Engineering and the Design and Operation of Manufacturing Systems

Stanley B. Gershwin
Laboratory for Manufacturing and Productivity
Massachusetts Institute of Technology
`gershwin@mit.edu`

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Factories and Aerospace

- Factories are like aerospace systems:
  - ⋆ They are complex.
  - ⋆ They are dynamic.
  - ⋆ They are random.
  - ⋆ They require stabilizing.
  - ⋆ Modern factories and modern aerospace systems depend on electronics, computation, and communication.

- Factories are *not* like aerospace systems:
  - ⋆ Stability is harder to achieve in aerospace.
  - ⋆ Simple factories are easier to design and manage than simple airplanes.
  - ⋆ The stakes are higher in aerospace.
    - ▶ When aerospace systems fail, people die; when factories fail, people lose jobs or money.

Factories and Aerospace

Consequently,

- It was understood early that sophisticated aerodynamic theory and control theory were needed to advance aerospace technology. These theories were developed and applied to the design and operation of aerospace systems.
- Common sense and relatively simple methods were sufficient for factory design and operation, even as manufacturing technology advanced. Sophisticated theory was not needed.

Factories and Aerospace

However,

- As the demand for manufactured products becomes more difficult to meet profitably due to variability, uncertainty, and randomness, ***sophisticated theory will be needed for the design and effective operation of future factories.***
- That theory is being developed, but it many important problems have not been solved ...
- ... and some important problems have been solved, but their solutions are not widely used.

Manufacturing Industry Challenges

- Short product lifetimes. Frequent factory reconfiguration or replacement. Limited time for real-time learning to optimize factory.
- Large product diversity. Factories must be flexible.
- Short lead times and impatient customers.
- Inventory is perishable. It loses value rapidly due to obsolescence, degradation, and other reasons.
- Design and operation of manufacturing systems must take place in the presence of *variability, uncertainty, and randomness.*

Message

- Manufacturing systems must be complex to meet these challenges, especially
  - ⋆ *Variability:* change over time.
  - ⋆ *Uncertainty:* incomplete knowledge.
  - ⋆ *Randomness:* unpredictability that has some regularity. Probability theory makes it possible to deal with randomness effectively in many cases.

  - ⋆ ***To design and operate manufacturing systems that deliver the best possible performance, we must use scientific tools for understanding variability, uncertainty, and randomness.***

- For the foreseeable future, factories cannot be designed or operated without people.

Message

- Complex manufacturing systems are challenging to design and operate.
  - ⋆ This is because the appropriate tools that have been developed by the research community are not widely used by manufacturers,
  - ⋆ and because the scientific community has not consistently been guided by the needs of manufacturers to develop more and better tools.

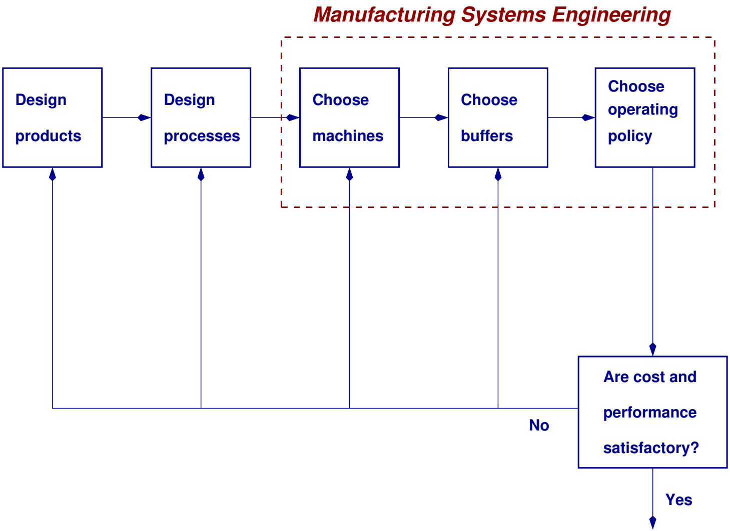
Message

Improvements in the design and operation of manufacturing systems require a **profound** understanding of the variability, uncertainty, and randomness in manufacturing systems. These improvements must

- ***reduce*** the variability, uncertainty, and randomness, or
- reduce the ***sensitivity*** of systems to variability, uncertainty, and randomness.

Manufacturing Systems Engineering

Product/Process/Factory Design



Manufacturing Systems Engineering

Design products

Design processes

Choose machines

Choose buffers

Choose operating policy

Are cost and performance satisfactory?

No

Yes

Manufacturing Systems Engineering

Some Objectives of a Manufacturing System

- Satisfy demand.
- Meet due dates.
- Keep quality high.
- Keep inventory low.

- ***Be robust.***
  - ***Be insensitive to disruptions.***
  - ***Respond gracefully to disruptions.***
  - ***Respond gracefully to demand changes, engineering changes, etc.***

The Team

A profound understanding of manufacturing systems can be achieved by creating *engineering research teams* consisting of:

1. people with practical knowledge and experience of manufacturing systems,
2. people with skill, experience, and knowledge of modern mathematical modeling and analysis, and
3. people who can develop advanced IT systems.

The modelers must work closely with those with practical experience, and they must become familiar with factory floors.

Team Objectives

- To do projects for new or existing systems in industry partners' factories,
- To do manufacturing systems research, and
- To document their work in order to educate manufacturing systems engineers. This will include education in the
  - theory,
  - analysis, design, and operation techniques, and
  - ***intuition***

  of manufacturing systems.

Team Deliverables

- Industry-supported projects for specific manufacturing systems, such as:
    - ⋆ Designing new systems to meet specified objectives.
    - ⋆ Analyzing existing systems to improve performance.
    - ⋆ Designing or improving real-time material flow and scheduling systems.
- Research that will lead to practical tools for design and operation of manufacturing systems.
- Development of educational materials and training of new manufacturing systems engineers.

The research and educational materials will be motivated by experience gained in projects.

Engineering Intuition

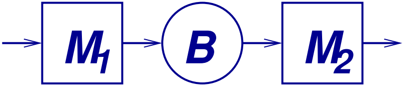
- Engineering intuition includes the abilities to
  - ⋆ distinguish between what is quantitatively important from what is not; and
  - ⋆ roughly predict the consequence of a design decision.
- ***The absence of intuition is expensive!***
  - ⋆ When simulation builders lack this kind of intuition, simulation projects can fail because:
    - ▸ they include irrelevant detail which can cause errors, can cause the simulation to run very slowly, or require parameters which cannot be obtained accurately, or
    - ▸ they leave out important mechanisms.
  - ⋆ Good intuition provides a good starting point for design. It can then be refined by computational tools.

Engineering Intuition

- Developing mathematical models helps generate intuition. Numerical experiments with such models also generates intuition.
- Intuition can be learned and taught. It is based on logic and experience. It can be explained. Its claims can be tested.
- *Simulation does not replace intuition or make intuition unnecessary.* Intuition does not replace precise computational tools or make them unnecessary.
- Intuition must initially be built with models of simple systems. Once they are understood, studying more complex systems can help further develop intuition.
- ***Manufacturing systems intuition must include intuition about variability, uncertainty, and randomness.***

Engineering Intuition

Two-Machine Line Behavior

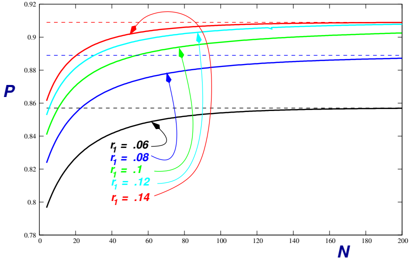


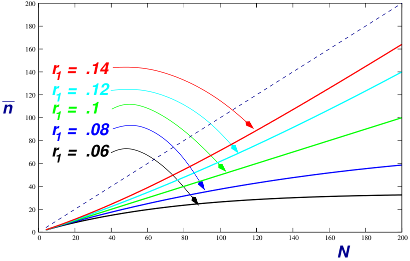
- Discrete time Markov chain
- Operation time = 1 time unit
- Probability of failure when M_i operating $= p_i, i = 1, 2$
- Probability of repair when M_i down $= r_i, i = 1, 2$
- Buffer size=N
- Performance measures:
  - ⋆ P = production rate
  - ⋆ $\bar{n}$ = average inventory in the buffer

In the next slide, $p_1 = p_2 = .01$; $r_2 = .1$. N and r_1 vary.

Engineering Intuition

Two-Machine Line Behavior





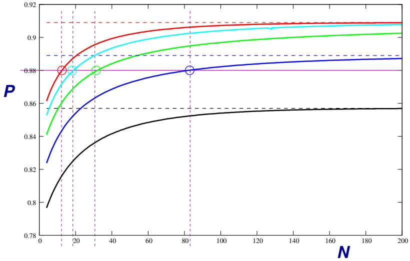
As $N \to \infty$,

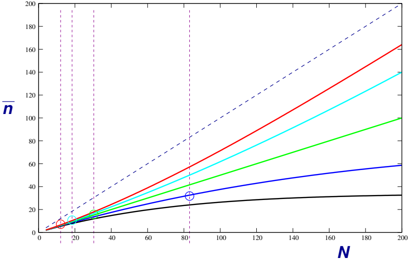
- Production rate approaches an upper limit monotonically.
- If the first machine is a bottleneck, average inventory $\bar{n}$ approaches an upper limit.
- If the second machine is a bottleneck, $N - \bar{n}$ approaches an upper limit.
- If the machines are identical, $\bar{n} = N/2$.

$\bar{n}$ increases as the first machine becomes faster (i.e., more productive).

Engineering Intuition

Two-Machine Line Behavior





Problem: Select M_1 and N so that $P = .88$.

Solution:

r_1	N	$\bar{n}$
.14	13	7.0819
.12	19	10.1153
.10	32	16.0000
.08	82	32.2112

Data Collection and Management

Data is needed to design and operate modern factories. But data is only valuable if

- it is accurate, ✓
- it is accessible, ✓
- it is relevant, and
- we know what to do with it.

Modern information technology provides the first two items. ✓

Manufacturing systems intuition and research are needed for the last two items.

Kinds of Data

What will we do with the data? There are two kinds of data:

- Static, which is treated as constant. Actually, it may change slowly or infrequently.
- Dynamic. This data is always changing.

Static and dynamic data are used differently.

Static Data

Static data includes the parameters of the factory. Examples:

- Machines
  - ⋆ MTTF (Mean Time to Fail)
  - ⋆ MTTR (Mean Time to Repair)
  - ⋆ setup times
- Buffer sizes
- Parts
  - ⋆ Routing (sequence of machines visited) for each part type
  - ⋆ Operation times for each part type at each machine

These parameters are used to design

- factories and
- real-time control policies for factories

Uses of Static Data

Examples:

- Factory design: Given a set of machines, how large do buffers have to be in order for the factory to meet a production rate target?
- Given a set of machines and buffers, what is the maximum number of parts to allow in a production line?

Dynamic Data

Dynamic data includes the *state* of the factory. Examples:

- Machines
  - Operational state (up, down, or being set up)
    - If up, the current setup; details of the current part being processed; the estimated time until the next maintenance
    - If down, the estimated time until completion of repair
    - If being set up, the time remaining until the setup is complete
- Buffers
  - The number of parts in the buffer
  - The mix of part types in the buffer
- Parts: For each type:
  - The number of good parts produced since start of current period
  - The number of good parts needed by the end of current period

Feedback Control Data

- Dynamic data is used for real-time feedback control.
- Each decision is made considering the system state. For example:
  - When a machine completes an operation on a part, what should it do next?
    - Work on the part with the shortest remaining processing time?
    - Work on the part with the earliest due date?
    - Work on the part that is most profitable?
    - Work on a part that does not require a setup change?
    - Sit idle for a while in order to limit downstream inventory?
  - When should a machine be maintained?
    - When a fixed number of parts have be processed since the last maintenance?
    - When there is sufficient downstream work in process to keep the downstream machines busy while it is being maintained?
    - When the measured wear on the machine has reached a specified threshold?

Data Quality and Relevance

- What data do we need?
  - ⋆ Collecting data before having a well-defined use for it can be dangerous and wasteful.
    - ▶ This is because there will be no clear definition of the data to be collected, so different collectors may have different interpretations of what is needed and how it should be collected.
    - ▶ Combining data sets or comparing results based on such data sets may lead to bad decisions.

Data Quality and Relevance

The specification of the data to be collected should follow from the analysis of the problem that the data will be used for. For example,

- Given a set of machines, how large do buffers have to be in order for the factory to meet a production rate target?
  - The MTTFs and MTTRs of all machines are needed.
  - To estimate these quantities, we need to record the times at which each machine fails and when it is repaired.
  - *We also need to know when the machines are idle* (that is, when they are prevented from working by starvation, blockage, or other reason).

Dangers of Commercial Generic Software

- It is difficult to develop intuition about a complex system. Using a black box to design a factory or its operating policy provides little intuition.

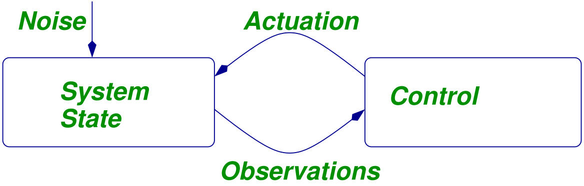
- Engineers are sometimes required to use specific commercial packaged software as *standard* tools. However, generic packaged software often does not reflect the reality of a specific factory.
    - ⋆ Bad assumptions, bad data, bad software lead to bad designs and bad real-time decisions. (GIGO)

- Engineering professionalism: Engineers are responsible for their work. They cannot blame poor performance on poor computational tools. Therefore they must understand how their tools work, the assumptions behind their tools, etc.

Feedback Control

Manufacturing Execution Systems

Real-time control: *real-time management of operations, material flow, release, dispatch, and possibly other events such as maintenance, set-up changes, etc.*



Feedback Control

- Reliance on black-box software is risky if important phenomena are not considered. For example:
  - ⋆ If randomness is important, then scheduling by deterministic optimization will lead to trouble.
  - ⋆ If set-up changes are costly, then scheduling operations on parts will not work well if the setup costs are not considered.

Feedback Control

The ideal approach:

- Formulate an optimal control problem.
    - ⋆ It includes a detailed model of the factory dynamics, including material movement, random events, setup times and costs, demand as a stochastic function of time, inspection, rework, batching, maintenance, etc.
    - ⋆ The objective would be to maximize expected profit, minimize expected cost, maximize service rate or to optimize another performance measure.
- Solve the problem to obtain an optimal feedback policy.
- Implement.
- ***Advantages:*** This would be the best possible way to run the factory.
- ***Disadvantages:*** The optimal control problem cannot be solved.

Feedback Control

Most frequent approaches:

- Formulate the scheduling problem as a large MILP (Mixed Integer Linear Program). Solve the MILP and implement the schedule. Then, whenever a (random) change in the system occurs, solve the MILP again and update the schedule.
- Use simple heuristics like FIFO (first in-first out), SRPT (shortest remaining processing time), etc.

Feedback Control

Problems with these approaches:

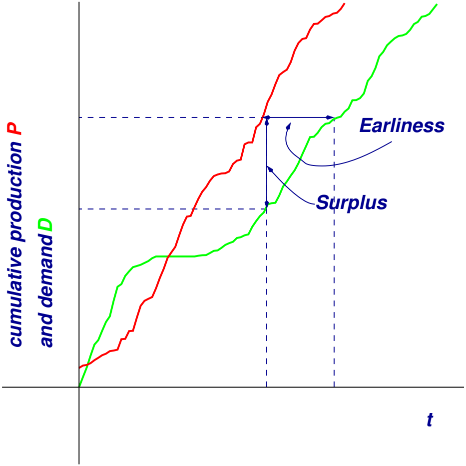
- Large MILP: frequent recalculation of schedules can create instability and confusion.
- Simple heuristics: may not account for important phenomena.

These problems can lead to reduced effective capacity and difficulties in predicting delivery dates.

Feedback Control

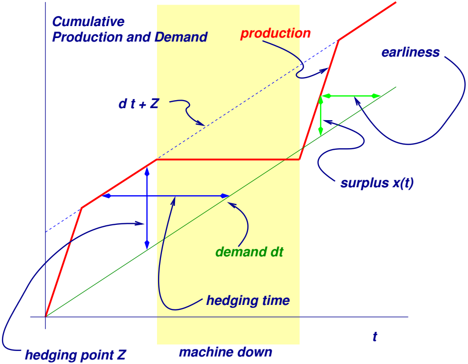
Real-Time Scheduling

- Goal: Keep cumulative production close to cumulative demand.
- Difficulty: Demand and machine reliability are both stochastic.



Feedback Control

- Optimal solution for single part type, single machine.
- Hedging point policy:
  - ⋆ When machine is up and surplus $< Z$, operate at maximum rate.
  - ⋆ When machine is up and surplus $= Z$, operate at demand rate.



Examples of Published Research Results Not Widely Known in Industry

These results have been obtained for important classes of systems.

- Production line performance analysis
  - Calculates production rate and average inventory
  - Method is decomposition approximation.
  - Results are accurate and fast.
  - Easy to use for sensitivity analysis and bottleneck detection.
  - Extended to assembly systems.

- Production line buffer optimization
  - Finds buffer sizes that
    - maximize profit or production rate for specified total buffer space
    - minimize total buffer space for a specified production rate
    - and other variations
  - Extension of performance analysis.

Examples of Published Research Results Not Widely Known in Industry

- Determination of production rate for production lines run by the ConWIP (constant work-in-process) policy.
- Control policy analysis and optimization: Real-time scheduling in a stochastic manufacturing environment
  - ⋆ Treats scheduling as an on-going process, not a large one-time calculation.
  - ⋆ Decides what to produce next and how much.
  - ⋆ Decisions based on current system state.
  - ⋆ Decentralized: decisions based on local information.

Successful Applications

- Hewlett-Packard
  - ⋆ HP had to redesign an automated assembly system for early model ink-jet printer when machine reliabilities were found to be worse than expected.
  - ⋆ A simulation project for the redesign was attempted. It was not successful
  - ⋆ The analytical decomposition method was then proposed by an MIT collaborator. It was easy to use and a good redesign was found.
  - ⋆ HP's implementation of this work yielded incremental revenues of about $280 million.
  - ⋆ The technology was successful because it allowed the joint HP/MIT design team to evaluate many designs very quickly.

Successful Applications

- PSA Peugeot Citroen
  - ⋆ "An R & D team conducted a project to support car-body production for PSA Peugeot Citroen. PSA manufactures over 75 percent of its cars on lines designed and continually improved with the team's new analytic operations research tools."
  - ⋆ "These OR tools, which combine simulation and Markov-chain models of series-parallel systems, have improved throughput with minimal capital investment and no compromise in quality — contributing US $130 million to the bottom line in 2001 alone."

Successful Applications

- General Motors
  - ⋆ Developed analytical software ("C-MORE") for production line performance analysis. It is based the decomposition approximation for on production lines.
  - ⋆ "Within six months of using C-MORE in the Detroit-Hamtramck assembly plant in November 1988, we found and removed bottlenecks, increased throughput by over 12 percent, attained the 63 jobs-per-hour (JPH) production target, and cut overtime hours per vehicle in half."
  - ⋆ "Using C-MORE, they can evaluate hundreds of line designs for each area of a plant, whereas in the past they considered fewer than 10 designs because of limited data and analysis capability."

Successful Applications

- Scania
  - ⋆ Scania–Milan Polytechnic team developed methodologies and tools to support production line design and reconfiguration. They are based the decomposition approximation.
  - ⋆ Application to a semi-automatic transfer line composed of 22 NC stations and a final quality control station.
  - ⋆ Error between production rate estimation and historical data: 3.65%.
  - ⋆ Used for analyzing the causes of starvation and blocking.
  - ⋆ Used for sensitivity analysis:
    - ▸ How much does production rate increase with an optimal allocation of the current buffer capacity? 7.32%.
    - ▸ How much does production rate increase with a better allocation of the current number of operators? 2.7%.

Research Challenges: Examples of Results That are Needed

- Real-time decision-making for setup changes.
- Maintenance scheduling based on
  - current buffer levels.
  - measured quality of parts
  - measured wear of machine.
- Extensions of published research to more general factory models:
  - Efficient computational tools to predict performance of proposed factory designs.
  - Efficient computational tools to propose factory designs that optimize performance.

Conclusions

- Manufacturing systems operate in an environment of variability, uncertainty, and randomness.
- The design and operation of manufacturing systems must limit the effects of variability, uncertainty, and randomness on their performance.
- This is possible only if manufacturing systems engineers have a fundamental understanding of the behavior of manufacturing systems, and of how variability, uncertainty, and randomness affect them.
- Such an understanding can be developed by teams consisting of people with manufacturing knowledge and understanding, researchers skilled in mathematical modeling and analysis, and IT professionals.

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Intuition from PSA Citroen

From Patchong et al. (2003):

- People used to think that the capacity of buffers that are always full must be increased so that there would be enough place to store more material for the good of the production. We proved that one must focus on half-full buffers and then, whenever possible, ***reduce*** the capacity of buffers that are full all of the time to increase the capacity of half-full buffers.
- People used to believe that buffer allocation did not really matter. We showed that given equal total buffer space, several smaller buffers are better than a few bigger buffers.
- People used to think that the action that paid back the most was decreasing cycle time. We demonstrated that for equivalent impact, the most profitable actions were, in order: (1) decreasing MTTR, (2) increasing MTTF, and (3) decreasing cycle time.

Intuition from PSA Citroen

- Some manufacturing people used to calculate the equivalent cycle time of a set of parallel machines as equal to the mean of their cycle times. We showed that the inverse of the equivalent cycle time of a set of parallel machines is the mean of the inverse of their cycle time.

- It was commonly believed that the resulting efficiency of a set of machines in a series without an intermediate buffer is the product of their efficiency. This is inaccurate, and for the kinds of systems we dealt with, the difference with the accurate formula is over four percent. Buzacott (1967) gives the accurate formula.