MIT 2.853/2.854

Introduction to Manufacturing Systems

Manufacturing Systems Overview

Stanley B. Gershwin
Laboratory for Manufacturing and Productivity
Massachusetts Institute of Technology

HP Printer Case

Background

- In 1993, the ink-jet printer market was taking off explosively, and manufacturers were competing intensively for market share.
- Manufacturers could sell all they could produce. Demand was much greater than production capacity.
- Hewlett Packard was designing and producing its printers in Vancouver, Washington (near Portland, Oregon).

HP Printer Case

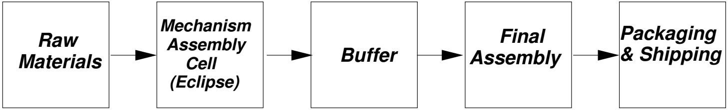
HP's needs

- Maintain quality.
- Meet increased demand *and* increase market share.
  - *Target: 300,000 printers/month.*
- Meet profit and revenue targets.
- Keep employment stable.
  - *Capacity with existing manual assembly: 200,000 printers/month.*

HP Printer Case

Printer Production

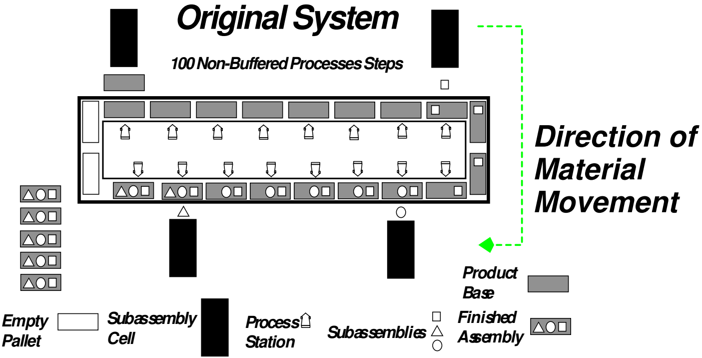
HP invested \$25,000,000 in "Eclipse," a new system for automated assembly of the print engine.



Two Eclipses were installed.

HP Printer Case

Printer Production



Design philosophy: minimal — essentially zero — buffer space.

HP Printer Case

The Problem

- Machine efficiencies[1] were estimated to be about .99.
- Operation times were estimated to be 9 seconds, and constant.
  - ⋆ Consequently, the total production rate was estimated to be about 370,000 units/month.
- BUT data was collected when the first two machines were installed:
  - ⋆ Efficiency was less than .99.
  - ⋆ Operation times were variable, often greater than 9 seconds.

Actual production rate would be about 125,000 units/month.

[1] *(to be defined)*

HP Printer Case

The Problem

- HP tried to analyze the system by simulation. They consulted a vendor, but the project appeared to be too large and complex to produce useful results in time to affect the system design.
  - ⋆ *This was because they tried to include too much detail.*
- Infeasible changes: adding labor, redesigning machines.

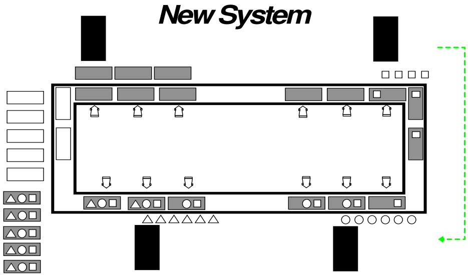
HP Printer Case

The Solution

- Feasible change: adding *a small amount* of buffer space within Eclipse.
- Design tools: *to be described in this course.*

HP Printer Case

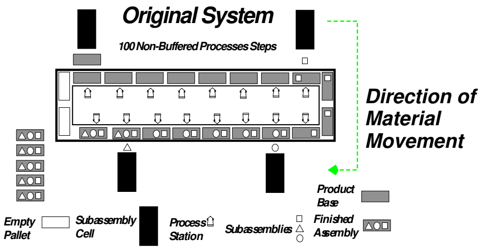
The Solution

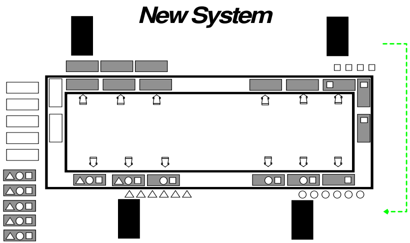


- Empty pallet buffer.
- WIP *(work in process)* space between subassembly lines and main line.
- WIP space on main line.
- Buffer sizes were large enough to hold about 30 minutes worth of material. This is a small multiple of the mean time to repair (MTTR) of the machines.

HP Printer Case

Comparison





HP Printer Case

Consequences

- Increased factory capacity — to over 250,000 units/month.
- Capital cost of changes was about $1,400,000.
- Incremental revenues of about $280,000,000.
- Labor productivity increased by about 50%.
- Improved factory design method.
- New research results which have been incorporated in courses.
- MIT spin-off: Analytics Operations Engineering, Inc., http://www.nltx.com/. (Soon to be part of McKinsey.)

HP Printer Case

Reasons for Success

- Early intervention.
- Rapid response by MIT researchers because much related work already done.
- HP managers' flexibility.
- The new analysis tool was fast, easy to use, and was at the right level of detail.

Reference: Burman, M., Gershwin, S. B., and Suyematsu, C., "Hewlett-Packard Uses Operations Research to Improve the Design of a Printer Production Line," *Interfaces*, Volume 28, Number 1, January-February, 1998, pp. 24–36.

Course Overview

Message

- *Manufacturing systems can be understood like any complex engineered system.*
- *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 design tools can have a big payoff.*

Course Overview

Goals

- To explain important measures of system performance.
- To show the importance of random, potentially disruptive events in factories.
- To give some intuition about behavior of these systems.
- To describe *and justify* some current tools and methods.
- But *not* to describe all current common-sense approaches.

Problems

- Manufacturing System Engineering (MSE) is not as advanced as other branches of engineering.
- Practitioners are encouraged to rely on gurus, slogans, and black boxes.
- A gap exists between theoreticians and practitioners.

Problems

- The research literature is incomplete,
  - ... but practitioners are often unaware of what does exist.

- Terminology, notation, basic assumptions are not standardized.

- There is typically a separation of product, process, and system design.
  - They should be done simultaneously or iteratively, *not* sequentially.

Problems

- Confusion about objectives:
  - *maximize capacity?*
  - *minimize capacity variability?*
  - *maximize capacity utilization?*
  - *minimize lead time?*
  - *minimize lead time variability?*
  - *maximize profit?*
- Systems issues are often studied last, if at all.

Problems

- Manufacturing gets less respect than it deserves.
  - *Systems not designed with engineering methods.*
  - *Product designers and sales staff are not informed of manufacturing costs and constraints.*

- Black box thinking.
  - *Factories not treated as systems to be analyzed and engineered.*
  - *Simplistic ideas often used for management and design.*

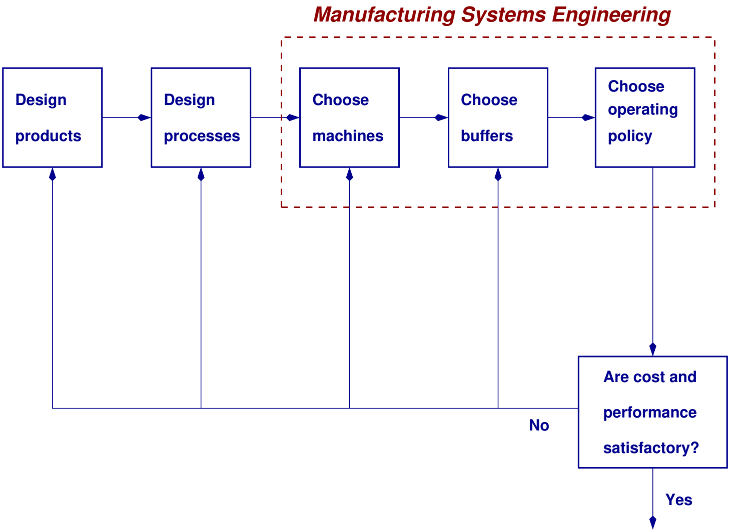
Problems

Reliable systems intuition is lacking. As a consequence, there is ...

- Management by software
  - ⋆ *Managers buy software to make production decisions, rather than to aid in making decisions.*
- Management by slogan
  - ⋆ *Gurus provide simple solutions which sometimes work. Sometimes.*

Product Realization

Products, Processes, Machines, Buffers,and Operating Policy



Rule proliferation

- *When a system is not well understood, rules proliferate.*
- This is because rules are developed to regulate behavior.
- But the rules lead to unexpected, undesirable behavior. *(Why?)*
- New rules are developed to regulate the new behavior.
- Et cetera.

Rule proliferation

Example

- A factory starts with one rule: *do the latest jobs first* .
- Over time, more and more jobs are later and later.
- A new rule is added: *treat the highest priority customers' orders as though their due dates are two weeks earlier than they are.*
- The low priority customers find other suppliers, but the factory is still late.
- *Why?*

Rule proliferation

Why?

- There are significant setup times from part family to part family. If setup times are not considered, changeovers will occur too often, and waste capacity.
- Any rules that do not consider setup times in this factory will perform poorly.

Definitions

- *Manufacturing:* the transformation of material into something useful and portable.
- *Manufacturing System:* A manufacturing system is a set of machines, transportation elements, computers, storage buffers, people, and other items that are used together for manufacturing. These items are *resources.*
  - ⋆ Alternate terms:
    - *Factory*
    - *Production system*
    - *Fabrication facility*
- Subsets of manufacturing systems, which are themselves systems, are sometimes called *cells, work centers,* or *work stations* .

Basic Issues

- Frequent new product introductions.
- Product lifetimes often short.
- Process lifetimes often short.

This leads to frequent building and rebuilding of factories. *There is little time for improving the factory after it is built; it must be built right.*

Basic Issues

Consequent Needs

- Tools to predict the performance of proposed factory designs.
- Tools for optimal factory design.
- Tools for optimal real-time management (control) of factories.
- Manufacturing Systems Engineering professionals who understand factories as complex systems.

Basic Issues

Quantity, Quality, and Variability

- Design Quality – the design of products that give customers what they want or would like to have *(features).*
  - Examples: Fuel economy in cars. Advanced electronics, attractive styling in cell phones.

- Manufacturing Quality – the manufacturing of products to *avoid* giving customers what they *don't* want or *would not* like to have *(bugs).*
  - Examples: Exploding airbags in cars. Exploding batteries in cell phones.

This course is about manufacturing, *not* product design.

- Quantity – *how much* is produced and *when* it is produced.
- Quality – *how well* it is produced.

In this course, we focus *mostly* on *quantity*.

General Statement: Variability is the enemy of manufacturing.

Basic Issues

Styles for Demand Satisfaction

- Make to Stock (Off the Shelf):
  - ⋆ items available when a customer arrives
  - ⋆ appropriate for large volumes, limited product variety, cheap raw materials

- Make to Order:
  - ⋆ production started only after order arrives
  - ⋆ appropriate for custom products, low volumes, expensive raw materials

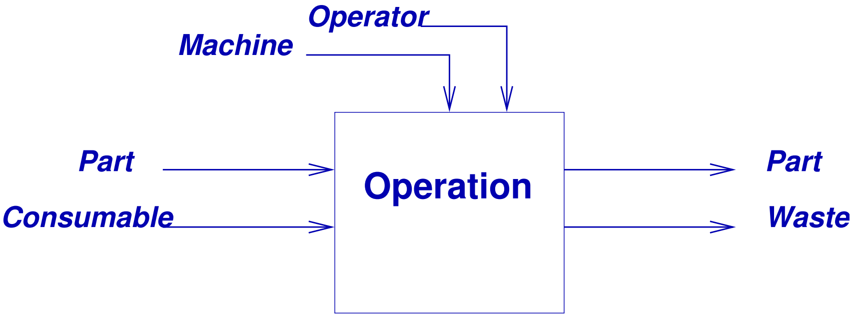
- Make to Stock:
  - ⋆ large finished goods inventories needed to prevent stockouts
  - ⋆ small finished goods inventories needed to keep costs low

Basic Issues

Conflicting Objectives

- Make to Order:
  - excess production capacity *(low utilization)* needed to allow early, reliable delivery promises
  - minimal production capacity *(high utilization)* needed to to keep costs low

- *Complexity:* collections of things have properties that are non-obvious functions of the properties of the things collected.
- *Non-synchronism (especially randomness) and its consequences:* Factories do not run like clockwork.



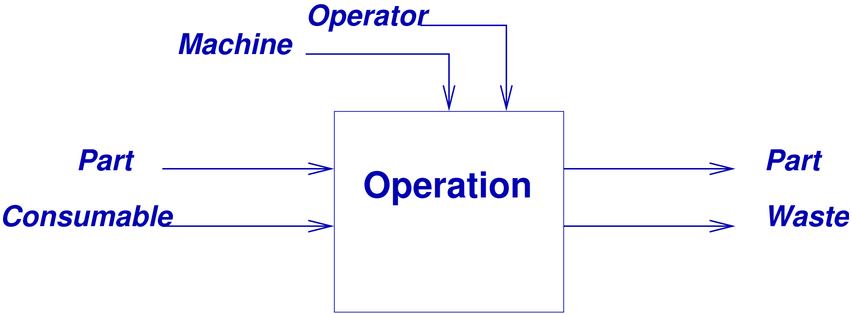
Nothing happens until everything is present.

Whatever does not arrive last must wait.

- *Inventory:* parts waiting.
- *Under-utilization:* machines waiting.
- *Idle work force:* operators waiting.

Basic Issues

Waiting



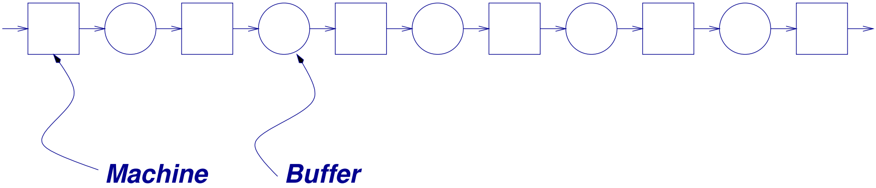
- *Reductions* in the availability, or ...
- *Variability* in the availability ...

... of any one of these items causes waiting in the rest of them and reduces performance of the system.

Kinds of Systems

Flow shop

... or *Flow line* , *Transfer line* , or *Production line.*

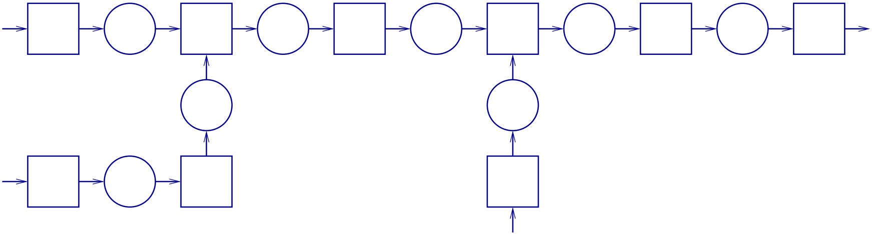


Traditionally used for high volume, low variety production.

What are the buffers for?

Kinds of Systems

Assembly system

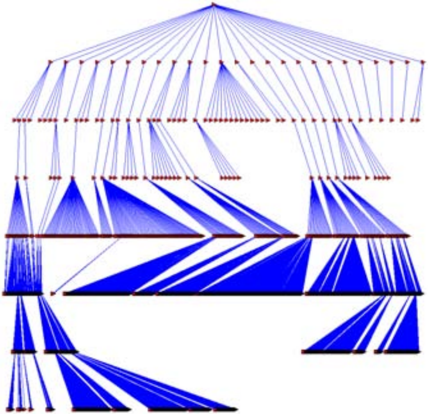


Assembly systems are *trees* , and may involve *thousands* of parts.

Kinds of Systems

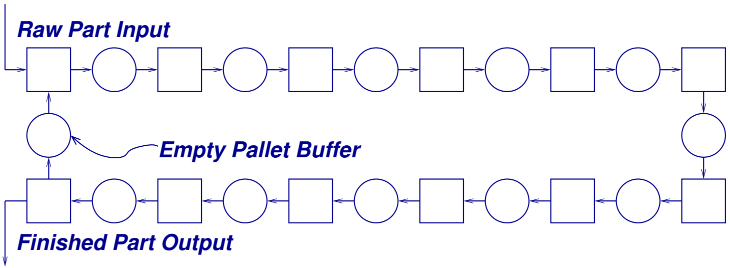
Assembly system

Bill of Materials of a large electronic product



Kinds of Systems — Loops

Closed loop *(1)*

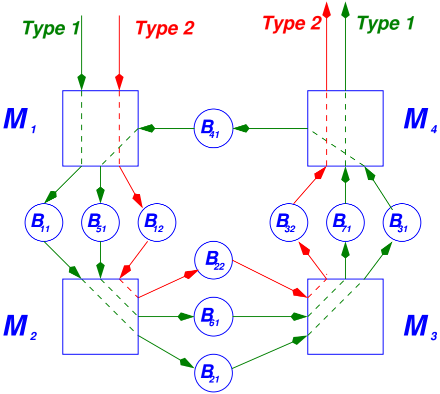


Pallets or fixtures travel in a closed loop. Routes are determined. The number of pallets in the loop is constant

Kinds of Systems — Loops

Reentrant loops *(2)*

System with reentrant flow and two part types

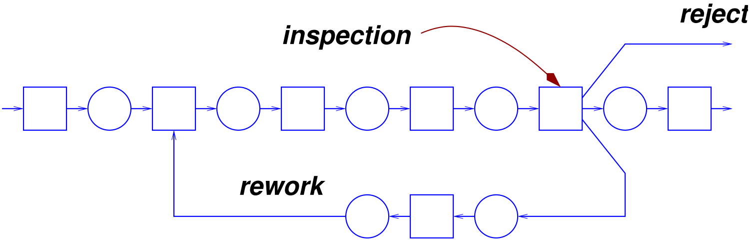


Routes are determined. The number of parts in the loop varies.

Semiconductor fabrication is highly reentrant.

Kinds of Systems — Loops

Rework loop *(3)*



Routes are random. The number of parts in the loop varies.

Kinds of Systems

Job shop

- Machines not organized according to process flow.
- Often, machines grouped by department:
  - mill department
  - lathe department
  - etc.
- Great variety of products.
- Different products follow different paths.
- Complex management.

Two Issues

- Efficient design of systems;
- Efficient operation of systems after they are built.

Time

- Many factory performance measures are about time.
  - ⋆ *production rate:* how much is made in a given time.
  - ⋆ *lead time:* how much time before delivery.
  - ⋆ *cycle time:* how much time a part spends in the factory.
  - ⋆ *delivery reliability:* how often a factory delivers on time.
  - ⋆ *capital pay-back period:* the time before the company get its investment back.

Time

Even inventory can be described in time units:

“we are holding x weeks of inventory”

means

*“customer demand could consume
all our inventory in x weeks.”*

Time

- Time appears in two forms:
  - ⋆ delay
  - ⋆ capacity utilization
- Every action has impact on both.

- An operation that takes 10 minutes adds 10 minutes to the *delay* that
  - ⋆ a workpiece experiences while undergoing that operation;
  - ⋆ every other workpiece experiences that is waiting while the first is being processed.

Time

Capacity Utilization

- An operation that takes 10 minutes takes up 10 minutes of the available time of
  - a machine,
  - an operator,
  - or other resources.
- Since there are a limited number of minutes of each resource available, there are a limited number of operations that can be done.

- *Operation Time:* the time that a machine takes to do an operation.
- *Production Rate:* the average number of parts produced in a time unit. (Also called *throughput.*)

If nothing interesting ever happens (no failures, etc.),

$$\text{Production rate} = \frac{1}{\text{operation time}}$$

... but something interesting *always* happens.

Time

Capacity

- *Capacity:* the maximum possible production rate of a manufacturing system, for systems that are making only one part type.
  - ⋆ *Short term capacity:* determined by the resources available right now.
  - ⋆ *Long term capacity:* determined by the average resource availability.
- Capacity is harder to define for systems making more than one part type. Since it is hard to define, it is *very* hard to calculate.

Randomness, Variability, Uncertainty

- *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.

Randomness, Variability, Uncertainty

- Factories are full of random events:
  - ⋆ machine failures
  - ⋆ changes in orders
  - ⋆ quality failures
  - ⋆ human variability
- The economic environment is uncertain
  - ⋆ demand variations
  - ⋆ supplier unreliability
  - ⋆ changes in costs and prices

Randomness, Variability, Uncertainty

Therefore, factories should be

- *designed* and *operated*

to minimize the

- *creation, propagation,* or *amplification*

of uncertainty, variability, and randomness.

Randomness, Variability, Uncertainty

- Therefore, all engineers should know probability...
  - ⋆ *especially manufacturing systems engineers.*

Models

- A *scientific or engineering model* of something is a representation that furthers understanding of it or is useful for estimating or predicting a quantity related to it.
- We will be concerned with two kinds of models:
  - ⋆ Mathematical models, which involve equations. The equations must be solved to get useful quantitities. Developing and analyzing a mathematical model is usually a research task.
  - ⋆ Simulation models, in which a computer program is created to mimic the events in the system to be analyzed. It is widely used in industry. Generating numbers is easy, but generating meaningful numbers is not.

Models

- Models are always approximate. The world has infinite complexity, but we can only deal with finite complexity.
- Developing good — useful — models requires judgment and intuition. The modeler must decide what is important and what is not.
- It is *essential* to define the purpose and scope of a model before trying to create it.
- Scope = boundary. The world is divided into two parts:
  - ⋆ the part you are studying, which is modeled in depth;
  - ⋆ the part you are not studying, which is approximated crudely.
- Most of our models will be mathematical, but this is not a math course!!

Engineering Intuition

1. Engineering intuition includes the ability to distinguish between what is quantitatively important from what is not.

   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.

2. Good intuition provides a good starting point for design. It can then be refined by computational tools.

Engineering Intuition

3. Developing mathematical models helps generate intuition. Numerical experiments with such models also generates intuition.

4. Intuition can be learned and taught. It is based on logic and experience. It can be explained. Its claims can be tested.

5. Simulation does not replace intuition or make intuition unnecessary. Intuition does not replace precise computational tools or make them unnecessary.

6. Intuition must initially be built with models of simple systems. Once they are understood, more complex systems can help further develop intuition.

7. ***Manufacturing systems intuition must include intuition about variability, uncertainty, and randomness.***

Course information

- Important data — including everything on this slide — is in the Syllabus. Some details of the Syllabus may change.
- Lecturer(s):
  - ⋆ Stan Gershwin.
  - ⋆ Maybe a guest speaker to discuss real-world experiences.
- Teaching Assistant: Shaswat Anand.
- Grading: 35% from Midterm Exam, 55% from Final Exam, 10% from Homework, *and* discretion based on class participation.
- Exams are take-home, open book.

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