On the Throughput of Clustered Photolithography Tools: Wafer Advancement and Intrinsic Equipment Loss

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Presentation Outline

- Motivation
- Model 1: Synchronous photolithography model
  - System Description
  - Time between lot completions with diverse lot populations
  - Time between lot completions with same class of lots
- Model 2: Asynchronous photolithography model
  - System Description
  - Wafer completion times with a single class of lots
  - Intrinsic equipment loss:
    - Reticle change (as a pause in the bottleneck module)
- Concluding remarks
Motivation

- **Goal:** One generic model for all classes of serial processing cluster tools

- Abstract models useful for clustered photolithography tools
  - Movement of individual wafers can be analyzed
  - Module level rather than conventional tool level approach

- Contribution to flow line literature
  - High fidelity models with direct application to fabricator simulation
  - A new class of failures – setup dependent upon state of system
  - Simplified recursions for system evolution
Synchronous Photolithography Model: System Description

- Wafers can only advance at the same instant as all others in the tool – their movement is synchronized.
- Process time in module $m_j$ for family $F$ lots is $\Delta F_j$.
  - May be 0 to model a buffer (only useful for module failure analysis).
- Let $k(i)$ denote the number of empty modules in advance of lot $l_i$. 

Lots may have different deterministic process times in a module.
Synchronous Photolithography Model: Wafer Advancement

- Rate of wafer advance is dictated by the maximum module time for all occupied modules

- For lot \( l_i \) with family \( \mathcal{F}(i) \), define the effective module process time as

\[
\Lambda_{p,q}^{\mathcal{F}(i)} = \max_{\{r: 1 \leq r \leq p \text{ or } q \leq r \leq M\}} \left\{ \Delta_{r}^{\mathcal{F}(i)} \right\}
\]

- The slowest possible effective process time is

\[
\Lambda^{\mathcal{F}(i)} = \max_{j} \Delta_{j}^{\mathcal{F}(i)}
\]
Synchronous Photolithography Model: Lot Completion for Diverse Lot Populations

- There are two families of lots
- Time between the departure of the previous lot and departure of lot $\ell_i$ may be calculated as:

\[
T_i = \sum_{j=M-k(i)}^{M-1} \Lambda_{j,M+1}^{F(i)} + (W - M + 1)\Lambda_{i+1}^{F(i)} + \sum_{j=1}^{k(i+1)} \Lambda_{0,j}^{F(i)} + \sum_{j=2+k(i+1)}^{M} \max(\Lambda_{0,j}^{F(i)}, \Lambda_{j-[1+k(i+1)],M+1}^{F(i+1)})
\]

Here, for notational simplicity, we assume that at most two lots can be on the tool at any instant.
Synchronous Photolithography Model: Lot Completion for Uniform Lot Population

- Lots are of same family
- Time between the departure of the previous lot and departure of lot $\ell_i$ may be calculated as:

$$T_i = \sum_{j=M-k(i)}^{M-1} \Lambda_{j,M+1} + (W - M + 1)\Lambda_{k(i+1), k(i+1)} + \sum_{j=1}^{M} \Lambda_{0,j} + \sum_{j=2+k(i+1)}^{M} \Lambda_{j-[1+k(i+1)],j}$$

Here, for notational simplicity, we assume that at most two lots can be on the tool at any instant.
Synchronous Photolithography Model: Example

Parameters:
M = 11 and W = 10

<table>
<thead>
<tr>
<th>Process Times</th>
<th>$\Delta_1$</th>
<th>$\Delta_2$</th>
<th>$\Delta_3$</th>
<th>$\Delta_4$</th>
<th>$\Delta_5$</th>
<th>$\Delta_6$</th>
<th>$\Delta_7$</th>
<th>$\Delta_8$</th>
<th>$\Delta_9$</th>
<th>$\Delta_{10}$</th>
<th>$\Delta_{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Family F1</td>
<td>20</td>
<td>25</td>
<td>40</td>
<td>35</td>
<td>30</td>
<td>50</td>
<td>15</td>
<td>35</td>
<td>45</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Family F2</td>
<td>30</td>
<td>35</td>
<td>50</td>
<td>45</td>
<td>40</td>
<td>60</td>
<td>25</td>
<td>45</td>
<td>55</td>
<td>30</td>
<td>40</td>
</tr>
</tbody>
</table>
Asynchronous Photolithography Model: System Description

- Assume that all wafers in the tool advance at their own rate so long as there are module locations available to do so.

- Process time in module $m_j$ for all lots is $\Delta_j$.
  - May be 0 to model a buffer.
  - Only one class of lots (can readily model many classes but requires full simulation approach).

Lots are of same class, but may have different size.
Asynchronous Photolithography Model: Parameters

- Number of modules in the cluster: $M$
- Process time for a wafer in module $m$: $\Delta_m$
- Largest (bottleneck) process time: $\Lambda$
- Number of wafers per lot: $W$
- Denote the $i$-th lot: $\ell_i$
- Arrival time of lot $\ell_i$: $a_i$

Lots are of same class, but may have different size

- Includes buffers
- Can easily generalize to depend upon the lot
Asynchronous Photolithography Model: Wafer Advancement

- The evolution equations for the system may be written
- Let $x_j(w)$ denote the entry time of wafer $w$ to module $m_j$,
- At the first module:
  \[ x_1(w) = \max \{a_w, x_2(w - 1)\} \]
- For the intermediate modules ($2 \leq w \leq M-1$):
  \[ x_j(w) = \max \{x_{j-1}(w) + \Delta_{j-1}, x_{j+1}(w - 1)\} \]
- For the last module:
  \[ x_M(w) = \max \{x_{M-1}(w) + \Delta_{M-1}, x_M(w - 1) + \Delta_M\} \]
Asynchronous Photolithography Model: Towards Completion Time

The completion $C_i$ time of lot $l_i$ is dictated by two possibilities:

- **Case i**: Lot $l_i$ arrives early enough so that its wafers begin to exit immediately after those of lot $l_{i-1}$

  $$C_i = C_{i-1} + W \Lambda$$

  One wafer exits every $\Lambda$ units of time

- **Case ii**: Lot $l_i$ arrives so late that it does not run into lot $l_{i-1}$ in front of it

  $$C_i = a_i + \sum_{j=1}^{M} \Delta_j + (W - 1)\Lambda$$

  Remaining wafers exit every $\Lambda$ units of time

  First wafer exits
Asynchronous Photolithography Model: Completion time

The completion $C(i)$ time of lot $l_i$ obeys the following recursion:

$$C_i = \max \left\{ a_i + e^T \Delta, C_{i-1} + \Lambda \right\} + (W - 1)\Lambda$$

with initial condition (for an empty tool)

$$C_i = a_i + e^T \Delta + (W - 1)\Lambda$$

where

$W = \text{Number of wafers in a lot}$

$a_i = \text{Arrival time of lot } i \text{ to the system}$

$e = (1, \ldots, 1)^T$

$M = \text{Number of modules in the track}$

$\Delta_m = \text{Processing time of a wafer in module } m$

$\Delta = (\Delta_1, \ldots, \Delta_M)^T$

$\Lambda = \max \{\Delta_i\}, \ 1 \leq i \leq M$

**Proof:** Start with the max-plus algebra representation of the evolution equations and employ an induction within an induction
Asynchronous Photolithography Model: Example 1

Example: $M = 5$, $W = 3$, $\Lambda = 50$ sec

\[ C_1 = a_1 + e^T \Delta + (W - 1)\Lambda = 0 + 80 + (3 - 1)30 = 140 \]

\[ C_2 = \max \left\{ a_2 + e^T \Delta, C_1 + \Lambda \right\} + (W - 1)\Lambda = \max \left\{ 85 + 80, 140 + 30 \right\} + (2)(30) = \max \left\{ 165, 170 \right\} + 60 = 230 \]
Asynchronous Photolithography Model: Example 2

**Example:** \( M = 5, W = 3, \Lambda = 50 \text{ sec} \)

\[
C_1 = a_1 + e^T \Delta + (W - 1)\Lambda = 0 + 80 + (3 - 1)30 = 140
\]

\[
C_2 = \max \left\{ a_2 + e^T \Delta, C_1 + \Lambda \right\} + (W - 1)\Lambda = \max \{100 + 80, 140 + 30\} + (2)(30)
\]

\[
= \max \{180, 170\} + 60 = 240
\]
Asynchronous Photolithography Model: One class of Intrinsic Equipment Loss

- If the bottleneck module fails (pauses), a recursion for the completion time of lots may be found
  - Time of the \( r \)-th pause: \( \tau_R(r) \)
  - Duration of the \( r \)-th pause: \( d_R(r) \)

- The first lot which may be delayed by the pause has the smallest lot index satisfying

\[
\left[ \max \left\{ a_i + e^T \Delta, c_{i-1} + \Lambda \right\} + (W - 1)\Lambda \right] - \sum_{j=B+1}^{M} \Delta_j > \tau_R(r)
\]

- Completion time of the lot had there been no pause
- Time after exiting the bottleneck

Departure time from the bottleneck if no pause
Asynchronous Photolithography Model: Completion time with Loss

- Adjust the completion time of the first possibly delayed lot (otherwise use the standard recursion)

\[ C_i = C_i^0 + \max \{0, g_i\} \]

where

\[ C_i^0 = \max \{a_i + e^T \Delta, c_{i-1} + \Lambda\} + (W - 1)\Lambda \]

\[ g_i = \min \left\{ d_R(r), \tau_R(r) + d_R(r) + W\Lambda + \sum_{j=B+1}^{M} \Delta_j - f_i \right\} \]

- Can be used to model **reticle change** events
Asynchronous Photolithography Model: Example with Loss

**Example:** \( M = 5, W = 3, \Lambda = 50 \text{ sec}, \tau_R(r)=95, d_R(r)=15 \)

\[
\begin{align*}
  f_1 &= a_1 + e^T \Delta + (W - 1) \Lambda = 0 + 80 + (3 - 1)30 = 140 \\
  g_1 &= \min \left\{ d_R(r), \tau_R(r) + d_R(r) + W \Lambda + \sum_{j=B+1}^{M} \Delta_j - f_1 \right\} = \min \{ 15, 75 \} = 15 \\
  C_1 &= f_1 + \max \{ 0, g_1 \} = 140 + \max \{ 0, 15 \} = 155 \\
  C_2 &= \max \{ a_2 + e^T \Delta, C_1 + \Lambda \} + (W - 1) \Lambda = \max \{ 100 + 80, 155 + 30 \} + (2)(30) \\
  &= \max \{ 180, 185 \} + 60 = 245
\end{align*}
\]
Concluding Remarks

- Synchronous model
  - Realistic manufacturing system – single robot transfers the wafers
  - K can be used to model intrinsic equipment losses such as
    - Complete tool failure
    - Late lot arrival
    - Setup change

- Asynchronous model
  - “Ideal” manufacturing system with efficient wafer transport system

- Future work
  - Synchronous model of generic arrivals, reticle change and setup change
  - Asynchronous model with setup times
  - Compare performance between models with real data
  - Incorporate into fab simulation
  - Recommend operational design principles