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Efficient Approach to Scheduling of Transient Processes for Time-Constrained Single-Arm Cluster Tools with Parallel Chambers

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***Abstract*-In wafer manufacturing, extensive research on the operations of cluster tools under the steady state has been reported. However, with the shrinking down of wafer lot size, such tools are frequently required to switch from handling one lot of wafers to another, resulting in more transient processes, including start-up and close-down processes. Also, wafer residency time constraint is critical for many wafer fabrication processes. To address the transient scheduling problem of time-constrained single-arm cluster tools with parallel chambers, based on a generalized backward strategy, this work first builds timed Petri net models for the two transient processes. Then, two linear programs are derived for the first time to search a feasible schedule with minimal makespan. Two industrial examples are given to demonstrate the effectiveness of the obtained results at last.**

Index Terms—**Cluster tools, wafer manufacturing, transient process, Petri net, scheduling.**

I. Introduction

As a kind of computer-controlled complex equipment, cluster tools are extensively used for processing wafers in semiconductor fabrication. Generally, they are formed by several process chambers (PCs), two loadlocks, and a robot. The robot located at the center of the tool could be single or dual-arm one, resulting in single and dual-arm cluster tools. In Fig. 1, the architecture of a single-arm cluster tool is illustrated. Through the loadlocks, raw wafers to be processed enter the tool in a cassette-by-cassette way. Then, the robot is instructed to pick up a wafer from a cassette and transport it to PCs for processing in a predetermined sequence. After visiting all processing steps, a completed wafer returns to the cassette [37].

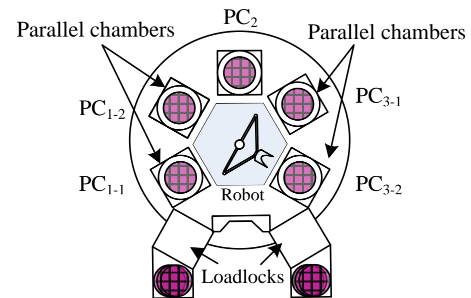

Fig. 1. (a) single-arm cluster tool.

Wafer residency time constraint (WRTC) is critical for many wafer fabrication processes, which requires that a processed wafer in a PC can stay there for no more than a given time and its violation could result in a quality problem [7, 28]. A cluster tool with such a constraint is called a time-constrained one.

In comparison with the scheduling problem of complex industrial processes [4, 33, 40, 41, 49], it seems that scheduling a cluster tool is relatively simple. However, due to WRTC and that it needs to schedule the robot tasks and wafer processing simultaneously, it is challenging to schedule a cluster tool. Thus, during the last two decades, much effort has been done for scheduling cluster tools [1, 7, 15, 28, 30, 32, 37-39, 42-44, 52]. In [15], methods for finding a feasible schedule for both single and dual-arm cluster tools with WRTC are derived. The drawback is that the proposed methods involve complex computation. In [30, 37-39], for time-constrained single and dual-arm cluster tools, an optimal and feasible schedule can be very efficiently obtained by their derived analytical expressions if the schedulability conditions are satisfied. In [44], two linear programs are developed to find a feasible schedule for single-arm cluster tools if the schedulability conditions are satisfied. In comparison with [30] where the scheduling strategy is limited to be backward, the strategy in [44] can be arbitrary.

For single-arm multi-cluster tools with WRTC, Zhu *et al.* [52] develop schedulability conditions for the existence of a

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feasible schedule and algorithms to find an optimal one if the conditions are met. Yang *et al.* [42] extend the result to hybrid multi-cluster tools that consist of both single and dual-arm cluster tools.

Due to product customization and shrinking down of wafer circuit line width, the wafer lot size is becoming smaller and smaller. Hence, a cluster tool often needs to switch from handling one lot of wafers to another, resulting in more transient processes [9, 11-13, 26, 53]. Also, corrective and preventive maintenance could lead to unexpected close-down of a tool, which is often accompanied by the emergence of transient processes. Thus, scheduling a transient process becomes an important issue to be addressed.

For lot switching, Lee *et al*. [12] obtain an optimal robot sequence with minimal makespan by using an MIP model. Given the robot sequences, Lee *et al*. [13] derive closed-form expressions for such a process to minimize the makespan for both single and dual-arm cluster tools. Kim *et al*., [9] propose a branch and bound procedure to minimize the makespan. In [11], by addressing single-arm cluster tools with parallel chambers, the authors propose a generalized backward strategy in an incremental and decremental way for start-up and close-down processes, respectively. It is proved that such a generalized backward strategy can obtain an optimal schedule in most cases in terms of makespan. However, in their work, no WRTC is taken into account.

In [26, 53], by developing a Petri Net (PN) model to describe the characteristics of single-arm cluster tools, scheduling algorithms are developed to search for an optimal and feasible schedule for the start-up and close-down processes with a WRTC. However, in their work, only one PC is configured for each processing step. A comprehensive survey on cluster tool scheduling can be found in [23].

In practice, to balance the workloads, multiple PCs need to be configured in parallel for a processing step. With parallel chambers at a step, in the transient processes, as the wafers processed in different PCs for the same step are unloaded during different robot cycles whose cycle times may not be identical, hence, the wafer residency time at the same step may also be different. Thus, in comparison with [26, 53], the addressed situations in this work are more practical and challenging, since parallel chambers are taken into consideration. As pointed out by Wu *et al*. [30], given a cyclic schedule under a steady state, when the system reaches the steady state via a start-up transient process, this state should be compatible with the given cyclic schedule in terms of the robot task scheduling; otherwise, the cyclic schedule cannot be implemented. This is also challenging to schedule a transient process, especially when there are parallel PCs at a step.

To obtain an optimal and feasible schedule for a transient period based on a generalized backward strategy, this work establishes two PN models to describe the characteristic of system for the two transient processes. Consequently, for the first time, it derives two linear programs to obtain a feasible schedule with minimal makespan for the start-up and close-down processes. Note that a linear program can be solved by a polynomial algorithm. Furthermore, with no more than six chambers in a cluster tool, the size of the developed linear programs cannot be large. Thus, a solution can be very efficiently found, which is significant in scheduling a cluster tool.

In the next Section, two timed PN models are developed for start-up and close-down processes, respectively. Based on them, Sections III and IV derive two linear programs to obtain an optimal and feasible schedule for the start-up and close-down processes, respectively. Examples are used to demonstrate the effectiveness of the proposed approach in Section V. Finally, conclusions are summarized in Section VI.

II. System Modeling and Control

Let $\mathbb{N}_n = \{1, 2, \ldots, n\}$ and $\boldsymbol{\Omega}_n = \mathbb{N}_n \cup \{0\}$. For a single-arm cluster tool, we assume that it consists of n processing steps (except the loadlocks) and m_i ($m_i \geq 1$) parallel PCs are configured for Step i. Thus, a wafer flow pattern can be indicated as (m_1, m_2, …, m_n). For concise presentation, the loadlocks are treated as both Steps 0 and n + 1 with no processing function.

For a single-arm cluster tool in the steady state, a backward strategy is optimal [17] due to that, in most cases, the wafer processing time in a PC is much longer than the robot activity time. For the start-up and close-down processes, Kim *et al*. [11] prove that a generalized backward strategy can obtain a schedule to achieve a minimal makespan in most cases. Furthermore, due to its simplicity and efficiency, such a generalized backward strategy is widely used for single-arm cluster tools [14]. Hence, such strategies are adopted for the steady state and transient process in this work. As backward strategy is well known in this field, we just explain how it is generalized for the start-up and close-down processes in the follows.

A. Generalized Backward Strategy for Transient Process

For the start-up process, let M_d, $d \in \mathbb{N}_n$, denote the state at which there are m_i wafers being processing at Step i, $i \in \mathbb{N}_d$, while Step j, $d < j \leq n$, is idle. M_0 represents the initial state at which each PC is empty.

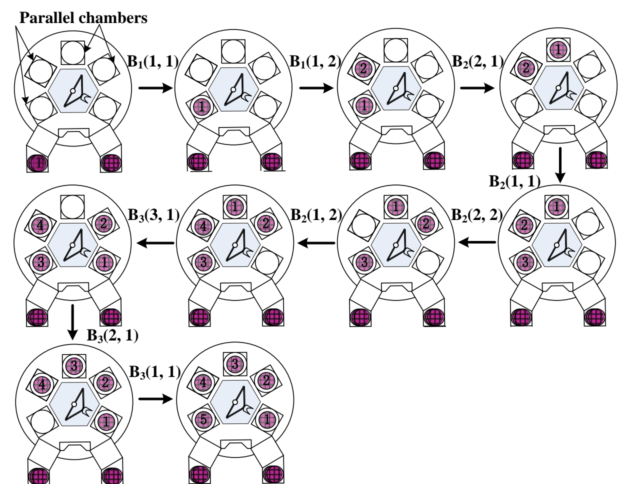

Fig. 2. The illustration of a generalized backward strategy for the start-up process.

Define a basic backward operation A_i performed by the robot at Step i with A_i = ⟨unloading a wafer from Step i - 1 → moving to Step i → loading it into Step i⟩, $i \in \mathbb{N}_{n+1}$. Further,

define $B_d(i, j)$ as the jth basic backward operation A_i at Step i during the evolution process from state M_{d-1} to M_d, $d \in \mathbb{N}_n$. For the steps with parallel chambers, wafers in them follow a "first-in-first-out" rule. Thus, the generalized backward strategy for the start-up process can be denoted as:

1) $B_1(1, 1) \rightarrow B_1(1, 2) \rightarrow \ldots \rightarrow B_1(1, m_1)$;
2) $B_d(d, 1) \rightarrow B_d(d\text{-}1, 1) \rightarrow \ldots \rightarrow B_d(1, 1) \rightarrow B_d(d, 2) \rightarrow \ldots \rightarrow B_d(d, m_d) \rightarrow B_d(d\text{-}1, m_d) \rightarrow \ldots \rightarrow B_d(1, m_d)$, $2 \leq d \leq n$.

After performing $B_n(1, m_n)$, for each PC in the tool, there is a wafer that is being processed, i.e., the start-up process is completed. The start-up process of a cluster tool with wafer flow pattern (2, 2, 1) is illustrated in Fig. 2.

For the close-down process, let W_d, $d \in \mathbb{N}_n$, denote the state at which there are m_i wafers being processing at Step i, $d \leq i \leq n$, while Step j, $1 \leq j < d$, is idle. Further, define $C_d(i, j)$ as the jth basic backward operation A_i at Step i during the state evolution process from W_d to W_{d+1}, $d \in \mathbb{N}_n$, where W_1 represents the state at which there is a wafer in processing in each PC and W_{n+1} represents that all PCs are emptied. With a "first-in-first-out" rule, the generalized backward strategy for the close-down process can be denoted as:

1) $C_d(n+1, 1) \rightarrow C_d(n, 1) \rightarrow C_d(n\text{-}1, 1) \rightarrow \ldots \rightarrow C_d(d+1, 1) \rightarrow C_d(n+1, 2) \rightarrow \ldots \rightarrow C_d(n+1, m_d) \rightarrow C_d(n, m_d) \rightarrow C_d(n\text{-}1, m_d) \rightarrow \ldots \rightarrow C_d(d+1, m_d)$, $1 \leq d \leq n\text{-}1$;
2) $C_n(n+1, 1) \rightarrow C_n(n+1, 2) \rightarrow \ldots \rightarrow C_n(n+1, m_n)$.

After performing $C_n(n+1, m_n)$, the last wafer is completed and loaded into a loadlock such that the tool goes to the initial idle state. The close-down process of a cluster tool with wafer flow pattern (2, 2, 1) is illustrated in Fig. 3.

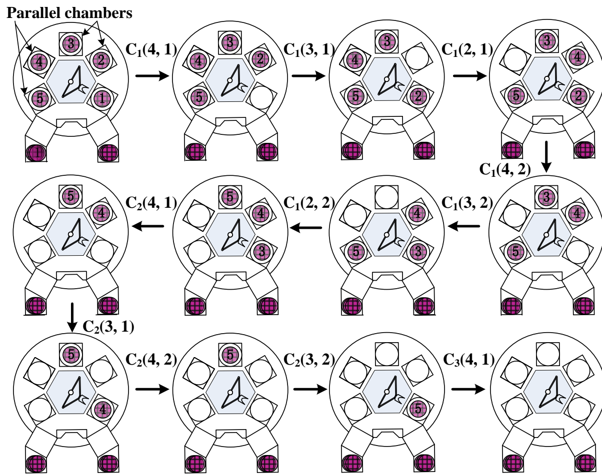

Fig. 3. The illustration of a generalized backward strategy for the close-down process.

B. Finite Capacity Petri Net

As an efficient tool for modeling, analysis, and control, PNs are widely applied in discrete manufacturing systems [2, 5-10, 14, 18-22, 24, 25, 27, 30-32, 45-50]. By following the work in [29, 30, 34-36, 51], the definition of a finite capacity PN is given as follows.

Definition 1: A finite capacity PN is a six-tuple digraph with the following set of elements.

1) $P = \{p_1, p_2, \ldots, p_m\}$ is a finite set of places.
2) $T = \{t_1, t_2, \ldots, t_n\}$ is a finite set of transitions, where $P \cap T = \emptyset$ and $P \cup T \neq \emptyset$.
3) I: $(P \times T) \rightarrow \mathbf{N} = \{0, 1, 2, \ldots\}$ is an input function specifying the existence of a directed arc from place p to transition t with weight $I(p, t)$.
4) O: $(P \times T) \rightarrow \mathbf{N}$ is an output function specifying the existence of a directed arc from t to p with weight $O(p, t)$.
5) $M(P) = (M(p_1), \ldots, M(p_m))^{\mathrm{T}}$ is a marking, where $M(p_i)$ represents the number of tokens in p_i.
6) $\mathcal{K}$: a capacity function with $\mathcal{K}(p)$ denoting the maximum number of tokens that p can accommodate.

Note that $I(p, t) = 0$ or $O(p, t) = 0$ implies that arc (p, t) or (t, p) does not exist. Usually, places and transitions in a PN model are denoted by circles and bars. Details about the transition enabling and firing rules of PNs can be found in [29, 34, 36]. Next, we use the finite capacity PN to model the system.

C. Modeling the Steady State Process

With a backward strategy, the PN model for a single-arm tool under the steady state is developed in [44] and it is depicted in Fig. 4.

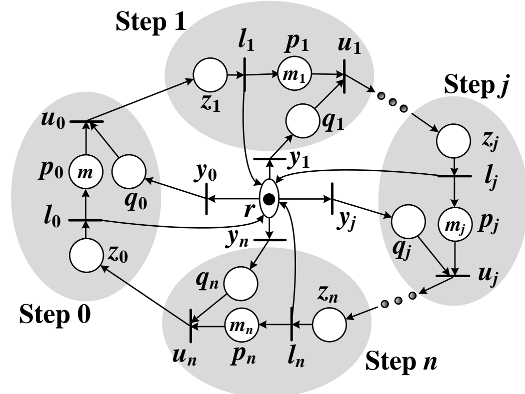

Fig. 4. The PN model for a single-arm cluster tool under the steady-state.

In Fig. 4, p_0 models the loadlocks with $\mathcal{K}(p_0) = m$ representing that there are always wafers to be processed in the loadlocks. For Step j, $j \in \mathbb{N}_n$, place p_j with $\mathcal{K}(p_j) = m_j$ models the step and indicates that there are m_j PCs. For each Step j, $j \in \mathbf{\Omega}_n$, place q_j with $\mathcal{K}(q_j) = 1$ models that the robot waits there and ready to remove a processed wafer from one of the PCs. Place z_j, $j \in \mathbf{\Omega}_n$ with $\mathcal{K}(z_j) = 1$, represents that the robot rotates from Steps j-1 to j with a wafer being held. Note that both Steps 0 and $n + 1$ model the loadlocks. Hence, z_0 models the robot moving from Steps n to 0 or $n + 1$ with a wafer being held. The robot is modeled by place r with $\mathcal{K}(r) = 1$, representing that there is one robot arm only.

The loading/unloading activity of the robot at Step j, $j \in \mathbf{\Omega}_n$, is modelled by transition l_j/u_j. The robot moving from a step to Step j with no wafer being held is modeled by y_j, $j \in \mathbf{\Omega}_n$. Note that y_j, $j \in \mathbb{N}_n$, can also denote the robot moving from one chamber to another at Step j with no wafer being held. Then, by adding arcs $(u_{j\text{-}1}, z_j)$, (z_j, l_j), (l_j, p_j), (p_j, u_j), (l_i, r), (r, y_j), (y_j, q_j), and (q_j, u_j), $j \in \mathbf{\Omega}_n$, we can obtain the PN structure for the system under the steady state as shown in Fig. 4.

For the start-up process, when the tool needs to start for operation, the robot acts according to the following task sequence: ⟨unloading wafer 1 from a loadlock → moving to

Step 1 → loading it there → moving back to the loadlock if $m_1 \geq 2$, otherwise, state M_1 is reached → unloading wafer 2 from the loadlock if $m_1 \geq 2$ → moving to Step 1 → loading it there → … → unloading wafer m_1 from the loadlock → moving to Step 1 → loading it there⟩ such that state M_1 is reached.

During the evolution process from M_{d-1} to M_d, $d \in \mathbb{N}_n \backslash \{1\}$, the robot follows the following task sequence: ⟨moving to Step d - 1 → unloading a wafer there → moving to Step d → loading the wafer there → moving to Step d - 2 → unloading a wafer there → moving to Step d - 1 → loading the wafer there → … → moving to a loadlock → unloading a wafer there → moving to Step 1 → loading the wafer there⟩. By repeating this process m_d times, M_d is reached. Finally, when M_n is reached, the start-up process is completed and the steady state is reached. Hence, the start-up process is defined as the process from M_0 to M_n. A PN model for the start-up process from state M_{d-1} to M_d, $d \in \mathbb{N}_n$, is shown in Fig. 5, where the meaning of the places and transitions is identical to that in Fig. 4. Note that, in Fig. 5, place p_d modeling Step d is marked by k tokens with $0 \leq k < m_d$.

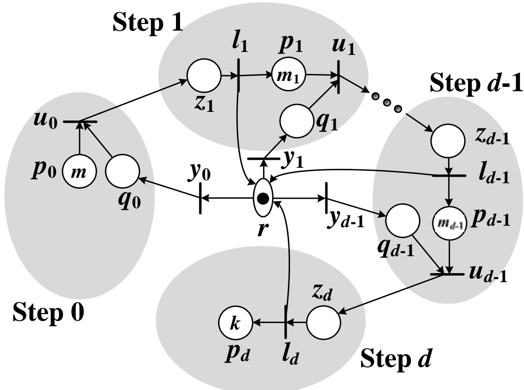

Fig. 5. The PN model for the start-up process of a single-arm cluster tool from state M_{d-1} to M_d, $d \in \mathbb{N}_n$.

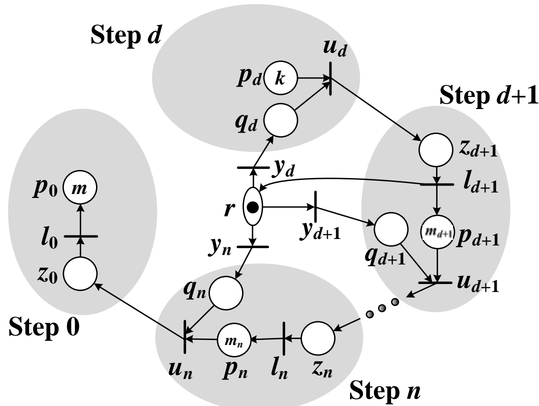

Fig. 6. The PN model for the close-down process of a single-arm cluster tool from state W_d to W_{d+1}, $d \in \mathbb{N}_n$.

Next, for the close-down process, during the process from state W_d to W_{d+1}, $d \in \mathbb{N}_{n-1}$, the robot acts according to the following task sequence: ⟨moving to Step n → unloading a wafer from it → moving to a loadlock → loading the wafer there → moving to Step n - 1 → unloading a wafer there → moving to Step n → loading the wafer there → … → moving to Step d → unloading a wafer there → moving to Step d + 1 → loading the wafer there⟩. By repeating this process m_d times, state W_{d+1} is reached.

From state W_n to W_{n+1}, the robot follows the following task sequence: ⟨unloading a wafer from Step n → moving to a loadlock → loading the wafer there → moving back to Step n if $m_n \geq 2$ → unloading a wafer from it → … → unloading the last wafer from Step n → moving to a loadlock → loading the wafer there⟩. Then, state W_{n+1} is reached and the close-down process is completed. Hence, the close-down process is defined as the process from W_1 to W_{n+1}. A PN model for the close-down process from state W_d to W_{d+1}, $d \in \mathbb{N}_n$, is shown in Fig. 6, where the meaning of the places and transitions is also identical to that in Fig. 4. Note that, in Fig. 6, place p_d modeling Step d is marked by k tokens with $1 \leq k \leq m_d$.

With the PN models in Figs. 4-6, we need to ensure that the backward strategy or generalized backward strategy can be realized with no deadlock. To do so, for the steady state, by following [30], a control policy is given as follows.

Definition 2: For the PN shown in Fig. 4, at any marking M, transition y_n is said to be control-enabled if $M(p_i) = m_i$, $i \in \mathbb{N}_n$; and y_i, $0 \leq i < n$, is said to be control-enabled if $M(p_{i+1}) = m_{i+1} - 1$.

With Definition 2, Wu *et al*. [30] show that the PN in Fig. 4 is deadlock-free under the steady state. Next, for the start-up process, a control policy is given as follows.

Definition 3: For the PN shown in Fig. 5, transition y_0 is said to be control-enabled if $M(p_1) < m_1$; and y_i, $1 \leq i < n$, is said to be control-enabled if $M(p_k) = m_k$, $k \in \mathbb{N}_i$, and $M(p_{i+1}) < m_{i+1}$.

By Definition 3, when a tool begins to work, $M(p_1) = 0 < m_1$, y_0 is control-enabled and it fires repeatedly until $M(p_1) = m_1$ such that State M_1 is reached. Then, y_1 is control-enabled due to that at this time $M(p_2) = 0 < m_2$ and $M(p_1) = m_1$. After firing y_1, $M(p_2) = 1$ and $M(p_1) = m_1 - 1$, y_0 is control-enabled again and it then fires. Repeat these processes until $M(p_2) = m_2$ and $M(p_1) = m_1$ such that State M_2 is reached. By continuing this process, finally State M_n is reached, that is to say that the generalized backward strategy for the start-up process can be realized with no deadlock.

For the close-down process, we also have a control policy which is given in Definition 4 below.

Definition 4: For the PN shown in Fig. 6, the following control policy is imposed:

1) y_n is said to be control-enabled if $M(p_i) = m_i$, $i \in \mathbb{N}_n \backslash \{1\}$;
2) y_i, $i \in \mathbb{N}_{n-1}$, is said to be control-enabled if $M(p_{i+1}) = m_{i+1} - 1$ and, $M(p_i) \neq 0$;
3) y_n is said to be control-enabled if $M(p_i) < m_i$, $i \in \mathbb{N}_{n-1} \backslash \{1\}$, $M(p_k) = 0$, $k \in \mathbb{N}_{i-1}$, and $M(p_j) = m_j$, $j \in \mathbb{N}_n \backslash \mathbb{N}_i$; and
4) y_n is said to be control-enabled if $M(p_n) > 0$, and $M(p_k) = 0$, $k \in \mathbb{N}_{n-1}$.

By Definition 4, when the close-down process begins, as $M(p_i) = m_i$, $i \in \mathbb{N}_n$, y_n is control-enabled. Firing y_n results in marking $M(p_n) = m_n - 1$ such that y_{n-1} is control-enabled. Firing y_{n-1} leads to $M(p_n) = m_n$ and $M(p_{n-1}) = m_{n-1} - 1$ such that y_{n-2} is control-enabled. In this way, y_{n-3} can fire and then y_{n-4}. Finally, y_1 is enabled and fires. Firing y_1 leads to $M(p_1) = m_1 - 1$ and

$M(p_i) = m_i$, $i \in \mathbb{N}_n\backslash\{1\}$, such that y_n is control-enabled again. By repeating the above processes, W_2 is then reached such that $M(p_1) = 0$ and $M(p_i) = m_i$, $i \in \mathbb{N}_n\backslash\{1\}$.

At State W_2, only y_n is control-enabled. Firing y_n transfers the system to a marking with $M(p_n) = m_n - 1$ such that y_{n-1} is control-enabled. Next, with y_{n-1}'s firing, y_{n-2} is control-enabled; then, y_{n-3}, until to y_2. By firing y_2, we reach marking $M(p_2) = m_2 - 1 < m_2$, $M(p_j) = m_j$, $j \in \mathbb{N}_n\backslash\mathbb{N}_2$, and $M(p_1) = 0$. Thus, by Step 3 of Definition 4, y_n is control-enabled. Repeat these processes until State W_3 is reached such that $M(p_1) = M(p_2) = 0$ and $M(p_i) = m_i$, $i \in \mathbb{N}_n\backslash\mathbb{N}_2$. In this way, we can reach State W_4 and finally State W_n.

At State W_n, as $M(p_k) = 0$, $k \in \mathbb{N}_{n-1}$ and $M(p_n) = m_n > 0$, y_n is control-enabled. After firing y_n, if $M(p_n) > 0$, y_n is still control-enabled. Then, y_n fires in a repeated way until $M(p_k) = 0$, $k \in \mathbb{N}_n$, or State W_{n+1} is reached. In this way, the generalized backward strategy for the close-down process can be realized with no deadlock.

D. Modeling Activity Time

To describe the temporal behavior of the PN models shown in Figs. 4-6, we associate both transitions and places with time. By following [3, 7], assume that:

1) The time taken by a robot loading/unloading activity at a step is a deterministic constant and denoted by λ; and
2) The time taken by a robot moving activity between two steps or two chambers at the same step with or without carrying a wafer is also a deterministic constant and denoted by μ.

Let α_i represent the wafer processing time at Step i, $i \in \mathbb{N}_n$. After being processed, a wafer can stay in a chamber for at most δ_i, $i \in \mathbb{N}_n$, time units. Let τ_i represent the wafer sojourn time at Step i, $i \in \mathbb{N}_n$, and it is required that $\tau_i \in [\alpha_i, \alpha_i+\delta_i]$ must hold. The time associated with different transitions and places is summarized in Table I.

Table I. Time duration associated with transitions and places.

Symbol	Transition or place	Action	Time duration
λ	$l_i \in T$	Loading a wafer into Step i, $i \in \mathbf{\Omega}_n$	λ
	$u_i \in T$	Unloading a wafer from Step i, $i \in \mathbf{\Omega}_n$	
μ	$z_i \in P$	Moving with a wafer being carried from Steps i - 1 to i, $i \in \mathbb{N}_{n+1}$	μ
μ	$y_i \in T$	Moving from a different step to Step i, $i \in \mathbf{\Omega}_n$, with no wafer being held, or moving between PCs at Step i, $i \in \mathbb{N}_n$, with no wafer being held	μ
τ_i	$p_i \in P$	A wafer stays in a chamber of p_i, $i \in \mathbb{N}_n$	$[\alpha_i, \alpha_i+\delta_i]$

With the WRTC, a feasible schedule is defined as follows.

Definition 5 [30]: In the PN models shown in Figs. 4-6, if the WRTC with time window $[\alpha_i, \alpha_i+\delta_i]$ is imposed on Step i, $i \in \mathbb{N}_n$, and by a schedule whenever u_i starts to fire, $\alpha_i \le \tau_i \le \alpha_i + \delta_i$ holds, then, this schedule is feasible.

III. Start-Up Process Scheduling

To test if a schedule is feasible, we need to calculate the wafer residency time in each chamber. At Step i, $i \in \mathbb{N}_n$, assume that the robot finishes loading a wafer into chamber at time instant ϕ_1 and the unloading of this wafer begins at time ϕ_2. Then, the wafer residency time at Step i is $\tau_i = \phi_2 - \phi_1$. Hence, for each wafer, to calculate τ_i, we need to determine ϕ_1 and ϕ_2. To do so, for the start-up process, let

1) $t_d(i, j, 2)$ denote the time when the robot starts to unload the jth wafer from Step i during the process from M_{d-1} to M_d, $d \in \mathbb{N}_n$, $i \in \mathbf{\Omega}_{n-1}$, and $1 \le j \le m_d$.
2) $t_d(i, j, 1)$ denote the time when the robot finishes loading the jth wafer into Step i during the process from M_{d-1} to M_d, $d \in \mathbb{N}_n$, $i \in \mathbb{N}_n$, and $1 \le j \le m_d$.
3) $\omega_d(i, j)$ denote the robot waiting time before it unloads the jth wafer from Step i during the process from M_{d-1} to M_d, $d \in \mathbb{N}_n$, $i \in \mathbf{\Omega}_{n-1}$, and $1 \le j \le m_d$.

Further, during the process from M_0 to M_1, let

$$t_1(0, 1, 2) = \omega_1(0, 1) = 0 \tag{3.1}$$

By (3.1), it means that the initial time is set to zero at which the robot starts to unload the first wafer from a loadlock. It follows from Table I that it takes λ time units to unload the wafer. Then, the robot moves this wafer to Step 1 and loads it there, which takes $\mu + \lambda$ time units. Hence, we have

$$t_1(1, 1, 1) = t_1(0, 1, 2) + 2\lambda + \mu \tag{3.2}$$

After the first wafer is loaded to Step 1, if $m_1 = 1$, State M_1 is reached; otherwise, if $m_1 > 1$, the robot needs to move back to a loadlock and unload another wafer. In this case, we have

$$t_1(0, j, 2) = t_1(1, j\text{-}1, 1) + \mu + \omega_1(0, j),\ 2 \le j \le m_1 \tag{3.3}$$

$$t_1(1, j, 1) = t_1(0, j, 2) + 2\lambda + \mu,\ 2 \le j \le m_1 \tag{3.4}$$

In this way, State M_1 is reached. Next, the model shown in Fig. 5 evolves from M_1 to M_2. During this process, if $m_1 = 1$, $t_2(1, 1, 2) = t_1(1, 1, 1) + \omega_2(1, 1)$; otherwise, $t_2(1, 1, 2) = t_1(1, m_1, 1) + \omega_2(1, 1) + \mu$, since that, with a "first-in first-out" rule, the robot moves from the chamber where the m_1th wafer is being processed to the chamber where the first wafer is being processed at Step 1, which takes μ time units. Also, if $m_1 = 1$ and $m_2 \ge 2$, during the process from States M_1 to M_2, after loading the jth wafer into Step 1 at time $t_2(1, j, 1)$, $1 \le j \le m_2$-1, the robot needs to wait at Step 1 until the wafer there is completed. Thus, we have

$$t_2(1, j, 2) = t_2(1, j\text{-}1, 1) + \omega_2(1, j),\ 2 \le j \le m_2$$

Similar to the process from States M_0 to M_1, with the generalized backward strategy, the system evolves from States M_{d-1} to M_d, $d \in \mathbb{N}_n\backslash\{1\}$, such that

$$t_d(d\text{-}1, 1, 2) = t_{d-1}(1, m_{d-1}, 1) + \mu + \omega_d(d\text{-}1, 1),\ 2 \le d \le n$$

and, if $m_1 = 1$,

$$t_2(1, 1, 2) = t_1(1, 1, 1) + \omega_2(1, 1) \tag{3.5}$$

$$t_d(d\text{-}1, j, 2) = t_d(1, j\text{-}1, 1) + \mu + \omega_d(d\text{-}1, j),\ 2 \le d \le n,\ 2 \le j \le m_d$$

and if $d = 2$ and $m_1 = 1$,

$$t_2(1, j, 2) = t_2(1, j\text{-}1, 1) + \omega_2(1, j),\ 2 \le j \le m_2 \tag{3.6}$$

$$t_d(d\text{-}m, j, 2) = t_d(d\text{-}m\text{+}2, j, 1) + \mu + \omega_d(d\text{-}m, j),\ 2 \le d \le n,\ 2 \le m \le d,\ 1 \le j \le m_d \tag{3.7}$$

$$t_d(d\text{-}m\text{+}1, j, 1) = t_d(d\text{-}m, j, 2) + 2\lambda + \mu,\ 2 \le d \le n,\ 1 \le m \le d,\ 1 \le j \le m_d \tag{3.8}$$

Expressions (3.5)-(3.7) present the time when the robot starts to unload a wafer from a step, while (3.8) gives the time when loading a wafer into a step ends. Note that in (3.6), if $d = 2$ and $m_1 = 1$, after loading a wafer into Step 1, the robot has to

wait there until the wafer finishes its processing, and then, unloads it, which means that no robot moving is required. Similarly, for (3.5), if $m_1 = 1$, no robot moving is required.

After loading the m_nth wafer into Step 1 at time $t_n(1, m_n, 1)$, there is a wafer in processing in each chamber such that State M_n (the steady state) is reached. With $t_n(1, m_n, 1)$ as the starting time of the steady state, we use c_1 to denote the first steady cycle that ends at the time when a wafer has just loaded into Step 1 during the steady state process. With c_d denoting the dth steady cycle, the system then goes into steady cycle c_2. For the following presentation, let

1) $t_{n+d}(i, 1, 2)$ denote the time when the robot starts to unload a wafer from Step i during steady cycle c_d, $d \geq 1$.
2) $t_{n+d}(i, 1, 1)$ denote the time when the robot finishes loading a wafer into Step i during steady cycle c_d, $d \geq 1$, and
3) $\omega_{n+d}(i, 1)$ denote the robot waiting time before unloading a wafer from Step i during steady cycle c_d, $d \geq 1$.

Note that Step 0 is same as Step n+1. During the start-up process, to complete the process as soon as possible, the robot waiting time at Step i, $i \in \mathbf{\Omega}_n$, needs to schedule to be different. However, under the steady state, they should be identical for different cycles. To ensure that the system can operate in a periodic way in the steady state, we let $\mathfrak{R} = \max\{m_i | i \in \mathbb{N}_n\}+1$. Then, similar to (3.5)-(3.8) we have

$$t_{n+1}(n, 1, 2) = t_n(1, m_n, 1) + \mu + \omega_{n+1}(n, 1) \quad (3.9)$$

$$t_{n+j}(n, 1, 2) = t_{n+j-1}(1, 1, 1) + \mu + \omega_{n+j}(n, 1), 2 \leq j \leq \mathfrak{R} \quad (3.10)$$

$$t_{n+j}(0, 1, 1) = t_{n+j}(n, 1, 2) + 2\lambda + \mu, 1 \leq j \leq \mathfrak{R} \quad (3.11)$$

$$t_{n+j}(n-m, 1, 2) = t_{n+j}(n-m+2, 1, 1) + \mu + \omega_{n+j}(n-m, 1), \quad 1 \leq j \leq \mathfrak{R}, 1 \leq m \leq n \quad (3.12)$$

$$t_{n+j}(n-m+1, 1, 1) = t_{n+j}(n-m, 1, 2) + 2\lambda + \mu, \quad 1 \leq j \leq \mathfrak{R}, 1 \leq m \leq n \quad (3.13)$$

To ensure that the waiting time for different cycles under the steady state is identical, we have

$$\omega_{n+j}(m, 1) = \omega_{n+k}(m, 1), m \in \mathbf{\Omega}_n, j \neq k \text{ and } j, k \in \mathbb{N}_{\mathfrak{R}} \quad (3.14)$$

Thus, by Constraints (3.9)-(3.14), it is sure that the obtained schedule for the start-up process is compatible to a cyclic schedule under the steady state. Since the robot waiting time should be nonnegative, we have

$$\omega_{n+j}(m, 1) \geq 0, j \in \mathbb{N}_{\mathfrak{R}} \quad (3.15)$$

$$\omega_d(d-m, j) \geq 0, 1 \leq d \leq n, 1 \leq m \leq d, 1 \leq j \leq m_d \quad (3.16)$$

It follows from the above analysis that, during the start-up process, the robot waiting time at Step i, $i \in \mathbf{\Omega}_n$, is varied when different wafers processed by different chambers at the same step are unloaded. Thus, the wafer residency time in different chambers at the same step is different, which makes the scheduling problem of transient process of single-arm cluster tool with parallel chambers more challenging and complicated than a tool with single PC for a process step. Also, to ensure that a robot task sequence during the transient process should be always compatible with the given steady-state cyclic schedule is another challenging issue. In this work, the generalized backward strategy becomes a backward strategy that adopted by the steady-state cyclic schedule, when there is a wafer in each PC. Furthermore, by (3.9)-(3.14), compatibility issue is ensured too.

In order to calculate the wafer sojourn time in a chamber, we assume that a wafer is loaded into Step i by executing $t_d(i, j, 1)$ with d, i and j being deterministic. With $M(p_k)$ representing the number of tokens (wafers) in p_k after $t_d(i, j, 1)$ is performed, if $\sum_{k=i}^{n} M(p_k) \leq \sum_{l=i+1}^{n} m_l$, we assume that the wafer is unloaded by performing $t_q(i, z, 2)$. Then, the values of q and z can be calculated as follows:

1) Find the value of q such that $\sum_{l=i+1}^{q-1} m_l < \sum_{k=i}^{n} M(p_k) \leq \sum_{l=i+1}^{q} m_l$;
2) $z = \sum_{k=i}^{n} M(p_k) - \sum_{l=i+1}^{q-1} m_l$.

With $\sum_{l=i+1}^{q-1} m_l < \sum_{k=i}^{n} M(p_k) \leq \sum_{l=i+1}^{q} m_l$, we can conclude that the $(\sum_{k=i}^{n} M(p_k) - \sum_{l=i+1}^{q-1} m_l)$th wafer in a PC at Step i is unloaded during the state evolution process from M_{q-1} to M_q.

With q and z being determined, to meet the WRTC, we have the following constraint.

$$\alpha_i \leq t_q(i, z, 2) - t_d(i, j, 1) \leq \alpha_i + \delta_i \quad (3.17)$$

However, if $\sum_{k=i}^{n} M(p_k) > \sum_{l=i+1}^{n} m_l$, we have that this wafer has been unloaded, which was performed by starting at time $t_{n+r}(i, 1, 2)$, where $r = \sum_{k=i}^{n} M(p_k) - \sum_{l=i+1}^{n} m_l$. Hence, we have the following constraint.

$$\alpha_i \leq t_{n+r}(i, 1, 2) - t_d(i, j, 1) \leq \alpha_i + \delta_i, 1 \leq r \leq \mathfrak{R} \quad (3.18)$$

Then, we present the following Linear Program denoted as LP1 to schedule the start-up process.

$$\text{Min}\{\sum_{j=1}^{m_d}\sum_{m=1}^{d}\sum_{d=1}^{n}\omega_d(d-m, j) + \sum_{j=1}^{\mathfrak{R}}\sum_{m=0}^{n}\omega_{n+j}(m,1)\} \quad (3.19)$$

Subject to: (3.1)-(3.18).

In LP1, the objective is to minimize the total robot waiting time. Generally, a linear program can be efficiently solved. Moreover, in practice, a cluster tool usually consists of no more than six PCs such that size of the above linear program relevantly small. Thus, it can be very efficiently solved by using a commercial solver, i.e., it is computationally efficient.

During the start-up process, with a generalized backward strategy, both the robot task sequence and activity (including unloading, moving and loading) time are deterministic and known. What we need to do for scheduling such a process is to determine the robot waiting time at the steps. The sum of time taken for the robot actions and waiting is the time taken for start-up process. By (3.19), the total robot waiting time is minimized. Thus, by solving LP1, the makespan for the start-up process is minimized. Furthermore, the WRTC is embedded into (3.17) and (3.18), i.e., the feasibility for the obtained schedule is ensured. Hence, we have the following result immediately.

Property 3.1: For the start-up process of a single-arm cluster tool with WRTC, if the generalized backward strategy is applied and a solution is found by solving LP1, then the obtained schedule is optimal and feasible.

With Property 3.1, the remaining question is if an optimal and feasible solution can be always found by solving LP1 for a single-arm tool. To answer this question, we introduce the virtual wafer method proposed by Wu *et al.* [30] for the

start-up and close-down processes. In [30], the virtual wafer method is proposed to implement an obtained cyclic schedule under the steady state for cluster tools with WRTC.

It should be pointed out that, at most of the time, a cluster tool operates under a steady state. Thus, after the start-up process ends, a tool enters a steady state and operates in a periodical way, also a close-down process begins when a steady state process ends. Hence, it is meaningful to schedule the start-up and close-down processes only a cyclic schedule under a steady state exists.

During the start-up process, with the virtual wafer method, it is assumed that there is a virtual wafer in each chamber at the beginning such that, during the process from the idle state to the steady state, a tool operates exactly according to a cyclic schedule under the steady state (such a schedule can be obtained using the method proposed by Wu *et al*. [30]). It assumed that initially there is a virtual wafer in each PC, during the start-up process, each time when the robot needs to unload a wafer from a loadlock, it unloads a real one and when it requires to load a wafer into a loadlock, it loads a virtual one. After all virtual wafers are removed from the system, it reaches the steady state. Note that, in this work, it is assumed that there is a feasible cyclic schedule for a time-constrained single-arm cluster tool. This assumption is reasonable since we do not need to optimize the start-up process if there is no feasible cyclic schedule. Then, we have the following result.

Theorem 3.1: For a single-arm cluster tool with WRTC, an optimal and feasible schedule for the start-up process can be obtained by solving LP1 if, under the steady state, a feasible periodic schedule exists.

Proof: For a single-arm cluster tool under the steady state, as the wafer processing time is much longer than the robot activity time, a backward strategy is optimal. With such a strategy, if there is a feasible periodic schedule, then, by using a virtual wafer method, during the process from state M_0 to M_1, operations $B_1(1, 1)$, $B_1(1, 2)$, …, and $B_1(1, m_1)$ are performed sequentially. According to the backward strategy and the PN model in Fig. 4, after performing $B_1(1, 1)$, the robot task sequence $\langle y_n \to u_n \to z_n \to l_0 \to y_{n-1} \to u_{n-1} \to z_{n-1} \to l_n \to y_{n-2} \to \ldots \to y_1 \to u_1 \to z_1 \to l_2 \to y_0 \to B_1(1, 2)\rangle$ is executed. In this sequence, tasks from y_n to l_2 are used to process virtual wafers, i.e., they are virtual operations. The time taken to perform these virtual operations can be seen as waiting time at Step 1. After performing this sequence, the robot moves to a loadlock by firing y_0 and it is followed by $B_1(1, 2)$.

Similarly, during the process from state M_0 to M_1, the time taken for performing the virtual operations can be seen as waiting time at Step 1. In this way, state M_1 can be reached and the WRTC must be satisfied.

Next, from state M_d to M_{d+1}, $2 \le d \le n - 1$, we can also treat the time taken for performing virtual operations as waiting time at Step d and the WRTC should always be met. The start-up process ends when M_n is reached.

From the above analysis we know that the obtained schedule by the method given in [30] is in the feasible region of LP1. Therefore, the theorem holds. ■

IV. Close-Down Process Scheduling

For the close-down process scheduling, we let

1) $T_d(i, j, 2)$ denote the time when the robot starts to unload the jth wafer from a PC at Step i during the process from W_d to W_{d+1}, $d \in \mathbb{N}_n$, $i \in \mathbb{N}_n$, and $1 \le j \le m_d$;
2) $T_d(i, j, 1)$ denote the time when the robot finishes loading the jth wafer into a PC at Step i during the process from W_d to W_{d+1}, $d \in \mathbb{N}_n$, $i \in \mathbb{N}_{n+1}\backslash\{1\}$, and $1 \le j \le m_d$; and
3) $w_d(i, j)$ denote the robot waiting time before unloading the jth wafer from a PC at Step i during the process from W_d to W_{d+1}, $d \in \mathbb{N}_n$, $i \in \mathbb{N}_n$, and $1 \le j \le m_d$.

Let T_0 (= 0) denote the time instant when the last wafer is loaded into Step 1 during the operation under the steady state, i.e., the time when the steady state operation ends and the close-down process starts. Then, with a generalized backward strategy stated in Section II, during the process from States W_1 to W_2, the robot goes to Step n with μ time units being taken and waits there for $w_1(n, 1)$ time units, i.e., we have

$$T_1(n, 1, 2) = T_0 + \mu + w_1(n, 1) = \mu + w_1(n, 1) \qquad (4.1)$$

After executing $T_1(n, 1, 2)$, we can easily obtain

$$T_1(0, 1, 1) = T_1(n, 1, 2) + 2\lambda + \mu,$$
$$T_1(n\text{-}1, 1, 2) = T_1(0, 1, 1) + \mu + w_1(n\text{-}1, 1),$$
$$T_1(n, 1, 1) = T_1(n\text{-}1, 1, 2) + 2\lambda + \mu, \ldots, \text{and},$$
$$T_1(2, 1, 1) = T_1(1, 1, 2) + 2\lambda + \mu.$$

Thereafter, if $m_1 \ge 2$, the robot goes to Step n to perform $T_1(n, 2, 2)$, or we have

$$T_1(n, 2, 2) = T_1(2, 1, 1) + \mu + w_1(n, 2).$$

In this way, after dropping the m_1th wafer into Step 2 at time $T_1(2, m_1, 1) = T_1(1, m_1, 2) + 2\lambda + \mu$, State W_2 is reached. Next, the system evolves from States W_2 to W_3 and the robot goes to Step n for unloading the 1st wafer from Step n at time $T_2(n, 1, 2)$. Thus, we have

$$T_2(n, 1, 2) = T_1(2, m_1, 1) + \mu + w_2(n, 1)$$

For the general case, we have

$$T_d(n, 1, 2) = T_{d\text{-}1}(d, m_{d\text{-}1}, 1) + \mu + w_d(n, 1), \quad 2 \le d \le n\text{-}1 \qquad (4.2)$$
$$T_d(n, j, 2) = T_d(d+1, j\text{-}1, 1) + \mu + w_d(n, j), \quad 1 \le d \le n\text{-}1,\ 2 \le j \le m_d$$

and if, $d = n$ -1, and $m_n = 1$,

$$T_{n\text{-}1}(n, j, 2) = T_{n\text{-}1}(n, j\text{-}1, 1) + w_{n\text{-}1}(n, j),\ 2 \le j \le m_{n\text{-}1} \qquad (4.3)$$
$$T_d(0, j, 1) = T_d(n, j, 2) + 2\lambda + \mu,\ 1 \le d \le n\text{-}1,\ 1 \le j \le m_d \qquad (4.4)$$
$$T_d(n\text{-}m, j, 2) = T_d(n\text{-}m+2, j, 1) + \mu + w_d(n\text{-}m, j), \quad 1 \le d \le n\text{-}1,\ 1 \le m \le n\text{-}d,\ 1 \le j \le m_d \qquad (4.5)$$
$$T_d(n\text{-}m+1, j, 1) = T_d(n\text{-}m, j, 2) + 2\lambda + \mu,\ 1 \le d \le n\text{-}1, \quad 1 \le m \le n\text{-}d,\ 1 \le j \le m_d \qquad (4.6)$$

Note that in (4.3), if $d = n$ -1 and $m_n = 1$, after loading a wafer into Step n, the robot needs to wait there until this wafer completes its processing and then unloads it, which means that no robot moving is required.

After loading the m_{n-1}th wafer into Step n at time $T_{n-1}(n, m_{n-1}, 1)$, State W_n is reached. Then, the system evolves from States W_n to W_{n+1}, at this time all PCs are emptied, i.e., the closed-down process ends. During this process, we have

$$T_n(n, 1, 2) = T_{n\text{-}1}(n, m_{n\text{-}1}, 1) + w_n(n, 1)$$

or

$$T_n(n, 1, 2) = T_{n\text{-}1}(n, m_{n\text{-}1}, 1) + w_n(n, 1) + \mu, \text{ if } 2 \le m_n \qquad (4.7)$$

At time $T_n(n, 1, 2)$, a wafer has been unloaded from a PC at Step n and is moved and loaded to a loadlock, or we have

$$T_n(0, 1, 1) = T_n(n, 1, 2) + 2\lambda + \mu$$

Next, if $m_n \geq 2$, the robot goes back to Step n again and unloads another wafer from it, or we have

$$T_n(n, 2, 2) = T_n(0, 1, 1) + w_n(n, 2) + \mu$$

For a general case, we have:

$$T_n(n, j, 2) = T_n(0, j\text{-}1, 1) + w_n(n, j) + \mu,\ 2 \leq j \leq m_n \quad (4.8)$$

and $$T_n(0, j, 1) = T_n(n, j, 2) + 2\lambda + \mu,\ 1 \leq j \leq m_n \quad (4.9)$$

To make sure that the waiting time at a step is nonnegative, we have (4.10) and (4.11).

$$w_d(d\text{-}m, j) \geq 0,\ 1 \leq d \leq n\text{-}1,\ 0 \leq m \leq n\text{-}d,\ 1 \leq j \leq m_d \quad (4.10)$$

$$w_n(n, j) \geq 0,\ 1 \leq j \leq m_n \quad (4.11)$$

With T_0 (= 0) being the time when the close-down process starts, there are two different cases for calculating the wafer sojourn time at a chamber:

Case 1: Wafers are loaded into a chamber before T_0, and

Case 2: Wafers are loaded into a chamber after T_0.

For Case 1, we need to know how long the wafers have already stayed in the chambers. To do so, let w_i, $i \in \mathbf{\Omega}_n$, denote the robot waiting time at Step i in the steady state, whose value can be determined by LP1, or $w_i = \omega_{n+j}(m, 1)$, $m \in \mathbf{\Omega}_n$, and $j \in \mathbb{N}_{\mathfrak{R}}$. Further, let ψ denote the system cycle time under the steady state. Then, according to Wu *et al*. [30], we have

$$\psi = 2(\lambda + \mu) + \sum_{i=0}^{n} w_i \quad (4.12)$$

Assume that, for Step i, $i \in \mathbb{N}_n$, Chamber 1 is occupied by the first wafer, Chamber 2 the second, … , and Chamber m_i the last. At T_0, let Υ_{ij}, $i \in \mathbb{N}_n$ and $1 \leq j \leq m_i$, denote the time duration for which a wafer has already stayed in Chamber j at Step i. For Chamber m_1 at Step 1, due to that the robot finishes its loading at T_0, we have $\Upsilon_{1(m_1)} = 0$. For a general case, we have

$$\Upsilon_{1j} = (m_1 - j) \times \psi,\ 1 \leq j \leq m_1 \quad (4.13)$$

To calculate $\Upsilon_{2(m_2)}$, we have the fact that after loading the last wafer into m_2, the robot executes task sequence ⟨moving to the loadlocks → waiting with time w_0 → unloading a wafer from it → moving to Step 1 → loading that wafer there⟩ which takes $2(\lambda + \mu) + w_0$ time units. Thus, we have

$$\Upsilon_{2(m_2)} = 2(\lambda + \mu) + w_0$$

Similar to (4.13), we have

$$\Upsilon_{2j} = 2(\lambda + \mu) + w_0 + (m_2 - j) \times \psi,\ 1 \leq j \leq m_2$$

For a general case, we have

$$\Upsilon_{ij} = 2 \times (i - 1) \times (\lambda + \mu) + \sum_{k=0}^{i-2} w_k + (m_i - j) \times \psi,\ 2 \leq i \leq n,\ 1 \leq j \leq m_i \quad (4.14)$$

With (4.13) and (4.14), we can calculate the wafer sojourn time as follows. For a wafer that is being processed in Chamber k at Step i, $i \in \mathbb{N}_n$ and $1 \leq k \leq m_i$, with k and i being deterministic, we first find the value of o such that $k \in (\sum_{p=1}^{o-1} m_p, \sum_{p=1}^{o} m_p]$. This wafer is unloaded during the state evolution process from W_o to W_{o+1}.

If $\|[1, m_i] \cap (\sum_{p=1}^{o-1} m_p, \sum_{p=1}^{o} m_p]\| = 1$, or $[1, m_i] \cap (\sum_{p=1}^{o-1} m_p, \sum_{p=1}^{o} m_p] = k$, then this wafer is unloaded from Step i, which is performed by starting at time $T_o(i, 1, 2)$. Hence, we have the following constraint.

$$\alpha_i \leq T_o(i, 1, 2) + \Upsilon_{ik} \leq \alpha_i + \delta_i,\ 1 \leq i \leq n,\ 1 \leq j \leq m_i \quad (4.15)$$

If $\|[1, m_i] \cap (\sum_{p=1}^{o-1} m_p, \sum_{p=1}^{o} m_p]\| > 1$, we first let $[1, m_i] \cap (\sum_{p=1}^{o-1} m_p, \sum_{p=1}^{o} m_p] = \{k_1, k_1+1, k_1+2, \ldots, k_1+j\}$, where the value of k_1 is given and the wafer in Chamber k_1 is loaded earlier than the one in Chamber k_1+1, and the one in k_1+p is loaded earlier than the one in k_1+p+1, $1 \leq p \leq j\text{-}1$. Then, we replace the numbers k_1, k_1+1, k_1+2, …, and k_1+j by 1, 2, …, and j+1. In this way, to satisfy the WRTC, we have the following constraint.

$$\alpha_i \leq T_o(i, h, 2) + \Upsilon_{i(k_1+h\text{-}1)} \leq \alpha_i + \delta_i,\ h \in \mathbb{N}_{j+1} \quad (4.16)$$

For Case 2, assume that a jth wafer has just loaded into Step i at time $T_d(i, j, 1)$ with i, j, and d being known, and this wafer is unloaded at time $T_o(i, h, 2)$, where i is known and, o and h need to be determined.

To determine the value of o and h, we have the following results:

1) If there is an s such that $\sum_{r=1}^{s} m_{i-r} < \sum_{k=1}^{i-1} M(p_k) - (m_i - 1) \leq \sum_{r=1}^{s+1} m_{i-r}$, then $o = i - (s + 1)$ and $h = m_i + m_o - \sum_{k=1}^{o} M(p_k) + 1$;
2) If $0 < \sum_{k=1}^{i-1} M(p_k) - (m_i - 1) \leq m_{i\text{-}1}$, then $o = i - 1$ and $h = m_i + m_o - \sum_{k=1}^{o} M(p_k)$; and
3) If $\sum_{k=1}^{i-1} M(p_k) - (m_i - 1) \leq 0$, then $o = i$ and $h = m_i - \sum_{k=1}^{i-1} M(p_k)$.

where $M(p_k)$ represents the number of tokens (wafers) in p_k at time $T_d(i, j, 1)$. By doing so, to meet the WRTC, we have Constraint (4.17).

$$\alpha_i \leq T_o(i, h, 2) - T_d(i, j, 1) \leq \alpha_i + \delta_i \quad (4.17)$$

Then, we have Linear Program 2 (LP2) for scheduling the close-down process as follows.

$$\text{Min}\{\sum_{j=1}^{m_d}\sum_{m=0}^{n-d}\sum_{d=1}^{n-1} w_d(n-m, j) + \sum_{j=1}^{m_n} w_n(n, j)\} \quad (4.18)$$

Subject to: (4.1)-(4.11) and (4.15)-(4.17).

Similar to LP1, LP2 is computationally efficient and we also have the following results for it.

Property 4.1: For the close-down process of a single-arm cluster tool with WRTC, by using the generalized backward strategy, a solution obtained by solving LP2 is optimal and feasible.

Theorem 4.1: For a single-arm cluster tool with WRTC, an optimal and feasible schedule for the close-down process can be obtained by solving LP2 if there exists a feasible cyclic schedule under the steady state.

Proof: By treating the time taken for performing virtual operations as waiting time, it can be shown similarly to that

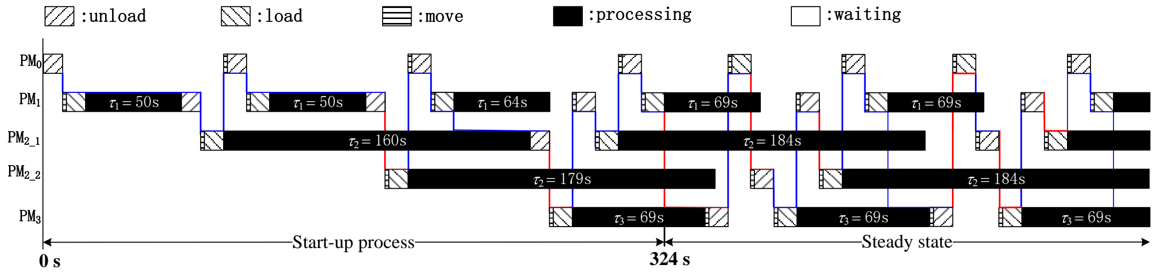

Fig. 7. Simulation result for Example 1.

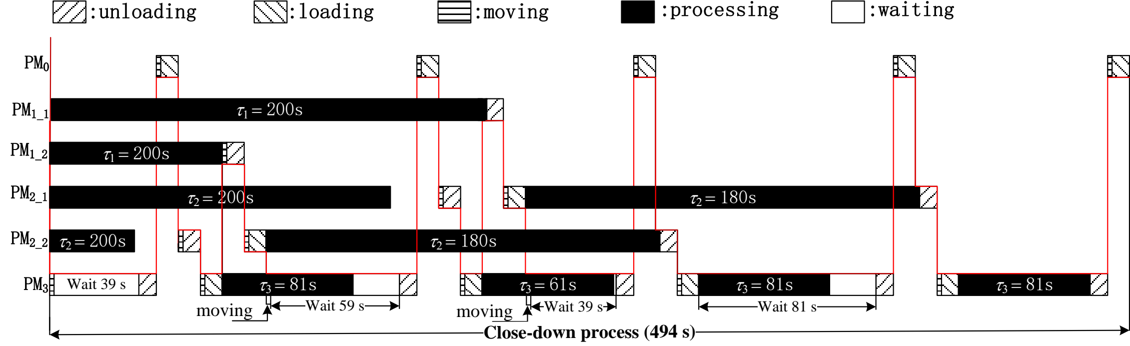

Fig. 8. Simulation result for Example 2.

for Theorem 3.1. ■

V. Illustrative Examples

Example 1: A cluster tool has a wafer flow pattern (1, 2, 1). It takes 50, 160, and 69 time units to process a wafer in a PC at Steps 1, 2, and 3, respectively. After being processed, a wafer can stay in the PC at Steps 1, 2, and 3 for at most 20, 26 and 15 time units, respectively. It needs 10 time units for the robot to unload/load a wafer from/into a PC and 2 time units to move between two different chambers with or without holding a wafer, i.e.,

$\alpha_1 = 50$, $\alpha_2 = 160$, $\alpha_3 = 69$;

$\delta_1 = 20$, $\delta_2 = 26$, $\delta_3 = 15$; and

$\lambda = 10$, and $\mu = 2$.

For this example, by Wu *et al.* [30], a feasible cyclic schedule under the steady state with cycle time 115 is obtained by setting the robot waiting as $w_0 = w_1 = w_2 = 0$, and $w_3 = 19$. With the virtual wafer method proposed by Wu *et al.* [30], it takes 367 time units to finish the start-up process.

With LP1, an optimal and feasible schedule for the start-up process is obtained with robot waiting time being set as shown in Table II. Thereafter, the system enters its steady state and the robot waiting time is set as

$\omega_4(3, 1) = \omega_5(3, 1) = \omega_6(3, 1) = 19$,

$\omega_4(2, 1) = \omega_5(2, 1) = \omega_6(2, 1) = 0$,

$\omega_4(1, 1) = \omega_5(1, 1) = \omega_6(1, 1) = 0$, and,

$\omega_4(0, 1) = \omega_5(0, 1) = \omega_6(0, 1) = 0$.

Note that they are exactly identical to that for the schedule under the steady state, i.e., this start-up process is compatible with the cyclic schedule. Its simulation result is shown in Fig. 7 and it takes 324 time units to complete the start-up process. Compared with the result obtained by Wu *et al.* [30], it shortens the time by 11.7% and it is significant.

Table II. Solution for the start-up process of Example 1.

Start-up process	**Robot waiting time setting**
From States M_0 to M_1	$\omega_1(0, 1) = 0$
From States M_1 to M_2	$\omega_2(1, 1) = 50$, $\omega_2(0, 1) = 0$, $\omega_2(1, 2) = 50$, $\omega_2(0, 2) = 0$
From States M_2 to M_3	$\omega_3(2, 1) = 38$, $\omega_3(1, 1) = 0$, $\omega_3(0, 1) = 0$

Example 2: A cluster tool has a wafer flow pattern (2, 2, 1). It takes 200, 180, and 86 time units to process a wafer in a PC at Steps 1, 2, and 3, respectively. After being processed, a wafer can stay in the PC at Steps 1, 2, and 3 for at most 18, 20 and 22 time units, respectively. It needs 8 time units for the robot to unload/load a wafer from/into a PC and 2 time units to move between two different chambers with or without holding a wafer, i.e.,

$\alpha_1 = 200$, $\alpha_2 = 180$, $\alpha_3 = 60$;

$\delta_1 = 18$, $\delta_2 = 20$, $\delta_3 = 22$; and

$\lambda = 8$, and $\mu = 2$.

For this example, by Wu *et al.* [30], a feasible cyclic schedule under the steady state with cycle time 119 is obtained by setting the robot waiting time as $w_0 = w_1 = w_2 = 0$, and $w_3 = 39$. With the virtual wafer method proposed by Wu *et al.* [30], it takes 535 time units to complete the close-down process. Note that the close-down process starts at the time when the last wafer is loaded into Step 1.

Table III. Solution for close-down process of example 2.

Close-down process	**Robot waiting time setting**
From States W_1 to W_2	$w_1(3, 1) = 39$, $w_1(2, 1) = 0$, $w_1(1, 1) = 0$; $w_1(3, 2) = 59$, $w_1(2, 2) = 0$, $w_1(1, 2) = 0$
From States W_2 to W_3	$w_2(3, 1) = 39$, $w_2(2, 1) = 0$; $w_2(3, 2) = 81$, $w_2(2, 2) = 0$
From States W_3 to W_4	$w_3(3, 1) = 60$

With LP2, an optimal and feasible schedule for the close-down process is obtained with robot waiting time being set as shown in Table III. Note that the robot waiting time setting is compatible with that for the steady state schedule.

Its simulation result is shown in Fig. 8 and it takes 494 time

units to complete the closed-down process. Compared with the result obtained by Wu *et al*. [30], it is reduced by 7.7%.

VI. Conclusions

Cluster tools are widely used to process wafers in semiconductor manufacturing. Recently, due to diversified customer demands, as well as corrective and preventive maintenance, there are frequent close-down and start-up processes for cluster tools. Some wafer manufacturing processes which are characterized by wafer residency time constraint require that a processed wafer should be removed from a chamber in a limited time. Such a requirement makes the scheduling problem of cluster tools more challenging. This work represents the first one that studies the challenging problem of scheduling both start-up and close-down processes for time-constrained single-arm cluster tools with parallel chambers for a processing step. Based on a generalized backward strategy, this work first develops two timed Petri net models to reveal the dynamic behavior during the two transient processes. Based on these models, two linear programs are formulated to search an optimal and feasible schedule. As a result, an optimal and feasible schedule for both processes can be efficiently found.

In this work, all the activity time is seen as deterministic. However, they may be subject to random variation, leading to residency time fluctuation in a chamber, which could make a feasible schedule obtained under fixed activity time infeasible. Hence, the scheduling problem becomes more complex and challenging and it is our future work. It is also very meaningful to extend the obtained result to dual-arm cluster tools.

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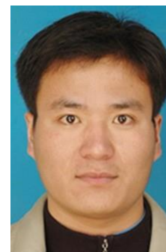

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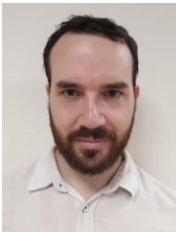

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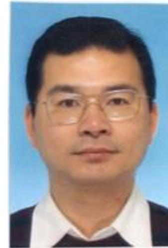

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