Uncertainty, Variability, Randomness, and Manufacturing Systems Engineering

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People

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- Chuan Shi and Fernando Tubilla, Ph.D. students, M.E.
- Firat Ileri and Kaan Karamanci, M.Eng. students, EECS
- Elisa Gebinnini, visiting Ph.D. student, Universitá Degli Studi Di Modena e Reggio Emilia (Unimore)
- Zheng Wang, Visiting Associate Professor in the MIT Engineering Systems Division; Associate Professor of the School of Automation, Southeast University, Nanjing, China

Philosophy

- *Manufacturing systems can be understood like any complex engineered system,*
  - *using predictive, quantitative methods.*
- *Engineers must have intuition about these systems in order to design and operate them most effectively.*
- *Such intuition can be developed by studying the elements of the system and their interactions.*
- *Using intuition and appropriate predictive, quantitative tools can have a big payoff.*

Basic Issues

- Frequent new product introductions.
- Short product lifetimes.
- Short process lifetimes.

This leads to short factory lifetimes and frequent building and rebuilding of factories.

There may be little time for improving the factory after it is built, and improving it after it starts operating is expensive; it must be built right.

Industry Needs

- Tools to predict performance of proposed factory designs.
- Tools for optimal real-time management (ie, control or operation) of factories.
- Manufacturing Systems Engineers with intuition for factories as complex systems.

Our goals: Development of predictive, quantitative, intuitive methods and tools for manufacturing systems design and operation; and education of Manufacturing Systems Engineers.

Uncertainty, Variability, and Randomness

- *Uncertainty:* Incomplete knowledge.
- *Variability:* Change over time.
- *Randomness:* A specific kind of incomplete knowledge that can be quantified and for which there is a mathematical theory.

Uncertainty, variability, and randomness are the enemies of manufacturing.

Uncertainty, Variability, and Randomness

- *Examples in the factory:*
  - machine failures
  - quality failures
  - human variability
- *Examples in the economic environment:*
  - demand variations, changes in orders
  - supplier unreliability
  - changes in costs and prices

Uncertainty, Variability, and Randomness

Therefore, factories should be

- *designed* and *operated*

to minimize the

- *creation*, *propagation*, or *amplification*

of uncertainty, variability, and randomness.

Our Research Approach

1. Identify an important systems issue by factory observation and discussion with practitioners.
2. Develop and analyze a *simple* analytical model.
    - Find compromise between accuracy and ease of analysis.
    - Test solution by comparison with with simulation.
3. Perform numerical experiments, ...
    - to develop intuition,
    - to assess usefulness of the solution.
4. Test in factory.
5. Go to Step 2 if revision of the model is warranted.
6. Go to Step 1 to further understand the issue, or to look for other important issues.

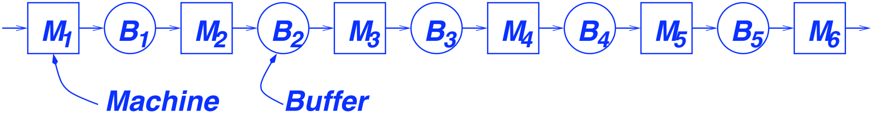
Our Research Approach

Comparisons with Practice

- *Qualitative methods,* including Toyota Production System, lean, value stream mapping, etc., are useful, important managerial tools, but they are not predictive or quantitative.
- *Computational methods,* often use unrealistic models.
  - Simulation is often excessively detailed, consequently slow to create and run and difficult to debug. It is also difficult to find accurate data for the parameters of the detailed models.
  - Large-scale optimization, when used for scheduling, has the same difficulties as simulation. In addition, it is based on the assumption that the system is deterministic. It is re-run when random events occur, but that can lead to instability.

Previous Research

1. Flow Line Analysis



- Machines are unreliable. Buffers are finite.
- *Issues:*
  - Machine failures propagate as disturbances when buffers become empty or full.
  - Large buffers reduce propagation and increase production rate *but* increase inventory.
  - System complexity makes performance prediction and analysis difficult.

Previous Research
1. Flow Line Analysis

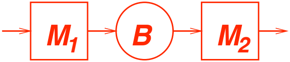
<u>Performance measures:</u> averages and other statistics on

- Production rate
- Inventory
- Lead time
- System yield, and other quality-related measures

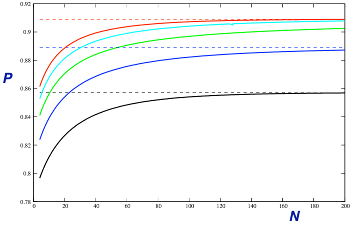
Two-machine lines can be analyzed exactly, but a special approximation *(decomposition)* was developed for larger systems because of the size of the state space.

Previous Research

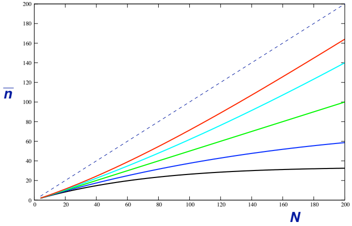
1. Flow Line Analysis



Five cases of two-machine lines:



Production rate vs Buffer space



Average inventory vs Buffer space

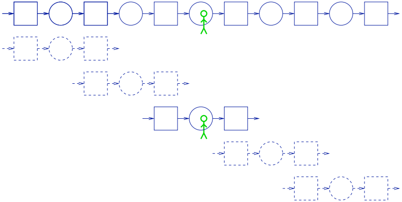
Small buffers can increase production rate with small inventory; large buffers provide little benefit at great cost. Appropriate buffer size depends on the amount of variability.

M_1, M_2 average uptimes: 100; M_2 average downtime: 10; M_1 average downtimes: 7.14, 8.33, 10, 12.5, 16.67.

Previous Research

1. Flow Line Analysis

Long Lines — Decomposition



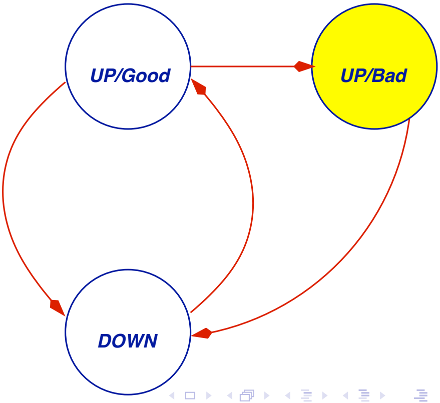
- Decomposition breaks up systems and then reunites them.
- Conceptually: put an observer in a buffer, and tell him that he is in the buffer of a two-machine line.
- Question: *What would the observer see, and how can he be convinced he is in a two-machine line? Construct the two-machine line. Construct all the two-machine lines.*

Previous Research

1. Flow Line Analysis

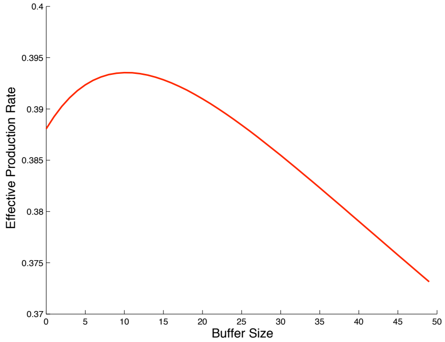
Quality and Quantity

- The *Good* state has high yield and the *Bad* state has low yield.
- The quality change is not visible until the first bad part reaches an inspection station.



Previous Research

1. Flow Line Analysis



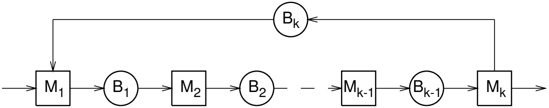
- Two-machine line where the first machine has quality issues and the inspection is located at the second machine.
- The shape of the graph depends on machine parameters: MTTFs, MTTRs, mean time until quality change, mean time to detect quality change.

Previous Research

1. Flow Line Analysis

Other Extensions

- Assembly/disassembly systems.
- Systems with closed loop flow of pallets, fixtures, or kanbans.



- Line design: minimal buffer space to achieve production rate target.
- Systems with complex machines, including multiple failure modes, general up- and down-time distributions, batches, etc.

Previous Research

1. Flow Line Analysis

Accomplishments: Fast analytical tools for ...

- performance evaluation of long flow lines, assembly/disassembly systems, systems with pallets, systems with various control policies;
- optimal allocation of buffer space;
- evaluating the interaction between buffer space and system yield.

Previous Research

2. Real-time scheduling

- Derived the *hedging point policy* and extensions, to determine inventory targets to compensate for machine failures and inventory and backlog costs.
- Evaluated various policies by decomposition, including kanban, CONWIP, etc.
- Established relationships among *time-based*, *surplus-based*, and *token-based* policies.

Previous Research

Industry Collaboration

- HP (benefit in hundreds of millions of dollars)
- GM
- Peugeot
- ... and many others

Subjects: line design, performance evaluation, system quality analysis, material flow control, ...

Current Research

1. Flow-Line Analysis

Consider a k-machine line. Processes and machines have already been selected, and now we must design the in-process inventory space. Let

$$\begin{aligned}
\mathbf{N} &= (N_1, ..., N_{k-1}), \text{the vector of buffer sizes,} \\
& \qquad \textit{the decision variables} \\
P(\mathbf{N}) &= \text{production rate, parts/time unit} \\
\hat{P} &= \text{required production rate, parts/time unit} \\
A &= \text{profit coefficient, \$/part} \\
\bar{n}_i(\mathbf{N}) &= \text{average inventory of buffer } i, i = 1, \cdots, k-1 \\
b_i &= \text{buffer cost coefficient, \$/part/time unit} \\
c_i &= \text{inventory cost coefficient, \$/part/time unit}
\end{aligned}$$

Current Research

1. Flow-Line Analysis

We are extending our buffer space design optimization methods to problems of the form

$$\max \quad J(\mathbf{N}) = AP(\mathbf{N}) - \sum_{i=1}^{k-1} b_i N_i - \sum_{i=1}^{k-1} c_i \bar{n}_i(\mathbf{N})$$

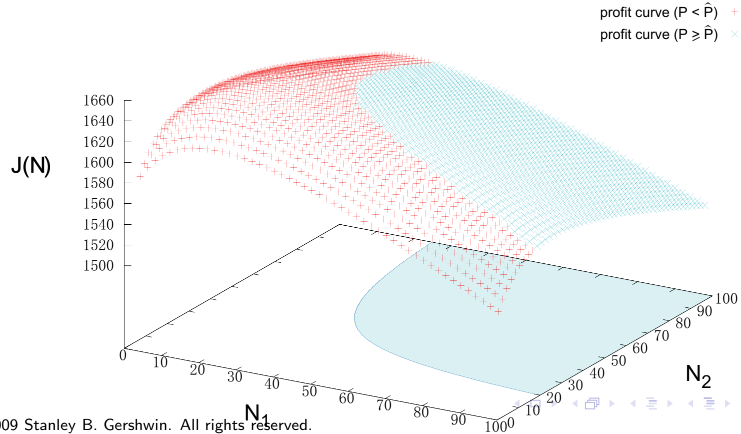
$$\text{s.t.} \quad P(\mathbf{N}) \geq \hat{P},$$

$$N_i \geq N_{min}, \forall i = 1, \cdots, k-1.$$

Current Research

1. Flow-Line Analysis

Optimization of a three-machine line.



Current Research

1. Flow-Line Analysis

- *New feature:* The objective includes the inventory cost *and* there is a production rate constraint.
- *Difficulty:* Both the objective and the constraint are non-linear. Earlier methods are not applicable.
- We developed a very simple (but very fast and effective) algorithm.
- We are currently extending this to the optimization of loop systems, which will allow us to optimize CONWIP control.
- *See Chuan Shi's poster!!*

Current Research

2. Real-time scheduling

Real-Time Setup Scheduling

- *Problem:*
  - Setups take up a resource's time. The more frequently setups are done, the less capacity is available for production. Production rate goes down.
  - However, the less frequently setups are done, the more inventory is produced. Production lead time goes up.
- Setups are often scheduled using large-scale deterministic mixed integer optimization techniques. However,
  - this is computation-intensive, and
  - when unpredictable or random events occur, the scheduled must be adjusted by recalculation or by manual adjustment. This can be time-consuming and can lead to instability.

Current Research

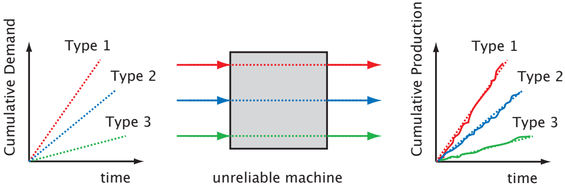
2. Real-time scheduling

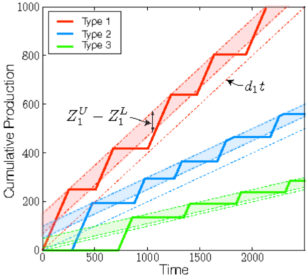
Proposed solution: the *Hedging Zone Policy*

- This is an extension of the *Hedging Point Policy* for systems with no setup costs.

finite–capacity buffer

- It is a heuristic feedback control law which is designed to respond to random events gracefully.





- Rank order the parts.
- Select upper and lower hedging limits for each part type.
- When the part that is currently being produced reaches its upper limit, switch to the highest ranking part that is below its lower limit.

Current Research

2. Real-time scheduling

- If the limits are too far apart, inventories are very large.
- If the limits are too close together, some part types are never made.
- We are developing methods for selecting good bounds.
- We are performing extensive simulation experiments.
- *See Fernando Tubilla's poster!!*

Conclusion

- There are many problems to be solved that are both interesting and of practical economic importance.
- We are always looking for opportunities to study factories and work with industry.