Analysis of Manufacturing Systems 4AB00

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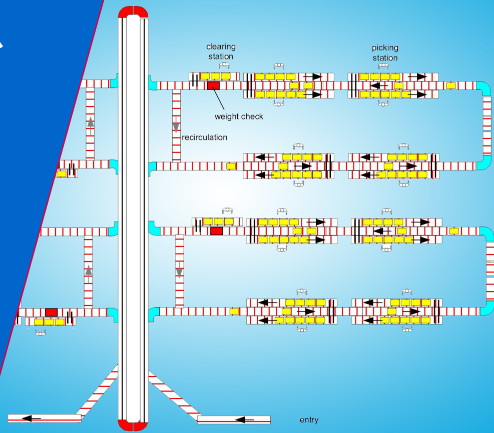

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Contents

Lecture notes on Analysis of Manufacturing Systems

- Chapter 3
- Chapter 6
- Chapter 7

Final examination: Open book

Recap: Variability interactions

- Inter-arrival time is general with mean t_a and standard deviation σ_a
- Process time is general with mean t_e and standard deviation σ_e
- m parallel identical machines

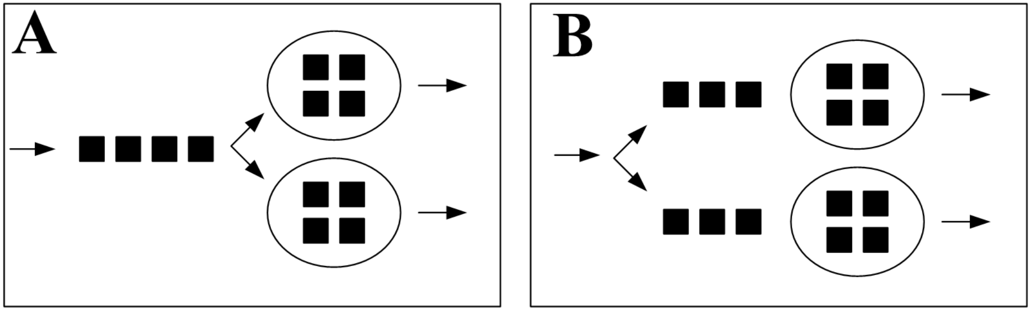
Then

$$\varphi \approx \gamma \cdot \frac{u^{\sqrt{2(m+1)}-1}}{1-u} \cdot \frac{t_e}{m} + t_e$$

with

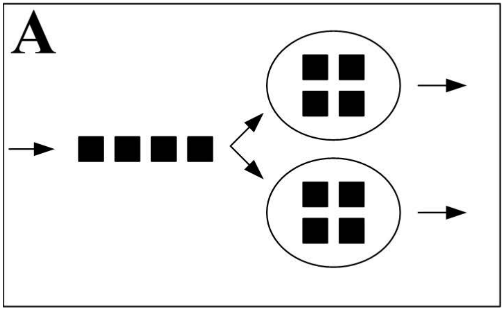
- $u = t_e/(m \cdot t_a)$ (utilization per machine)
- $\gamma = \frac{1}{2} \cdot (c_a^2 + c_e^2)$
- $c_a = \sigma_a / t_a$
- $c_e = \sigma_e / t_e$

Example: Two configurations



- 2 parallel batch machines
- Batch size is $k = 4$
- Jobs arrive according to Poisson stream with rate $r_a = 1$ jobs per hour
- Mean batch processing time is $t_e = 6$ hours
- Variance is $\sigma_e^2 = 18$ hours^2

Example: Configuration A

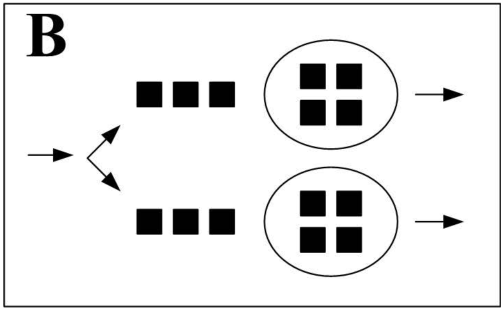


Single common buffer

Questions:

- What is utilization of each machine?
- Determine mean flow time φ

Example: Configuration B



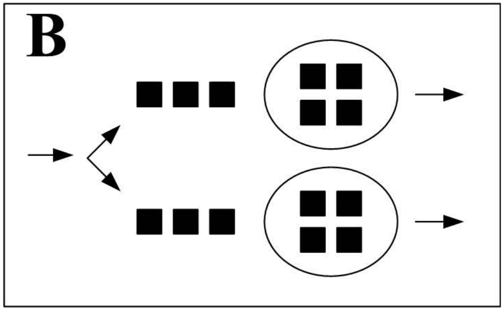
Each machine with own local buffer and round robin assignment

So job 1, 3, ... is sent to buffer 1, and job 2, 4, ... to buffer 2

Questions:

- What is utilization of each machine?
- Determine mean flow time φ
- Compare φ with Configuration A: Explanation?

Example: Configuration B



Each machine with own local buffer and random assignment

So each lot is sent to buffer 1 with probability $\frac{1}{2}$ and to buffer 2 otherwise

Questions:

- What is utilization of each machine?
- Determine mean flow time φ
- Compare φ with Configuration B with round robin: Explanation?

Example: Rework

- Jobs arrive according to Poisson stream with rate $r_a = 0.75$ jobs per hour
- Jobs are processed by single machine, one by one
- Process time of jobs is constant, $t_e = 1$ hour
- Probability of rework is p

Questions:

- What is mean and cv of effective process time?
- For which p is system stable?
- Set $p = 0.2$ and estimate mean flow time in buffer φ_B
- What is effect of reducing $p = 0.2$ to $p = 0.18$? Explain!

Recap: Batching

Types of batches:

- Process batch: Many parts processed together
  - Sequential:
    Parts are produced sequentially before change-over to other family
  - Simultaneous:
    Parts are produced simultaneously (e.g., in furnace)
- Transfer batch: Many parts are moved together
  - The smaller the batch the less time waiting to form the batch
  - The smaller the batch the more material handling

Transfer batches

Model:

- Two-machine serial line
- Single parts arrive with rate r_a at machine 1
- Machine 1 processes parts one-by-one
- Processed parts are transferred to machine 2 in batches
- Transfer batch size is k
- Machine 2 processes parts one-by-one
- $t_e(i)$ and $c_e(i)$ are mean and cv of process time of machine i

Question:

How does mean flow time depend on batch size k?

Transfer batches

- $u(i) = r_a t_e(i)$ is utilization of machine i
- $c_a(1)$ and $c_d(1)$ are cv of arrivals and departures of parts at machine 1

$$c_a(1) = c_a$$

$$c_d^2(1) = u^2(1)c_e^2(1) + (1 - u^2(1))c_a^2(1)$$

- Mean flow time at machine 1

$$\varphi(1) = \left(\frac{c_a^2(1) + c_e^2(1)}{2}\right)\left(\frac{u(1)}{1 - u(1)}\right) t_e(1) + t_e(1)$$

Transfer batches

- Mean wait-to-batch time at machine 1

$$\frac{k-1}{2r_a} = \frac{k-1}{2u(1)}\, t_e(1)$$

- Mean flow time at machine 2 (note $c_a^2(2) = c_d^2(1)$)

$$\begin{aligned}\varphi(2) &= \left(\frac{c_d^2(1)/k + c_e^2(2)/k}{2}\right)\left(\frac{u(2)}{1-u(2)}\right) k t_e(2) + \frac{k+1}{2} t_e(2) \\ &= \left(\frac{c_d^2(1) + c_e^2(2)}{2}\right)\left(\frac{u(2)}{1-u(2)}\right) t_e(2) + \frac{k+1}{2} t_e(2)\end{aligned}$$

- Mean flow time in line

$$\varphi(1) + \frac{k-1}{2u(1)}\, t_e(1) + \varphi(2)$$

Transfer batching interactions

Observations:

- Total flow time increases proportionally with batch size
- This increase has nothing to do with process or arrival variability
- It is caused by variability due to bad control
- Impact of transfer batching is largest when utilization $u(1)$ is low

Cycle time, lead time and service

Cycle (or flow) time T is made up of:

- Move time
- Queue time
- Setup time
- Process time
- Wait-to-batch time
- Wait-in-batch time

Manufacturing lead time l is:

- Time allowed to finish an individual job from start to end of the line

Service s is:

$$s = P(T \leq l) = F(l)$$

where F is distribution function of T

Cycle time, lead time and service

If cycle times T are normally distributed, then for service s

$$l = E(T) + z_s \sigma(T)$$

where z_s is the value for which $\Phi(z_s) = s$

Example:

- Cycle time has mean of 10 days and standard deviation of 3 days
- $z_{0.95} = 1.645$
- Then required manufacturing lead time for service $s = 0.95$ percent

$$l = 10 + 1.645 \cdot 3 = 14.94 \approx 15 \text{ days}$$

- Above additional 5 days are called safety lead time

Lean performance

Performance is closely related to amount of buffers in the system:

- A perfect system will have no buffers at all
- A poorly performing system will contain large buffers

This implies that a manufacturing system is lean if:

- It reaches its objective (e.g. target throughput) with minimal buffering cost

Diagnostics and improvements

Increasing throughput:

Thoughput TH of line is

$$\text{TH} = \text{bottleneck utilization} \times \text{bottleneck rate}$$

Checklist:

- Increase bottleneck rate:
  Add equipment, add staff, improve quality, and so on
- Increase bottleneck utilization:
  Reduce blocking and starvation by buffering
  - WIP by increasing buffers (immediately) in front and after bottleneck
  - Capacity by increasing rates of (highest utilization) non-bottlenecks

Diagnostics and improvements

Reducing cycle time:

Cycle time includes

- Queue time
- Process (wait-to and wait-in) batch time

Checklist:

Queue time is caused by utilization and variability

- Reduce utilization of bottleneck:
  Add equipment, reduces setups, decrease repairs, reduce flow, and so on
- Reduce variability in process times and arrivals:
  Reduce repair and setup times, improve quality, and so on

Process batch time is driven by process batch size

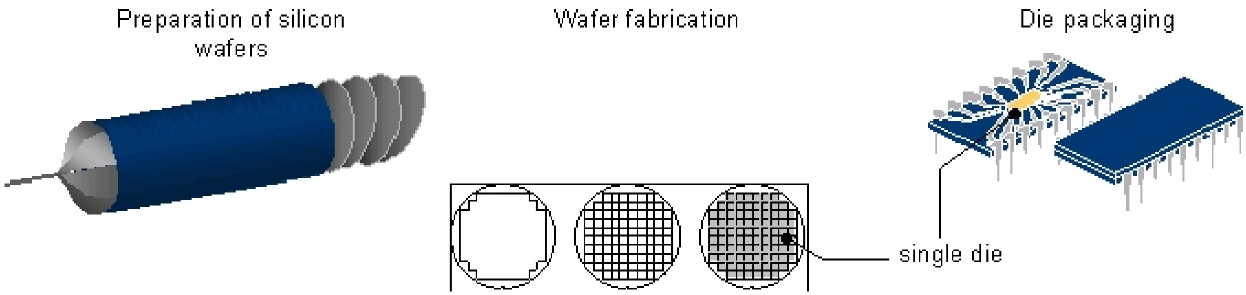
- Batching optimization
- Setup reduction

Example: Enhance throughput

Overview in a waferfab [NXP, Crolles, Grenoble].

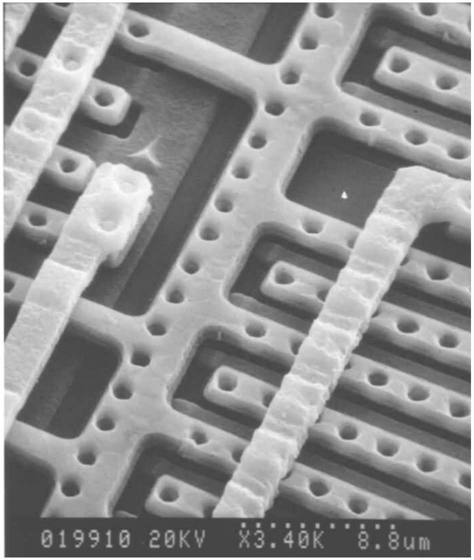
- Most electronic devices contain chips
- Chips contain Integrated Circuits (ICs)
- ICs are made on wafers: complex manufacturing process

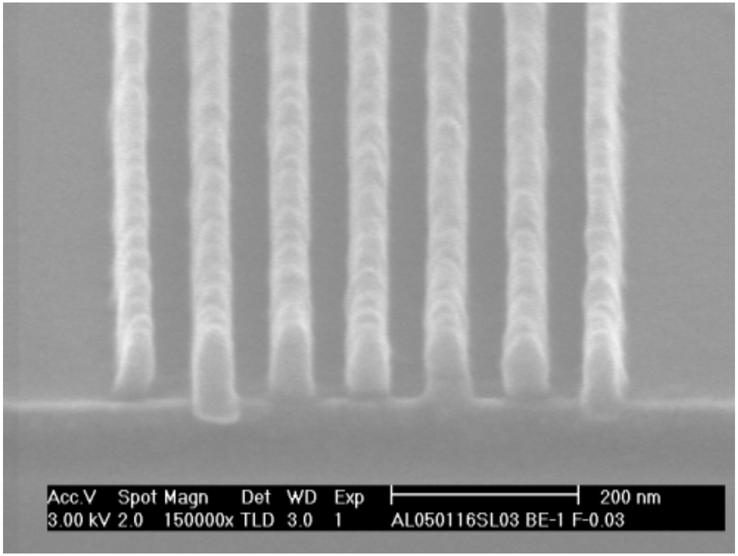
Example: Enhance throughput



- Raw silicon is extracted from sand
- Silicon is sliced into wafers
- Wafers are processed to create dies
- Dies are sawn out and packaged

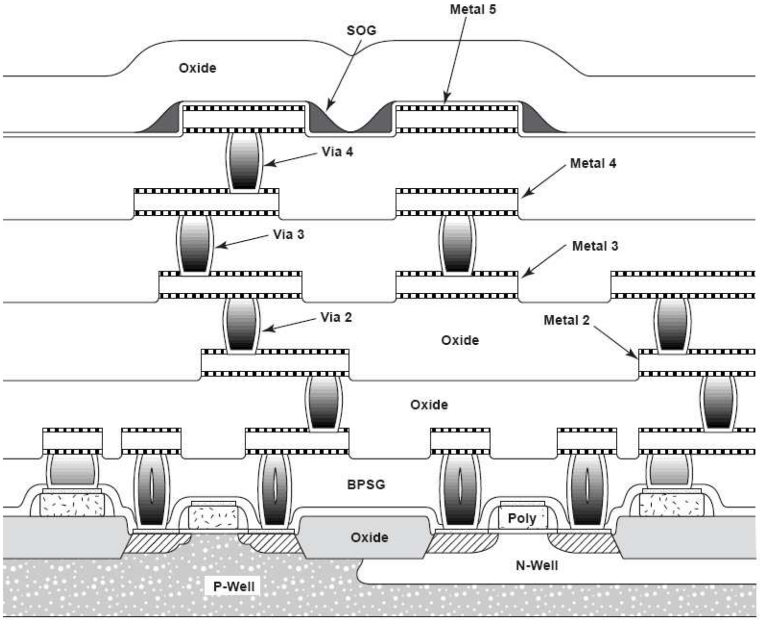
Example: Enhance throughput





Scanning electron microscope image of a wafer [AcceleratedAnalysis, IMEC].

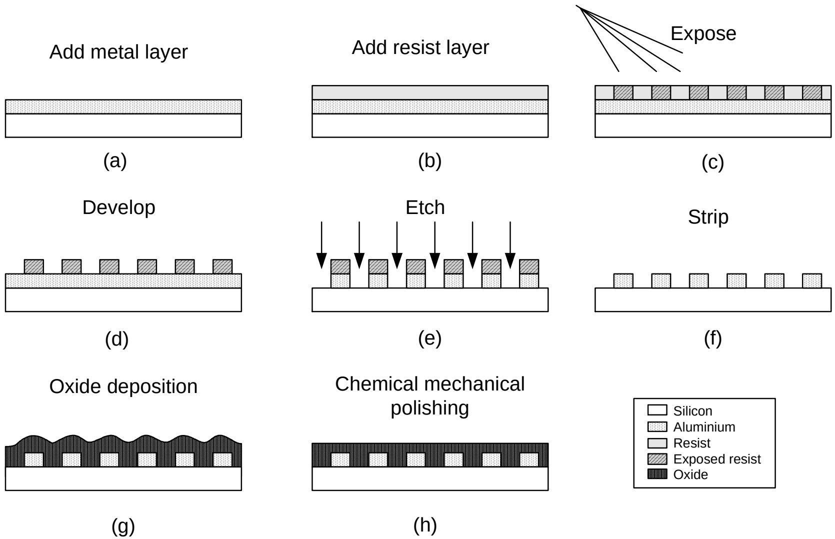
Example: Enhance throughput



Cross section of a wafer

- Five metal layers (contains interconnections, lines and vias)
- Zero layer (contains functionality)

Example: Enhance throughput



- Wafer processing takes a few hundred of process steps
- Typical processes: deposition, exposure, etching, stripping, and oxidation
- Wafer fabrication shows re-entrant behavior:
  A pod contains some 10 wafers and revisits the various process areas

Example: Enhance throughput

A printed-circuit board line with two stations:

- Station 1 (resist apply) applies photoresist material to circuit boards
- Station 2 (expose) exposes boards to ultraviolet light
- Space for WIP between two stations is 20 jobs
- Mean process time $t_0(2) = 22$ (min), cv $c_0(2) = 1$
- Mean process time $t_0(1) = 19$ (min), cv $c_0(1) = 0.5$
- $m_f(2) = 3\frac{1}{3}$ (hour), $m_r(2) = 10$ (min)
- $m_f(1) = 48$ (hour), $m_r(1) = 8$ (hour)
- Arrivals cv $c_a = 1$
- Desired throughput is 2.4 jobs per hour

Question: How to achieve target throughput?

Example: Enhance throughput

Assume unlimited buffer between stations and $r_a = 2.4$ jobs per hour:

$$\begin{aligned}\varphi_q(1) &= 645\text{(min)}\\ \varphi_q(2) &= 887\text{(min)}\end{aligned}$$

so by Little's law

$$\begin{aligned}w_q(1) &= 25.8\\ w_q(2) &= 35.5 > 20!\end{aligned}$$

Hence problem is rooted in long queue at station expose!

Example: Enhance throughput

$$\begin{aligned}
\varphi_q(2) &= \left(\frac{c_a^2(2) + c_e^2(2)}{2}\right)\left(\frac{u(2)}{1 - u(2)}\right) t_e(2) \\
&= (3.116)(12.15)(23.1)(\text{min}) \\
&= 887(\text{min})
\end{aligned}$$

Effective process time

$$\begin{aligned}
t_e(2) &= \frac{t_0(2)}{A(2)} \\
&= \frac{t_0(2)(m_f(2) + m_r(2))}{m_f(2)} \\
&= \frac{22(31/3 + 1/6)}{31/3} \\
&= 23.1(\text{min})
\end{aligned}$$

so little improvement possible by increasing availability $A(2)$

Decreasing $u(2)$ is expensive option

Example: Enhance throughput

Variability inflation factor

$$c_e^2(2) = 1.04, \quad c_a^2(2) = 5.27$$

so arrival variability is dominant source of variability

$$\begin{aligned} c_a^2(2) &= c_d^2(1) \\ &= u^2(1)c_e^2(1) + (1 - u^2(1))c_a^2(1) \\ &= (0.887^2)(6.437) + (1 - 0.887^2)(1.0) \\ &= 5.05 + 0.22 \\ &= 5.27 \end{aligned}$$

so $c_e^2(1)$ makes $c_a^2(2)$ large

Example: Enhance throughput

$c_e^2(1)$ is composed of:

$$
\begin{aligned}
A(1) &= \frac{m_f(1)}{m_f(1)+m_r(1)} \\
&= \frac{48}{48+8} = 0.8571
\end{aligned}
$$

$$
t_e(1) = \frac{t_0(1)}{A(1)} = \frac{19}{0.8571} = 22.17(\text{min})
$$

$$
\begin{aligned}
c_e^2(1) &= c_0^2(1) + \frac{2m_r(1)A(1)(1-A(1))}{t_0(1)} \\
&= 0.25 + \frac{2(480)(0.8571)(0.1429)}{19} = 6.44
\end{aligned}
$$

So improve breakdown situation at resist apply! How?

Note that resist apply is problem, though expose is the bottleneck