibility analysis

Cycle time flexibility allows for the generation of new cycle values without affecting the selected processing durations. For example, shifting from (C, u, v) = (260, 207.41, 50.09) to a new mode with a change of cycle $\Delta C = -3$ (new cycle value C = 257) requires the computation of new hoist waiting times $w^*_{g,k}$, without changing the sequence or soak times, using equations (10) and (11). This gives $(w^*_{0,1}, w^*_{1,2}, w^*_{2,0}) = (0, 3, 47)$. The loading operation time becomes $d_0 = 97$, and soak times remain unchanged $(d_1, d_2, d_3) = (140, 100, 53)$. However, once soak times have been selected, cycle time flexibility depends on the existence of feasible solutions in term of hoist waiting times. To study the influence of soak times selection on cycle time flexibility, a set of 100 triplets (d_1, d_2, d_3) were generated using a parameter $\alpha \in [0,1]$ according to the formula: $d_i = a_i + (b_i - a_i) \cdot \alpha$, $i = 1, 2, 3$. For instance, a selection $(d_1, d_2, d_3) = (173, 101, 60)$ corresponds to $\alpha = 0.5$. A maximum number of 22 feasible functioning modes (14 distinct) were found for this selection (see Figure 5). Functioning modes search is achieved by testing 100 different cycle time values C randomly generated using: $C = C_{min} + (C_{max} - C_{min}) \cdot \text{UNIF}(0,1)$. UNIF(0, 1) is the uniform distribution on the interval [0, 1].

A simulation study with Matlab^{TM} software was conducted as follows: α is varied in the interval [0, 1], a number of 100 randomly generated cycle time values are tested for every α . The test is performed using 20 replications and waiting times are computed accordingly. The numbers of functioning modes found feasible among the 100 generated are represented in Figure 6 as a function of α . Cycle time flexibility is measured for each α value (soak times selection) by the ratio of feasible functioning modes found to the total generated (i.e. 100). For example, the value $\alpha = 0.6$ leads to a cycle time flexibility ratio of 35 % (35 cycle values found feasible out of 100).

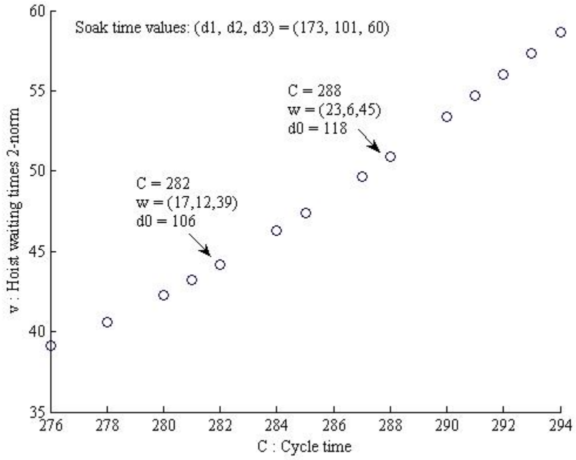


Figure 5: Functioning modes for different cycle value, α = 0.5

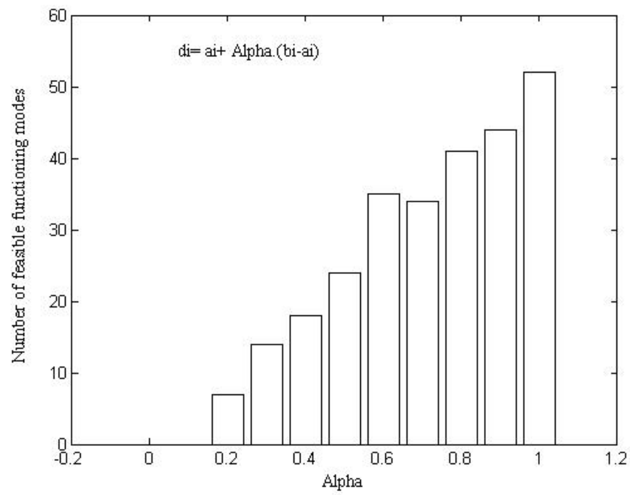


Figure 6: Feasible functioning modes as a function of soak time selection parameter α .

The relation between cycle time value and hoist waiting times 2-norm $v = \sqrt{\sum_{p_{g,k} \in \omega\langle j \rangle} w_{g,k}^2}$ tends to be linear (see Figure 5). Single forward and backward circuit equations confirm this trend as any variation $\Delta w_{g,k}$ results in a variation of the same amount on the cycle time. However, Figure 6 shows that greater cycle time flexibility can be achieved when soak times are selected closer to their maximal value b_i (α closer to 1). Larger soak times tend to slow processing at the tank level allowing the hoist to perform greater waiting times. Thus, cycle time flexibility increases since it depends on these waiting times $w_{g,k}$.

5.2 Processing duration flexibility analysis

Processing duration flexibility allows fine tuning of soak time durations without affecting the selected cycle time value. For example, shifting from (C, u, v) = (260, 207.41, 50.09) to a new functioning mode with Δd = (5, 2, 1) (d_1 = 145, d_2 = 102, d3 = 54) requires new hoist waiting times $w^*_{g,k}$. These values are computed using equations (13) and (14). This gives ($w^*_{0,1}$, $w^*_{1,2}$, $w^*_{2,0}$) = (0, 7, 45). The loading operation time becomes d_0 = 95, and cycle time remains unchanged C = 260. Processing duration flexibility depends on the existence of feasible solution for (13) and (14) once cycle time value has been selected. For instance, a selection C = 300, leads to a maximum number of 41 modes found feasible out of 100 generated (see Figure 7). Functioning modes search is achieved by testing 100 different processing duration triplets (d_1, d_2, d_3) randomly generated using uniform distribution: $d_i = a_i + (b_i - a_i)$.UNIF(0,1).

Using a similar approach as in section 5.1, a simulation study with Matlab™ software was conducted as follows: C is varied in the interval [239, 362], a number of 100 randomly generated soak time values are tested for every cycle value C. The test is performed using 20 replications and waiting times are computed accordingly. The numbers of soak time triplets found feasible among the 100 generated represents the number of feasible functioning modes. They are represented in Figure 8 as a function of the selected cycle time value C. Processing duration flexibility is measured for each selected cycle value by the ratio of feasible functioning modes found to the total generated (i.e. 100). For example, the value C=290 leads to a processing duration flexibility ratio of 36 % (36 soak times triplets found feasible out of 100 generated). Figure 8, shows that greater processing duration flexibility can be achieved when cycle time is selected in the centre of its interval [C_{min}, C_{max}] = [239, 362] (C ≅ 300).

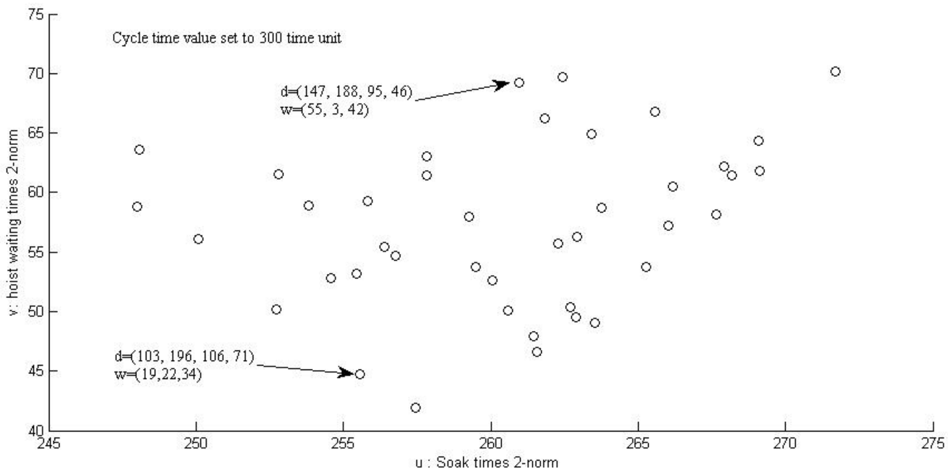


Figure 7: Number of functioning modes equal to 41, for a cycle value C = 300

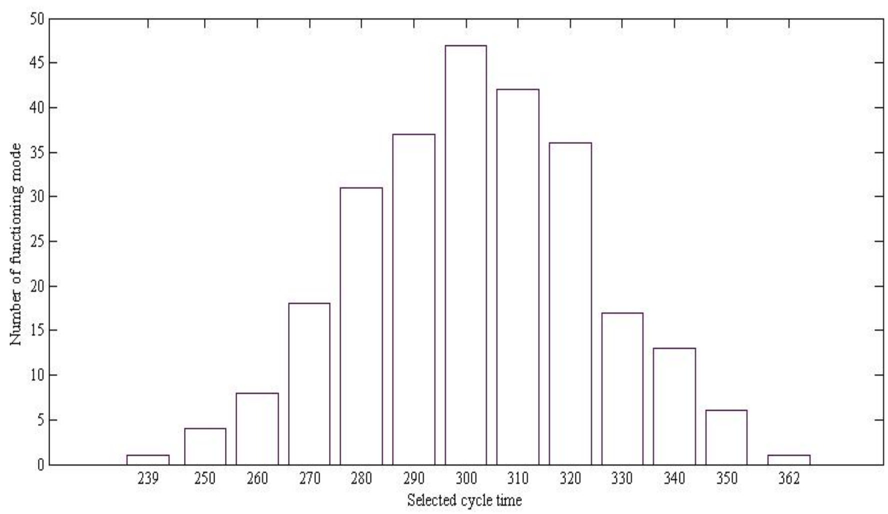


Figure 8: Number of functioning modes for different C values

6. SUMMARY AND CONCLUSION

Extensive studies were conducted on the hoist scheduling problem (HSP) due to its importance for the efficiency of the electroplating industry. Predictive methods focus on finding an optimal hoist move schedule while reactive methods seek a new schedule, in real time, as a reaction to the occurring disturbance. Since scheduling problems are NP-hard, finding new hoist schedules in real time is difficult. The proposed flexible control avoids re-scheduling by exploiting process flexibility in front of disturbances (Chetouane, *et al.*, 2007). The proposed flexible control approach is based on P-time Petri nets modeling tools. Once the hoist moves sequence has been modeled using P-time PN graph, circuit constraints are formulated in a linear programming model. The LP model is then used to calculate cycle time interval [C_{min}, C_{max}].

The key contribution of the proposed method is that, in contrast to existing scheduling methods which compute an optimal cycle time value, it provides a *cycle time interval* that contains all cycle time values for any hoist moves sequence. The approach is also applicable to any electroplating system with a cyclical operating mode. In this study we focused on flexibility in order to synthesise a control approach which takes into account tuning requirements to compensate variations in throughput or in product quality. Two types of flexibility were characterised: cycle time flexibility and processing duration flexibility. A model is associated to the study of each type by using a simple re-formulation of the proposed LP model and by taking into consideration variations made on the cycle time (ΔC) or the processing duration (Δd).

Cycle time flexibility enables the production operator to adjust cycle time to a new target value without affecting soak times, thus ensuring quality requirements. Processing duration flexibility allows chemists to adjust soak times without affecting cycle time, thus maintaining throughput. The study of cycle time flexibility shows (see Figure 6) that the value of this characteristic is at a maximum when soak times are selected closer to their maximum values b_i. In fact, at these values the chemical process becomes the bottleneck and hoist waiting durations ($w_{g,k}$) are more frequent and longer, making it possible to find several other functioning set-points with different cycle values using equations (10). Figure 8 demonstrates that processing duration flexibility is at a maximum when cycle time is selected closer to its interval centre value C_{mean}: $C_{mean}= (C_{min} + C_{max})/2$. Operating strictly at limit cycle values C_{min} or C_{max} doesn't provide enough hoist waiting time possibilities to achieve tuning of soak time durations.

Based on these flexibility types the chemist or production operator will be able to proceed with on-line tuning operations without changing hoist moves sequence (or schedule) when faced with unexpected delays. The proposed control approach is easy to implement on programmable logic controllers: the sequence can be programmed using state flow chart or Grafcet tools while time duration on each place can be set using timers. Timers controlling empty-hoist moves will contain waiting time values ($w_{g,k}$) computed using the LP model of the corresponding flexibility type.

7. ACKNOWLEDGEMENT

This work is supported by National Sciences and Engineering Research Council of Canada under research grant # 249484-02. The author thanks Professor Réjean Hall for his assistance in proofreading the manuscript.

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BIOGRAPHICAL SKETCH

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