How Do Quantity and Quality Really Interact?
Precise Models Instead of Strong Opinions

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Goals of Talk

- To show that there is great benefit in treating quality and quantity *simultaneously* in the design and operation of manufacturing systems.
- To describe recent MIT research.
- To propose directions for further research.
In manufacturing,

- *Quantity* is about how much is produced, when it is produced, and what resources are required to produce it.

- *Quality* is about how well it is made, and how much of it is made well. Production quality is about not giving customers what they do not want.
Introduction

- **Quantity measures** include production rate, lead time, inventory, utilization.

- **Quality measures** include yield and output defect rate.
Introduction

- **Quantity strategies** include optimizing local inventories, optimizing global inventory, other release/dispatch policies, make-to-order, etc.

- **Quality strategies** include inspection, statistical process control, etc.
The problem is that, conventionally, ...

- Quantity strategies are selected according to how they affect quantity measures, and
- Quality strategies are selected according to how they affect quality measures, but ...
- in reality, both affect both.
Others doing closely related research include:

- General Motor Research and Development Center (Marin, Inman, Blumenfeld, Huang, Li, and others)

- Politecnno di Milano (Tolio, Colledani, and others)
- Two-machine, one-buffer production line.
- All production is perfect quality.
- The machines are unreliable — they fail at random times and are repaired at random times.
- We vary the buffer size $N$ and observe its effect on the production rate $P$.
- *Observation:* the production rate increases monotonically up to a limit.
Quantity

Machine Reliability Dynamics

Simplest machine model

UP

DOWN
Quality

Statistical Process Control

- Goal is to determine when a process has gone out of control.
- Upper and lower control limits (UCL, LCL) usually chosen to be $6\sigma$ apart.
- Basic idea: which is the most likely distribution that sample comes from?
Inspection

- Motivation — why inspect?
  
  ★ To take action on parts (accept, rework, or scrap).
  
  ★ To take action on machines (leave alone or repair).
Inspection

- Effects of perfect inspection:
  - ★ Bad parts rejected or reworked.
  - ★ Machine maintained when necessary.

- Effects of inspection errors:
  - ★ Some good parts rejected or reworked; some bad parts accepted.
  - ★ Unnecessary downtime and/or more bad parts.

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Quality Dynamics

• **Definition:** How the quality of a machine changes over time.

• The quality literature distinguishes between *common causes* and *special causes*. (Other terms are also used.)
  
  ★ **Common cause:** successive failures are equally likely, regardless of past history.
  
  GGGGBGGGBGGG GGGGBGGGBGGGGGGGG . . . .

  ★ **Special cause:** something happens to the machine, and failures become much more likely.

  GGGGBGGGGGBGGGGGGGGGBBBB BBBGBBBBGBBBGB . . . .

• We use this concept to extend quantity models.
Versions:

- The *Good* state has 100% yield and the *Bad* state has 0% yield.
- The *Good* state has high yield and the *Bad* state has low yield.
The relationship between quality dynamics and statistical process control:

Note: The operator does not know when the machine is in the bad state until it has been detected.
Separation of Operation and Inspection

Opinions

- Quantity-oriented people tend to assume that increasing a buffer *increases* the production rate.

- Quality-oriented people tend to assume that increasing a buffer *decreases* the production rate of good items.

- However, we have found that the picture is not so simple.
Separation of Operation and Inspection

- $M_1$ has variable quality; the inspection occurs at $M_2$.
- $M_1$ makes only good parts in the $G$ state and only bad parts in the $B$ state.
- Stoppages occur at both machines at random times for random durations.
- The buffer is operated according to FIFO.
- Detection of the $M_1$ state change cannot take place until a bad part reaches $M_2$. 
Separation of Operation and Inspection

Effective production rate = production rate of good parts.

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Separation of Operation and Inspection

Harmful Buffer

![Graph showing the relationship between buffer size and effective production rate]

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Separation of Operation and Inspection

- When the inspection detects the first bad part after a good part, the buffer contains only bad parts.

- In the harmful buffer case, the first machine has a higher isolated total production rate than the second. Therefore, the buffer is usually close to full, no matter how large the buffer is.

- Increasing the size of the buffer increases the number of bad parts in the system when the $M_1$ state change is detected.

- It also increases the total production rate, but not as much as it increases the production rate of bad parts.
In the beneficial buffer case, the first machine has a smaller isolated production rate than the second.

Therefore, even if the buffer size increases, the number of parts in the system is almost always small.

Therefore it is rare for there to be many bad parts in the buffer when the first bad part is inspected.

Consequently, the production rate of bad parts remains limited even as the buffer size increases.
Separation of Operation and Inspection

Mixed-Benefit Buffer

Effective Production Rate vs. Buffer Size

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How many inspections should there be? And where?

- **Intuition:** more inspection improves quality.
- **Reality:** increasing inspection can actually reduce quality, if it is not done intelligently.
Inspections

- We simulated a 15-machine, 14-buffer line.
- All machines and buffers were identical.
- Inspection was not perfect: false positives and negatives occurred.
- We looked at all possible combinations of inspection stations in which all operations were inspected.
  - Example: Inspection stations just after Machines 6, 9, 13, and 15.
  - The first inspection looks at the results from Machines 1 – 6; the second looks at results from Machines 7 – 9; the third from 10 – 13; and the last from 14 and 15.
  - There is always one inspection after Machine 15.
- A total of \(2^{14}=16,384\) cases were simulated.
## Inspections

### Range of Good Production Rates for Different Numbers of Inspection Stations

<table>
<thead>
<tr>
<th>Number of Inspection Stations</th>
<th>Good Production Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.10040</td>
</tr>
<tr>
<td>2</td>
<td>0.295</td>
</tr>
<tr>
<td>3</td>
<td>0.305</td>
</tr>
<tr>
<td>4</td>
<td>0.315</td>
</tr>
<tr>
<td>5</td>
<td>0.325</td>
</tr>
<tr>
<td>6</td>
<td>0.335</td>
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<tr>
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<tr>
<td>8</td>
<td>0.355</td>
</tr>
<tr>
<td>9</td>
<td>0.365</td>
</tr>
<tr>
<td>10</td>
<td>0.375</td>
</tr>
</tbody>
</table>

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A few inspection stations deployed well can do as well or better than many stations deployed poorly.

- The best distribution of 3 stations has a higher effective production rate than the worst distribution of 7 stations.

- The best distribution of 8 stations performs almost as well as 15 inspection stations.
Conclusions

- Combining Q/Q produces unexpected behavior.
- **Yield:**
  - System yield is not a simple function of machine yields.
  - Yield is a function of the system (including the sizes of buffers) and how it is operated.
- This is an important area with many kinds of problems to be studied.
Recent and Current MIT Work

Analytic evaluation of long lines

Ubiquitous inspection:

Single remote inspection of a single machine:

Single remote inspection of multiple machines:

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The three-state machine model is much too simple. One extension is

\begin{itemize}
  \item ... but even this leaves out important features.
\end{itemize}
Another extension is

This allows more general wear or aging models.
A maintenance strategy could be modeled as

\[
\begin{align*}
G_k &\rightarrow G_{k-1} \\
D_k &\rightarrow D_{k-1}
\end{align*}
\]

if we have perfect knowledge of the machine state.
If the machine state is not known perfectly, a better strategy might be:

Here, the machine quality state might be estimated according to the time since the last maintenance, and/or according to measurement data.
Recent and Current MIT Work

Recent and Current MIT Work

Inspection Strategy

• When should we maintain a machine?
• If we repair a machine immediately after seeing one bad part, we may repair machines when they are good.
• If we wait until we see $n$ bad parts, we may make unnecessary bad parts.

• Common *ad hoc* methods:
  ★ Repair for some fixed $n$.
  ★ Repair after inspection measurement has $k$ successive increases or decreases.
Recent and Current MIT Work

Inspection Strategy

Bayes risk methods

- **Bayesian statistics** allows us to update the probability of each machine state after each inspection.

- Bayes risk methods use Bayesian statistics to determine the best time to take an action — such as starting a repair — after obtaining measurement information.

- This leads to a *closed-loop* strategy.
Future Work

General machine model

Machine is making BAD parts

Machine is making GOOD parts

Machine is DOWN
Future Work

Quality dynamics and SPC

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Future Work

Validation and application

- Collect data from factories to assess the realism of our models and methods.
- Apply our results to factory design.
- This activity is already under way with GM.
Future Work

- **Collaborators:** Irvin C. Schick, Jongyoon Kim, Andrea Poffe, Gianpietro Bertuglia

- **Industry Support:** General Motors R & D has generously contributed to the support of this work.