Proceedings of the 2015 Winter Simulation Conference
L. Yilmaz, W. K. V. Chan, I. Moon, T. M. K. Roeder, C. Macal, and M. D. Rossetti, eds.

MAKESPAN COMPUTATION OF LOT SWITCHING PERIOD IN SINGLE-ARMED CLUSTER TOOLS

Hyun-Jung Kim

Department of Systems Management Engineering
Sungkyunkwan University
Suwon, 440-746, Republic of Korea

Jun-Ho Lee

Manufacturing Technology Center
SAMSUNG ELECTRONICS
Suwon, 443-742, Republic of Korea

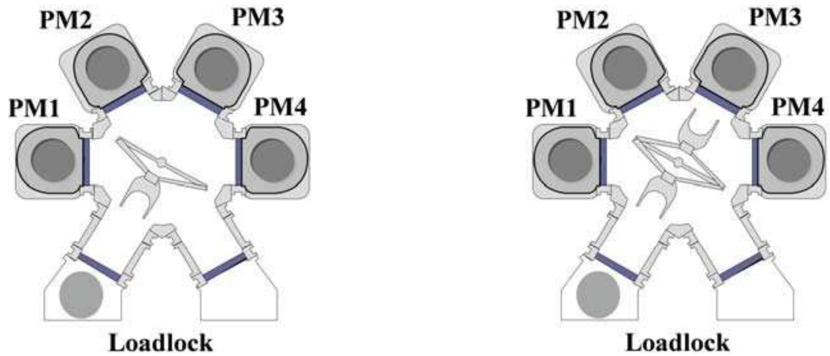
ABSTRACT

In semiconductor manufacturing, wafer cassettes often contain two to three different wafer types due to the larger wafer size, the continual circuit width reduction and the increasing demand for customized products. Hence, the lot switching operation in which the last few wafers of the preceding lot and the first few wafers of the next lot are processed together in cluster tools occurs frequently. In this paper, we analyze an efficient robot task sequence proposed by the previous work for the lot switching operation in single-armed cluster tools and derive closed-form expressions of the makespan of the lot switching period for the first time. With this research, the completion time of a wafer lot can be easily estimated, and then idle times of tools and turnaround times of wafers can be reduced by sending automated material handling systems in advance to unload completed cassettes.

1 INTRODUCTION

Cluster tools, each of which consists of processing modules (PMs), a transport robot, and loadlocks where wafer cassettes are loaded and unloaded, perform most wafer fabrication processes such as lithography, etching, deposition, and even testing in semiconductor manufacturing. In a fab, an overhead hoist transport (OHT) carries a wafer cassette with 25 wafers between cluster tools or a cluster tool and a stocker where wafer cassettes are stored. After a wafer cassette is loaded into the loadlock, each wafer is transported by the robot and processed in the PMs according to its recipe which specifies wafer flow patterns and processing times in each process step. A wafer which finishes all the processes returns to the loadlock. Figure 1 shows single-armed and dual-armed cluster tools. A wafer lot or a lot indicates a set of wafers with the same recipe in a cassette. If a cluster tool keeps processing wafer lots with the same recipe, the robot repeats a certain sequence such as the backward sequence or swap sequence for a single-armed or a dual-armed cluster tool, respectively, and the tool is operated cyclically in steady state (Lee 2008).

Figure 2 shows Gantt charts of the lot switching period in a single-armed cluster tool where the preceding lot and the next lot have the wafer flow patterns of PM1 $\rightarrow$ PM3 and PM1 $\rightarrow$ PM2 $\rightarrow$ PM3, respectively. The preceding lot contains k wafers, and the symbols U, L, and T indicate an unloading, loading, and transporting task of the robot, respectively. The number in each bar is for the wafer identification, and the black box means a wafer waiting for the robot after finishing a process in the corresponding PM. The processing times of the preceding and next lots are 60 s and 75 s, and 90 s, 57 s, and 87 s, respectively. All the robot tasks are assumed to take 3 s. In Figure 2(a), the next lot starts to be processed after the preceding lot is completed whereas the first wafer of the next lot is unloaded from the loadlock right after PM1 becomes available in Figure 2(b). It takes 402 s and 318 s from loading the kth wafer of the preceding lot into PM1 to loading the 3rd wafer of the next lot into PM1 for the two schedules in Figures 2(a) and 2(b), respectively.



(a) Single-armed cluster tool (b) Dual-armed cluster tool

Figure 1: Cluster tools

For such lot switching operation, Lee, Kim, and Lee (2013) have developed *backward operation-based scheduling for switching* (BOSS) 1 and BOSS 2 for single-armed cluster tools and *swap operation-based scheduling for switching* (SOSS) 1 and SOSS 2 for dual-armed cluster tools. The proposed robot task sequences have been embedded in most of the cluster tools in a fab, and their efficiency has been proved experimentally (Lee, Kim, and Lee 2013). There have been a few studies on transient period scheduling of cluster tools. Ahn and Morrison (2010) have presented an approximation model for the makespan of a wafer lot in a single-armed cluster tool. Nishi and Matsumoto (2015) have proposed a Petri net decomposition approach to derive a near-optimal noncyclic schedule of a dual-armed cluster tool. There have also been studies on developing optimal algorithms for noncyclic scheduling of cluster tools (Kim et al. 2013; Kim, Lee, and Lee 2015a; Kim, Lee, and Lee 2015b; Wikborg and Lee 2013). We note that many studies have been performed on cyclic scheduling of cluster tools with reentrant wafer flows and time window constraints (Venkatesh et al. 1997; Rostami, Hamidzadeh, and Camporese 2001; Kim et al. 2003; Kim and Lee 2008; Jung and Lee 2012; Wu et al. 2013; Wu et al. 2013; Qiao, Wu, and Zhou 2012; Lee, Kim, and Lee 2014).

Obtaining the makespan of the lot switching period is critical in integrating the operation of OHTs and cluster tools. In a fab, when a wafer lot finishes all the processes in a tool, the tool sends a signal to a material control system which assigns an OHT to carry the lot. Then the OHT starts to move to the tool and transports the lot to the next destination. Hence, the completed lot should wait for the OHT to arrive, and the tool becomes idle unless there is another lot in the loadlock. All these throughput degradation problems are mostly caused by a lack of information about the lot completion time. However, it is not easy to compute the lot completion time because of the lot switching operation of two different wafer lots during transient periods.

Hence, in this paper, we analyze the proposed sequence in Lee, Kim, and Lee (2013) and derive closed-form expressions of the makespan of the lot switching period in single-armed cluster tools for the first time. With this research, the lot completion time can be estimated easily, which leads to the reduction of waiting times of wafer lots because OHTs can be sent just in time to unload the completed lots. Then the operation of OHTs and cluster tools can finally be integrated and synchronized. In addition to the integrated operation, wafer lots can be assigned to cluster tools efficiently while minimizing the lot switching period. We first describe our problem in detail by introducing the sequence in Lee, Kim, and Lee (2013) and some notation.

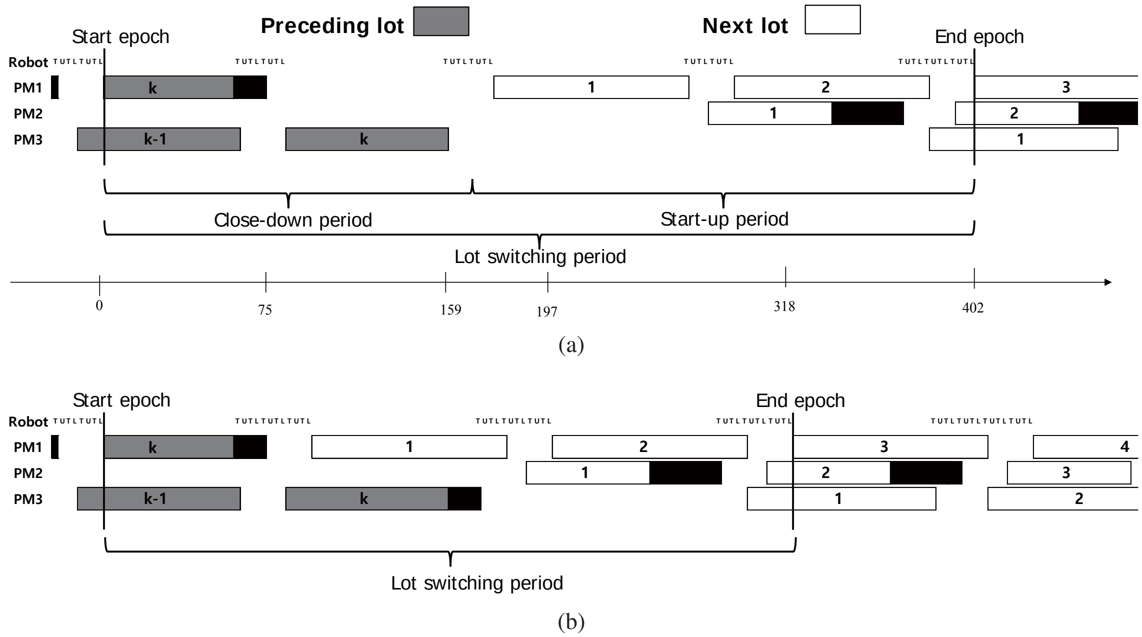


Figure 2: Gantt charts for the lot switching period of a single-armed cluster tool

2 PROBLEM DESCRIPTION

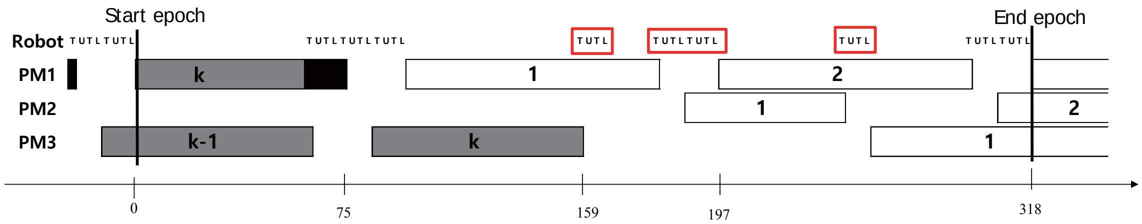
2.1 Preliminaries

We introduce BOSS 1 for a single-armed tool in Lee, Kim, and Lee (2013). The difference between BOSS 1 and BOSS 2 comes from the input timing of wafers of the next lot into the first process step. BOSS 2 makes the robot task sequence more complicated by putting wafers of the next lot into PMs as soon as they are available. The engineers prefer BOSS 1 because they are simpler to operate and provide the similar performance with BOSS 2. To explain BOSS 1, we introduce some notation. We let n_p and n_n denote the numbers of process steps of the preceding and the next lots, respectively. The number of shared PMs by the preceding and next lots is indicated by n_s. We also let PM^i denote the ith shared PM, and d_i^p and d_i^n indicate the numbers of PMs located between PM^{i-1} and PM^i, including PM^i, in the wafer flow patterns of the preceding and next lots, respectively. p_i^p and p_i^n represent the processing times of the ith process step of the preceding lot and next lot, respectively. The robot unloading, loading, and transporting times are indicated by u, l, and t, respectively.

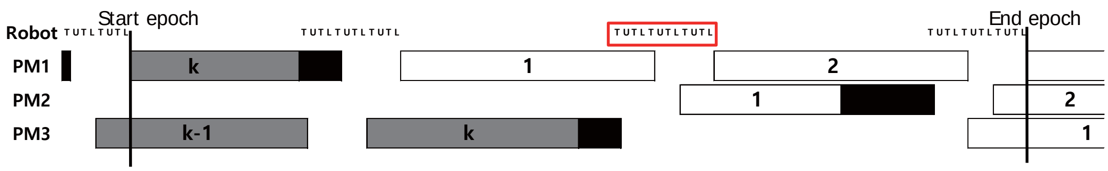
BOSS 1 consists of *backward operation for switching* (BOS) defined as a sequence of robot tasks; unloading a wafer from a PM of process step a, transporting, loading it into a PM of process step $a+1$, moving to a PM of process step b, unloading a wafer from the PM and then loading it into a PM of process step $b+1$ where a and b are the indices for the process steps of the preceding and the next lots, respectively (Lee, Kim, and Lee 2013). BOS(P,N) and BOS(P) indicate the sequences of BOS applied for wafers of both preceding and next wafer lots and only wafers of the preceding lot, respectively. More detailed explanation can be found in Lee, Kim, and Lee (2013).

To avoid deadlock, *difference in flow patterns* (DFP), which identifies the difference between the flow patterns of the two lots, is introduced (Lee, Kim, and Lee 2013). DFP is computed by $\sum_{i=1}^{n_s} \max(d_i^p - d_i^n, 0)$. Lee, Kim, and Lee (2013) have proved that BOS is free from deadlock if and only if DFP is equal to 0. Then BOSS 1 can be presented as follows (Lee, Kim, and Lee 2013):

- BOSS 1:
  If DFP=0,



(a)



(b)

Figure 3: Robot task timing assumption in a single-armed tool

then, repeat BOS(P,N) n_n times.
Else,
then, repeat BOS(P) DFP times, and
then, repeat BOS(P,N) n_n times.

If DFP is 0, wafers of the next lot are loaded into PMs right after the corresponding PMs become available. Otherwise, the robot first performs BOS for wafers of the preceding lots DFP times and then unloads the first wafer of the next lot from the loadlock.

2.2 Description of Lot Switching Operation

The lot switching period starts when the last n_p wafers of the preceding lot are loaded into each PM and ends when the first n_n wafers of the next lot are loaded into PMs as in Figure 2. We do not consider the reentrant flows or time window constraints. The setup time during the lot switching is ignored because lots with similar recipes are mostly operated in the same tool and dummy wafers, which can be considered as a new wafer lot, are often used to adjust the gases or pressure in PMs. In addition, the processing times of the preceding and next lots are mostly well-balanced; that is, the difference in the processing times is not large, which follows the practice.

We assume that the robot follows BOSS 1 for single-armed tools during the lot switching period and the preceding and next lots share at least one PM. The well-known backward sequence is used only in steady state operation. The earliest starting policy, in which the robot performs all the tasks at the earliest possible time, is not assumed. Figures 3(a) and (b) show Gantt charts of a single-armed cluster tool with and without the earliest starting policy, respectively. The robot in Figure 3(b) performs its tasks for a cycle consecutively as indicated by the rectangle in red while causing no delay in the bottleneck PM, PM1 in this case. We call such a policy *bottleneck-based starting policy* (BSP). However, it loads and unloads wafers as soon as the corresponding activity is completed under the earliest starting policy in Figure 3(a). We can see that the two schedules in Figure 3 give the same makespan. In this paper, we follow the BSP for a single-armed tool as in Figure 3(b) to analyze the makespan of the lot switching period systematically. Under the BSP, the processing times of wafers in PMs can be considered the same as the maximum processing time in the bottleneck PM in each cycle. For example, in Figure 3(b), p_2^n is 57 s but we can think of it as 90 s because of the wafer delay in the PM.

If we focus on the processes in PM1 of Figure 2(b), the makespan of the lot switching period can be obtained by $p_1^p + (u+l+3t) + R + p_1^n + R + p_1^n + R$ where R indicates the robot task time required to unload a finished wafer from a PM and load a new wafer into the PM under the backward operation, which is $2u+2l+3t$. The formula for the makespan can be generalized to $p_1^p + (u+l+3t) + R + \max(p_2^p, p_1^n) + R + \max(p_1^n, p_2^n) + R$. If the 3rd wafer was in progress in PM1 at the end epoch, then we also need to add the past processing time to the formula. Hence, to obtain the makespan of the lot switching period, we need to compute the remaining processing and waiting times of wafers in PMs from the start epoch, the maximum processing time in each cycle, and the past processing times of wafers in PMs at the end epoch. Then we only need to add the robot task time R as much as required.

3 LOT SWITCHING OPERATION

3.1 Analysis of the Remaining and Past Processing Times

We first find a shared PM which keeps processing wafers of the preceding and next lots without any long idle time under BOSS 1. Such PM can be easily determined by comparing PMs used for the $(q+DFP)$th process step of the preceding lot and the qth process step of the next lot where $1 \le q \le \min(n_p - DFP, n_n)$. Since the preceding and next lots have similar recipes to be processed in the same tool, there can be several such PMs used by both lots. In this case, we select a PM with the smallest index without loss of generality and let s_p and s_n denote the process steps of the preceding and next lots, respectively. In Figure 3, s_p and s_n are both 1. We also let $p_{max}^p = \max_{i \le n_p}(p_i^p - (i-1)(u+l+2t))$ and $j^* = \arg\max_{i \le n_p}(p_i^p - (i-1)(u+l+2t))$ which indicate the maximum remaining processing time and the corresponding process step at the start epoch, respectively. Then, in a single-armed cluster tool, $p_{s_p}^s$, the remaining time of a wafer in the s_pth process step of the preceding lot from the start epoch to the arrival of the robot to unload the wafer, can be computed as follows:

$$p_{s_p}^s = p_{max}^p - (s_p - j^*)(u+l+2t). \tag{1}$$

We note that the processing times are mostly much larger than the robot task time (Kim, Lee, Lee, and Park 2003). Hence, it is reasonable to assume that $p_{s_p}^s$ is always larger than or equal to 0. We can also compute the past processing time of a wafer in the s_nth process step of the next lot at the end epoch, $p_{s_n}^s$, as follows:

$$p_{s_n}^s = (s_n - 1)(u+l+2t). \tag{2}$$

During the lot switching period, there are $(n_n - 1 + DFP)$ cycles except the ongoing processes at the start and end epochs, and $(n_n + DFP)$ R's are required with BOSS 1. Then the makespan of the lot switching period is obtained by $p_{s_p}^s + \sum_{i=1}^{n_n-1+DFP} C_i + p_{s_n}^s + (n_n+DFP)R$ where C_i indicates the maximum processing time in cycle i. We now only need to compute C_i for each cycle i.

3.2 Maximum Processing Time in a Cycle

We analyze the maximum processing time in each cycle. Computing C_i is not easy because it depends on the processing times of the two consecutive lots, their flows and DFP. In Figure 4 which has the same schedule as in Figure 2(b), $C_1 = \max(p_1^n, p_2^p)$ and $C_2 = \max(p_1^n, p_2^n)$. We first consider the case in which the DFP is 0.

3.2.1 DFP = 0

If DFP is 0, the robot unloads the first wafer of the next lot right after the PM of the first process step becomes empty as in Figure 4, and follows the backward operation n_n times. Then C_1 is equal to $\max(p_1^n, p_2^p, p_3^p, \cdots, p_{n_p}^p)$ because there are $n_p - 1$ wafers processed in PMs when the first wafer of

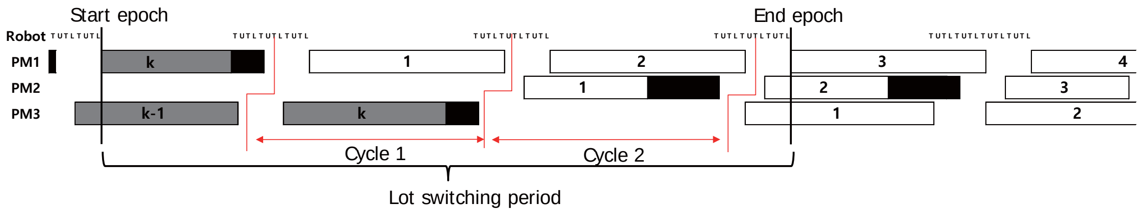


Figure 4: Analysis for the lot switching period

the next lot is loaded into the first process step. In a similar way, $C_2 = \max(p_1^n, p_2^n, p_3^p, \cdots, p_{n_p}^p)$, $C_3 = \max(p_1^n, p_2^n, p_3^n, p_4^p, \cdots, p_{n_p}^p)$, and so on. We can generalize C_i as follows:

$$\text{When } n_p > n_n,\ \ C_i = \max(p_1^n, \cdots, p_i^n, p_{i+1}^p, \cdots, p_{n_p}^p) \quad 1 \le i \le n_n - 1. \tag{3}$$

$$\text{When } n_p \le n_n,\ \ C_i = \max(p_1^n, \cdots, p_i^n, p_{i+1}^p, \cdots, p_{n_p}^p) \quad 1 \le i \le n_p, \tag{4}$$

$$C_i = \max(p_1^n, \cdots, p_i^n) \quad n_p < i \le n_n - 1. \tag{5}$$

3.2.2 DFP $\neq$ 0

If DFP is not 0, the robot first applies the backward operation for the wafers of the preceding lot DFP times and then unloads the first wafer of the next lot into the first process step to avoid the deadlock. Then unlike the case of DFP=0, there is no wafer of the next lot until the DFPth cycle. Hence, $C_1 = \max(p_2^p, p_3^p, \cdots, p_{n_p}^p)$, $C_2 = \max(p_3^p, \cdots, p_{n_p}^p)$, and $C_{DFP} = \max(p_{DFP+1}^p, p_3^p, \cdots, p_{n_p}^p)$. Then $C_{DFP+1} = \max(p_1^n, p_{DFP+2}^p, \cdots, p_{n_p}^p)$. The followings show the generalized C_i's.

$$\text{When } n_p > n_n,\ \ C_i = \max(p_{i+1}^p, p_{i+2}^p, \cdots, p_{n_p}^p) \quad 1 \le i \le DFP, \tag{6}$$

$$C_i = \max(p_1^n, p_2^n, \cdots, p_{i-DFP}^n, p_{i+1}^p, \cdots, p_{n_p}^p) \quad DFP < i \le n_n - 1 + DFP. \tag{7}$$

$$\text{When } n_p \le n_n,\ \ C_i = \max(p_{i+1}^p, p_{i+2}^p, \cdots, p_{n_p}^p) \quad 1 \le i \le DFP, \tag{8}$$

$$C_i = \max(p_1^n, p_2^n, \cdots, p_{i-DFP}^n, p_{i+1}^p, \cdots, p_{n_p}^p) \quad DFP < i \le n_p - 1, \tag{9}$$

$$C_i = \max(p_1^n, p_2^n, \cdots, p_{n_n-1}^n) \quad n_p \le i \le n_n - 1 + DFP. \tag{10}$$

From the above analysis, we now can obtain the complete makespan of the lot switching period in a single-armed cluster tool with $p_{s_p}^s + \sum_{i=1}^{n_n-1+DFP} C_i + p_{s_n}^s + (n_n + DFP)R$. Even though the makespan can also be obtained with a linear programming model or a critical path algorithm, we have derived the closed-form expressions for the first time.

In Figure 4, $p_{s_p}^s$ and $p_{s_n}^s$ as 75 s and 0 s, respectively. For computing C_i, we utilize formula (4) because $n_p < n_n$ and $n_p = n_n - 1$. Then $C_1 = \max(p_1^n, p_2^p)$ and $C_2 = \max(p_1^n, p_2^n)$ as explained with the Gantt chart. Then the makespan becomes 318 s ($= 75 + 90 + 90 + 0 + 63$).

4 DISCUSSION

After the end epoch, a single-armed tool can be operated with the backward sequence because each PM has a wafer of the next lot. Hence, the completion time of a wafer lot can be obtained by adding the makespan of the transient periods and the cycle times from the backward sequence. As we previously mentioned, the completion time can be utilized to integrate the operation of OHTs and cluster tools so that the tool idle time and the wafer turnaround time can be reduced. In addition, the makespan of the lot switching operation can be used for assigning wafer lots to cluster tools while minimizing the lot switching period. When there are multiple wafer lots and multiple cluster tools, assigning lots to tools can be considered as the traditional scheduling problem, scheduling jobs on parallel machines with sequence-dependent setup times. In this case, the makespan of the lot switching period becomes the setup time.

5 CONCLUSION

In this paper, we have analyzed the lot switching period of single-armed cluster tools with BOSS 1. We first have derived the remaining and past processing times at the start epoch and at the end epoch, respectively. Then we have presented the maximum processing time in each cycle depending on DFP, n_n, and n_p. We have provided the closed-form expressions for the first time which can be used for sending OHTs to tools in advance and assigning wafers lots to tools to minimize the setup times.

The sequence, BOSS 1, has been widely used in cluster tools but its efficiency has only been proved experimentally. We are working on analyzing the optimality of the sequences and planning to provide new assignment rules of wafer lots based on the makespan derived in this study. In addition, release timing of OHTs to tools should also be analyzed since we now can estimate the completion time of a wafer lot. Our work can be extended to dual-armed cluster tools with SOSS 1. However, the robot task timing assumption should be further analyzed because the BSP can increase the lot switching period in dual-armed cluster tools.

ACKNOWLEDGEMENT

This work was supported by the ICT R&D program of MSIP/IITP. [B0364-15-1008, Development of Open FaaS IoT Service Platform for Mass Personalization]

REFERENCES

Ahn, Y., and J. R. Morrison. 2010. “Analysis of circular cluster tools: Transient behavior and semiconductor equipment models”. In *Proceedings of the 2010 IEEE Conference on Automation Science and Engineering*, 39–44. Toronto, Canada.

Jung, C., and T.-E. Lee. 2012. “An efficient mixed integer programming model based on timed Petri nets for diverse complex cluster tool scheduling problems”. *IEEE Transactions on Semiconductor Manufacturing* 25 (2): 186–199.

Kim, D.-K., T.-E. Lee, and H.-J. Kim. 2015. “Optimal scheduling of transient cycles for single-armed cluster tools with parallel chambers”. *IEEE Transactions on Automation Science and Engineering* to appear.

Kim, H.-J., J.-H. Lee, C. Jung, and T.-E. Lee. 2013. “Scheduling cluster tools with ready time constraints for consecutive small lots”. *IEEE Transactions on Automation Science and Engineering* 10 (1): 145–159.

Kim, H.-J., J.-H. Lee, and T.-E. Lee. 2015a. “Noncyclic scheduling of cluster tools with a branch and bound algorithm”. *IEEE Transactions on Automation Science and Engineering* 12 (2): 690–700.

Kim, H.-J., J.-H. Lee, and T.-E. Lee. 2015b. “Time-feasible reachability tree for noncyclic scheduling of timed Petri nets”. *IEEE Transactions on Automation Science and Engineering* DOI: 10.1109/TASE.2014.2313979.

Kim, J.-H., and T.-E. Lee. 2008. “Schedulability analysis of time-constrained cluster tools with bounded time variation by an extended Petri net”. *IEEE Transactions on Automation Science and Engineering* 5 (3): 490–503.

Kim, J.-H., T.-E. Lee, H.-Y. Lee, and D.-B. Park. 2003. “Scheduling analysis of time-constrained dual-armed cluster tools”. *IEEE Transactions on Semiconductor Manufacturing* 16 (3): 521–534.

Kim, T.-K., C. Jung, and T.-E. Lee. 2013. “Scheduling start-up and close-down periods of dual-armed cluster tools with wafer delay regulation”. *International Journal of Production Research* 50 (10): 2785–2795.

Lee, J.-H., H.-J. Kim, and T.-E. Lee. 2013. “Scheduling lot switching operations for cluster tools”. *IEEE Transactions on Semiconductor Manufacturing* 26 (4): 592–601.

Lee, J.-H., H.-J. Kim, and T.-E. Lee. 2014. "Scheduling cluster tools for concurrent processing of two wafer types". *IEEE Transactions on Automation Science and Engineering* 11 (2): 525–536.

Lee, T.-E. 2008. "A review of scheduling theory and methods for semiconductor manufacturing cluster tools". In *Proceedings of the 2008 Winter Simulation Conference*, 2127–2135. Austin, TX, USA.

Nishi, T., and I. Matsumoto. 2015. "Petri net decomposition approach to deadlock-free and non-cyclic scheduling of dual-armed cluster tools". *IEEE Transactions on Automation Science and Engineering* 12 (1): 281–294.

Qiao, Y., N. Q. Wu, and M. C. Zhou. 2012. "Petri net modeling and wafer sojourn time analysis of single-arm cluster tools with residency time constraints and activity time variation". *IEEE Transactions on Semiconductor Manufacturing* 25 (3): 432–446.

Rostami, S., B. Hamidzadeh, and D. Camporese. 2001. "An optimal periodic scheduler for dual-armed robots in cluster tools with residency constraints". *IEEE Transactions on Robotics and Automation* 17 (5): 609–349.

Venkatesh, S., R. Davenport, P. Foxhoven, and J. Nulman. 1997, November. "A steady-state throughput analysis of cluster tools: Dual-blade versus single-blade robots". *IEEE Transactions on Semiconductor Manufacturing* 10 (4): 418–424.

Wikborg, U., and T.-E. Lee. 2013. "Noncyclic scheduling for timed discrete-event systems with application to single-armed cluster tools using Pareto-optimal optimization". *IEEE Transactions on Automation Science and Engineering* 10 (3): 699–710.

Wu, N. Q., F. Chu, C. Chu, and M. C. Zhou. 2013. "Petri net modeling and cycle time analysis of dual-arm cluster tools with wafer revisiting". *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 43 (1): 196–207.

Wu, N. Q., M. C. Zhou, F. Chu, and C. Chu. 2013. "A Petri-net-based scheduling strategy for dual-arm cluster tools with wafer revisiting". *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 43 (5): 1182–1194.

AUTHOR BIOGRAPHIES

Hyun-Jung Kim is an Assistant Professor with the Department of Systems Management Engineering at Sungkyunkwan University. She holds a Ph.D. in industrial and systems engineering from Korea Advanced Institute of Science and Technology. Her research interests include discrete-event system modeling, scheduling and control. Her email address is kim.hj@skku.edu.

Jun-Ho Lee is a Senior Engineer in the Manufacturing Technology Center at SAMSUNG ELECTRONICS. He holds a Ph.D. in industrial and systems engineering from Korea Advanced Institute of Science and Technology. His research interests include modeling, scheduling, and control of integrated manufacturing equipment for semiconductor manufacturing. His e-mail address is leejh85@gmail.com.