Agenda

Web Resources

Factory Physics

Chapter 6: A Science of Manufacturing (From 2nd Ed)
Chapter 7: Basic Factory Dynamics

(New Assignment
Chapter 6: Problem 1
Chapter 7: Problems 5, 8, 10)

Web Resources

http://sdmines.sdsmt.edu/sdsmt/directory/courses/2009fa/tm663M021-099

I have completed and e-mailed solutions through last week.
## Tentative Schedule

<table>
<thead>
<tr>
<th>Date</th>
<th>Chapters Assigned</th>
<th>Date</th>
<th>Chapters Assigned</th>
</tr>
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<tr>
<td>8/31/2009</td>
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<td>4, 5 Study Q's</td>
<td>11/18/2009</td>
<td>18, 19 Not covered We may rearrange a bit. We could skip chapter 11 &amp; 12 and do 18 &amp; 19</td>
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<td>11/16/2009</td>
<td>13, 14</td>
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### Objectives, Measures, and Controls

*I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but have scarcely, in your thoughts, advanced to the stage of Science, whatever the matter may be.*

- Lord Kelvin

### Why a Science of Manufacturing?

**Confusion in Industry:**
- too many “revolutions”
- management by buzzword
- sales glitz over substance

**Confusion in Academia:**
- high-powered methodology applied to non-problems
- huge variation in what is taught

**Example of Other Fields:**
- Civil Engineering—statics, dynamics
- Electrical Engineering—electricity and magnetism
- Many others
Automobile Design

Requirements:
- Mass of car of 1000 kg
- Acceleration of 2.7 meters per second squared (zero to 60 in 10 seconds)
- Engine with no more than 200 Newtons of force

Can we do it?

Answer: No way!

\[ F = ma \]
\[ 200 \text{ N} \neq (1000 \text{ kg})(2.7 \text{ m/s}^2) = 2,700 \text{ N}. \]

Factory Design

Requirements:
- 3000 units per day,
- with a lead time of not greater than 10 days,
- and with a service level (percent of jobs that finish on time) of at least 90%.

Can we do it?

Answer: Who knows?

Factory Tradeoff Curves

\[ \text{Service in %} \]
\[ \text{Lead Time (days)} \]

- 2400
- 2600
- 2800
- 3000

Frank Matejcik  SD School of Mines & Technology
Goals of a Science of Manufacturing

Tools:
• descriptive models
• prescriptive models
• solution techniques

Terminology:
• rationalize buzzwords
• recognize commonalities across environments

Perspective:
• basics
• intuition
• synthesis

The Nature of Science

Purpose:
The grand aim of all science is to cover the greatest number of empirical facts by logical deduction from the smallest number of hypothesis or axioms.

--- Albert Einstein

Steps:
1. Observation.
2. Classification.
3. Theoretical Conjecture.
4. Experimental verification/refutation.
5. Repeat.

Conjecture and Refutation

Philosophical Implication: Cannot use science and logic to find “Truth.”

If we have made (explaining the world using laws and explanatory theories) our task, then there is no more rational procedure than the method of trial and error — of conjecture and refutation: of boldly proposing theories; of trying our best to show that these are erroneous; and of accepting them tentatively if our critical efforts are unsuccessful.

--- Karl Popper

Practical Implication: Conjecture and refutation is a problem solving tool.
Systems Analysis

Definition: Systems analysis is a structured approach to problem-solving that involves
1. Identification of objectives (what you want to accomplish), measures (for comparing alternatives), and controls (what you can change).
2. Generation of specific alternatives.
3. Modeling (some form of abstraction from reality to facilitate comparison of alternatives).
4. Optimization (at least to the extent of ranking alternatives and choosing "best" one).
5. Iteration (going back through the process as new facets arise).

System Analysis Paradigm

REAL WORLD
- Conjecture Objectives
- Verify constraints
- Identify Alternatives

OPERATIONS ANALYSIS
- Compare Alternatives
- Choose Policies
- Ask "What If" Questions

SYSTEMS DESIGN
- Implement Policies
- Train Users
- Fine Tune System

ANALOG WORLD
- Compare Controls
- Optimize Control Levels
- Sensitivity Analysis

IMPLEMENTATION
- Validate Model Predictions
- Question Assumptions
- Identify Other Controls

EVALUATION
- Evaluate System Performance
- Look For Oversights
- Identify Future Opportunities

General Measures and Objectives

Fundamental Objective:
- elementary starting point
- source of agreement
- example - make money over the long-term

Hierarchy of Objectives:
- more basic objectives that support fundamental objective
- closer to improvement policies

Tradeoffs: objectives conflict
- we need models
Hierarchical Objectives

Corporate Measures and Objectives

Fundamental Objective: Maximize the wealth and well-being of the stakeholders over the long term.

Financial Performance Measures:
1. Net-profit.
2. Return on investment.

Components:
1. Revenue.
2. Expenses.
3. Assets.

Plant Measures and Objectives

Measures:
- Throughput: product that is high quality and is sold.
- Costs: Operating budget of plant.
- Assets: Capital equipment and WIP.

Objectives:
- Maximize profit.
- Minimize unit costs.

Tradeoffs: we would like (but can’t always have)
1. Throughput
2. Cost
3. Assets
Systems Analysis Tools

**Process Mapping:**
- identify main sequence of activities
- highlight bottlenecks
- clarify critical connections across business systems

**Workshops:**
- structured interaction between various parties
- many methods: Nominal Group Technique, Delphi, etc.
- roles of moderator and provocateur are critical

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Systems Analysis Tools (cont.)

**Conjecture and Refutation:**
- promotes group ownership of ideas
- places critical thinking in a constructive mode
- everyday use of the scientific method

**Modeling:**
- always done with specific purpose
  - value of model is its *usefulness*
  - modeling is an iterative process

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The Need for Process Mapping

**Example:** North American Switch Manufacturer -- 10-12 week leadtimes in spite of dramatically reduced factory cycle times:
- 10% Sales
- 15% Order Entry
- 15% Order Coding
- 20% Engineering
- 10% Order Coding
- 15% Scheduling
- 5% Premanufacturing and Manufacturing
- 10% Delivery and Prep

**Conclusion:** Lead time reduction must address entire value delivery system.
Process Mapping Activities

**Purpose:** understand current system by
- identifying main sequence of activities
- highlighting bottlenecks
- clarifying critical connections across business system

**Types of Maps:**
- **Assembly Flowchart:** diagram of activities to assembly product.
- **Process Flowchart:** diagram of how pieces of system interrelate in an organization.
- **Relationship Map:** diagram of specific steps to accomplish a task, without indication of functions or subsystems.
- **Cross-Functional Process Map:** diagram of specific steps to accomplish a task organized by function or subsystem responsible for the step.

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**Sample Assembly Flowchart**

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**Process Flowchart for Order Entry**

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Sample Relationship Map

Sample Cross-Functional Process Map

Conclusions

Science of Manufacturing:
- important for practice
- provides a structure for OM education

Systems Approach:
- one of the most powerful engineering tools
- a key management skill as well (e.g., re-engineering)

Modeling:
- part, but not all, of systems analysis
- key to a science of manufacturing
- more descriptive models are needed
Basic Factory Dynamics

*Physics should be explained as simply as possible, but no simpler.*

– Albert Einstein

HAL Case

**Large Panel Line:** produces unpopulated printed circuit boards

**Line runs 24 hr/day** (but 19.5 hrs of productive time)

**Recent Performance:**

- throughput = 1,400 panels per day (71.8 panels/hr)
- WIP = 47,600 panels
- CT = 34 days (663 hr at 19.5 hr/day)
- customer service = 75% on-time delivery

*Is HAL lean?*

What data do we need to decide?

HAL - Large Panel Line Processes

- **Lamination (Cores):** press copper and prepreg into core blanks
- **Machining:** trim cores to size
- **Internal Circuitize:** etch circuitry into copper of cores
- **Optical Test and Repair (Internal):** scan panels optically for defects
- **Lamination (Composites):** press cores into multiple layer boards
- **External Circuitize:** etch circuitry into copper on outside of composites
- **Optical Test and Repair (External):** scan composites optically for defects
- **Drilling:** holes to provide connections between layers
- **Copper Plate:** deposits copper in holes to establish connections
- **Procoat:** apply plastic coating to protect boards
- **Sizing:** cut panels into boards
- **End of Line Test:** final electrical test
HAL Case - Science?

External Benchmarking
• but other plants may not be comparable

Internal Benchmarking
• capacity data: what is utilization?
• but this ignores WIP effects

Need relationships between WIP, TH, CT, service!

Definitions

Workstations: a collection of one or more identical machines.
Parts: a component, sub-assembly, or an assembly that moves through the workstations.
End Items: parts sold directly to customers; relationship to constituent parts defined in bill of material.
Consumables: bits, chemicals, gasses, etc., used in process but do not become part of the product that is sold.
Routing: sequence of workstations needed to make a part.
Order: request from customer.
Job: transfer quantity on the line.

Definitions (cont.)

Throughput (TH): for a line, throughput is the average quantity of good (non-defective) parts produced per unit time.
Work in Process (WIP): inventory between the start and endpoints of a product routing.
Raw Material Inventory (RMI): material stocked at beginning of routing.
Crib and Finished Goods Inventory (FGI): crib inventory is material held in a stockpoint at the end of a routing; FGI is material held in inventory prior to shipping to the customer.
Cycle Time (CT): time between release of the job at the beginning of the routing until it reaches an inventory point at the end of the routing.
**Factory Physics®**

**Definition:** A manufacturing system is a *goal-oriented network of processes* through which *parts flow*.

**Structure:** Plant is made up of routings (lines), which in turn are made up of processes.

**Focus:** *Factory Physics®* is concerned with the network and flows at the routing (line) level.

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**Parameters**

**Descriptors of a Line:**

1) **Bottleneck Rate** ($r_b$): Rate (parts/unit time or jobs/unit time) of the process center having the highest long-term utilization.

2) **Raw Process Time** ($T_0$): Sum of the long-term average process times of each station in the line.

3) **Congestion Coefficient** ($\alpha$): A unitless measure of congestion.

   - Zero variability case, $\alpha = 0$.
   - “Practical worst case,” $\alpha = 1$.
   - “Worst possible case,” $\alpha = W_0$.

   *Note: we won’t use $\alpha$ quantitatively, but point it out to recognize that lines with same $r_b$ and $T_0$ can behave very differently.*

**Critical WIP** ($W_0$): WIP level in which a line having no congestion would achieve maximum throughput (i.e., $r_b$) with minimum cycle time (i.e., $T_0$).

$$W_0 = r_b T_0$$
The Penny Fab

Characteristics:
- Four identical tools in series.
- Each takes 2 hours per piece (penny).
- No variability.
- CONWIP job releases.

Parameters:
\[
\begin{align*}
    r_t &= 0.5 \text{ pennies/hour} \\
    T_0 &= 8 \text{ hours} \\
    W_0 &= 0.5 \times 8 = 4 \text{ pennies} \\
    \sigma &= 0 \text{ (no variability, best case conditions)}
\end{align*}
\]

The Penny Fab (WIP=1)

Time = 0 hours
The Penny Fab (WIP=1)

Time = 2 hours

The Penny Fab (WIP=1)

Time = 4 hours

The Penny Fab (WIP=1)

Time = 6 hours
The Penny Fab (WIP=1)

Time = 8 hours

The Penny Fab (WIP=1)

Time = 10 hours

The Penny Fab (WIP=1)

Time = 12 hours
The Penny Fab (WIP=1)

Time = 14 hours

The Penny Fab (WIP=1)

Time = 16 hours

Penny Fab Performance

<table>
<thead>
<tr>
<th>WIP</th>
<th>TH</th>
<th>CT</th>
<th>TH × CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.125</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Penny Fab (WIP=2)

Time = 0  hours

The Penny Fab (WIP=2)

Time = 2  hours

The Penny Fab (WIP=2)

Time = 4  hours
The Penny Fab (WIP=2)

Time = 6 hours

The Penny Fab (WIP=2)

Time = 8 hours

The Penny Fab (WIP=2)

Time = 10 hours
The Penny Fab (WIP=2)

Time = 12 hours

The Penny Fab (WIP=2)

Time = 14 hours

The Penny Fab (WIP=2)

Time = 16 hours
The Penny Fab (WIP=2)

Time = 18 hours

Penny Fab Performance

<table>
<thead>
<tr>
<th>WIP</th>
<th>TH</th>
<th>CT</th>
<th>TH×CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.125</td>
<td>8</td>
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</tr>
<tr>
<td>2</td>
<td>0.250</td>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>

The Penny Fab (WIP=4)

Time = 0 hours
The Penny Fab (WIP=4)

Time = 2 hours

The Penny Fab (WIP=4)

Time = 4 hours

The Penny Fab (WIP=4)

Time = 6 hours
The Penny Fab (WIP=4)

Time = 8 hours

The Penny Fab (WIP=4)

Time = 10 hours

The Penny Fab (WIP=4)

Time = 12 hours
The Penny Fab (WIP=4)

Time = 14 hours

The Penny Fab (WIP=5)

Time = 0 hours

Penny Fab Performance

<table>
<thead>
<tr>
<th>WIP</th>
<th>TH</th>
<th>CT</th>
<th>TH \times CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.125</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.250</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>0.375</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>0.500</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Penny Fab (WIP=5)

Time = 2 hours

The Penny Fab (WIP=5)

Time = 4 hours

The Penny Fab (WIP=5)

Time = 6 hours
The Penny Fab (WIP=5)

Time = 8 hours

The Penny Fab (WIP=5)

Time = 10 hours

The Penny Fab (WIP=5)

Time = 12 hours
### Penny Fab Performance

<table>
<thead>
<tr>
<th>WIP</th>
<th>TH</th>
<th>CT</th>
<th>TH×CT</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.125</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.250</td>
<td>8</td>
<td>2</td>
</tr>
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<td>3</td>
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<td>5</td>
</tr>
<tr>
<td>6</td>
<td>0.500</td>
<td>12</td>
<td>6</td>
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</table>

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### TH vs. WIP: Best Case

![Graph showing TH vs. WIP: Best Case](image)

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### CT vs. WIP: Best Case

![Graph showing CT vs. WIP: Best Case](image)
**Best Case Performance**

**Best Case Law:** The minimum cycle time \( (C_{T \text{best}}) \) for a given WIP level, \( w \), is given by:

\[
C_{T \text{best}} = \begin{cases} 
T_v, & \text{if } w \leq W_v \\
\frac{w}{r_v}, & \text{otherwise.}
\end{cases}
\]

The maximum throughput \( (T_{H \text{best}}) \) for a given WIP level, \( w \) is given by:

\[
T_{H \text{best}} = \begin{cases} 
\frac{w}{T_v}, & \text{if } w \leq W_v \\
\frac{1}{r_v}, & \text{otherwise.}
\end{cases}
\]

**Example:** For Penny Fab, \( r_v = 0.5 \) and \( T_v = 8 \), so \( W_v = 0.5 \times 8 = 4 \),

\[
C_{T \text{best}} = \begin{cases} 
8, & \text{if } w \leq 4 \\
2w, & \text{otherwise.}
\end{cases}
\]

\[
T_{H \text{best}} = \begin{cases} 
\frac{w}{8}, & \text{if } w \leq 4 \\
0.5, & \text{otherwise.}
\end{cases}
\]

which are exactly the curves we plotted.

**A Manufacturing Law**

**Little’s Law:** The fundamental relation between WIP, CT, and TH over the long-term is:

\[
\text{WIP} = \frac{\text{TH} \times \text{CT}}{\text{parts per hr} \times \text{hr}}
\]

**Insights:**
- Fundamental relationship
- Simple units transformation
- Definition of cycle time (CT = WIP/TH)
Penny Fab Two

<table>
<thead>
<tr>
<th>Station Number</th>
<th>Number of Machines</th>
<th>Process Time</th>
<th>Station Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>5 hr</td>
<td>0.4 j/hr</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>10 hr</td>
<td>0.6 j/hr</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>3 hr</td>
<td>0.67 j/hr</td>
</tr>
</tbody>
</table>

\[ r_p = 0.4 \text{ j/hr} \]

\[ T_i = 20 \text{ hr} \]

\[ W_0 = 8 \text{ pennies} \]
Penny Fab Two Simulation (Time=16)

Penny Fab Two Simulation (Time=17)

Penny Fab Two Simulation (Time=19)

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Note: job will arrive at bottleneck just in time to prevent starvation.

And so on...
Bottleneck will just stay busy; all others will starve periodically.
**Worst Case**

Observation: The Best Case yields the minimum cycle time and maximum throughput for each WIP level.

Question: What conditions would cause the maximum cycle time and minimum throughput?

Experiment:
- set average process times same as Best Case (so $r_i$ and $T_i$ unchanged)
- follow a marked job through system
- imagine marked job experiences maximum queueing

**Worst Case Penny Fab**

Time = 0 hours

**Worst Case Penny Fab**

Time = 8 hours
Worst Case Penny Fab

Time = 16 hours

Worst Case Penny Fab

Time = 24 hours

Worst Case Penny Fab

Time = 32 hours

Note:

CT = 32 hours
= 4 x 8 = wT_o

TH = 4/32 = 1/8 = 1/T_o
Worst Case Performance

**Worst Case Law:** The worst case cycle time for a given WIP level, \( w \), is given by,

\[
CT_{\text{worst}} = w \cdot T_0
\]

The worst case throughput for a given WIP level, \( w \), is given by,

\[
TH_{\text{worst}} = \frac{1}{T_0}
\]

Randomness?

None - perfectly predictable, but bad!
### Practical Worst Case

**Observation:** There is a BIG GAP between the Best Case and Worst Case performance.

**Question:** Can we find an intermediate case that:
- divides "good" and "bad" lines, and
- is computable?

**Experiment:** consider a line with a given $t_0$ and $T_0$ and:
- single machine stations
- balanced lines
- variability such that all WIP configurations (states) are equally likely

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#### PWC Example – 3 jobs, 4 stations

<table>
<thead>
<tr>
<th>State</th>
<th>Vector</th>
<th>State</th>
<th>Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(3,0,0,0)</td>
<td>11</td>
<td>(1,0,2,0)</td>
</tr>
<tr>
<td>2</td>
<td>(0,3,0,0)</td>
<td>12</td>
<td>(0,1,2,0)</td>
</tr>
<tr>
<td>3</td>
<td>(0,0,3,0)</td>
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<td>(0,0,2,1)</td>
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<tr>
<td>4</td>
<td>(0,0,0,3)</td>
<td>14</td>
<td>(1,0,0,2)</td>
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<td>5</td>
<td>(2,1,0,0)</td>
<td>15</td>
<td>(0,1,0,2)</td>
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<td>7</td>
<td>(2,0,0,1)</td>
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<td>(1,1,1,0)</td>
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<td>8</td>
<td>(1,2,0,0)</td>
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<td>(1,1,0,1)</td>
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<td>9</td>
<td>(0,2,1,0)</td>
<td>19</td>
<td>(1,0,1)</td>
</tr>
<tr>
<td>10</td>
<td>(0,2,0,1)</td>
<td>20</td>
<td>(0,1,1)</td>
</tr>
</tbody>
</table>

**Note:** average WIP at any station is $15/20 = 0.75$, so jobs are spread evenly between stations.

---

### Practical Worst Case

Let $w =$ jobs in system, $N =$ no. stations in line, and $t =$ process time at all stations:

- **$CT_{\text{single}} =$** $(1 + (w-1)/N) t$
- **$CT_{\text{line}} =$** $N \left[1 + (w-1)/N\right] t$
  
  $= Nt + (w-1)t$
  
  $= T_0 + (w-1)t_0$

- **$TH =$** WIP/$CT$_L

*From Little’s Law*
Practical Worst Case Performance

Practical Worst Case Definition: The practical worst case (PWC) cycle time for a given WIP level, \( w \), is given by,

\[
CT_{\text{PWC}} = T_0 + \frac{w-1}{r_0}
\]

The PWC throughput for a given WIP level, \( w \), is given by,

\[
TH_{\text{PWC}} = \frac{w}{w+1} - r_0
\]

where \( W_0 \) is the critical WIP.

TH vs. WIP: Practical Worst Case

CT vs. WIP: Practical Worst Case
Penny Fab Two Performance

Note: process times in PF2 have var equal to PWC.

But... unlike PWC, it has unbalanced line and multi machine stations.

Penny Fab Two Performance (cont.)

Back to the HAL Case - Capacity Data

<table>
<thead>
<tr>
<th>Process</th>
<th>Rate (p/hr)</th>
<th>Time (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamination</td>
<td>191.5</td>
<td>4.7</td>
</tr>
<tr>
<td>Machining</td>
<td>186.2</td>
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<td>Internal Circuite</td>
<td>114.0</td>
<td>3.6</td>
</tr>
<tr>
<td>Optical Test/Repair- Int</td>
<td>150.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Lamination - Composites</td>
<td>158.7</td>
<td>2.0</td>
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<tr>
<td>External Circuite</td>
<td>159.9</td>
<td>4.3</td>
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<tr>
<td>Optical Test/Repair - Ext</td>
<td>150.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Drilling</td>
<td>185.9</td>
<td>10.2</td>
</tr>
<tr>
<td>Copper Plate</td>
<td>136.4</td>
<td>1.0</td>
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<tr>
<td>Procoat</td>
<td>117.3</td>
<td>4.1</td>
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<tr>
<td>Sizing</td>
<td>126.5</td>
<td>1.1</td>
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<tr>
<td>ESL Test</td>
<td>109.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$r_b$, $T_0$</td>
<td>114.9</td>
<td>33.9</td>
</tr>
</tbody>
</table>
HAL Case - Situation

Critical WIP: $r_0T_0 = 114 \times 33.9 = 3,869$

Actual Values:
- CT = 34 days = 663 hours (at 19.5 hr/day)
- WIP = 47,600 panels
- TH = 71.8 panels/hour

Conclusions:
- Throughput is 63% of capacity
- WIP is 12.3 times critical WIP
- CT is 24.1 times raw process time

HAL Case - Analysis

TH Resulting from PWC with WIP = 47,600?

\[ TH = \frac{w}{w + W_0 - 1} r_0 = \frac{47,600}{47,600 + 3,869 - 1} \times 114 = 105.4 \]

Much higher than actual TH!

WIP Required for PWC to Achieve TH = 0.63$r_0$?

\[ TH = \frac{w}{w + W_0 - 1} r_0 = 0.63r_0 \]

\[ w = \frac{0.63(W_0 - 1)}{0.37(3,869 - 1)} = 3,716 \]

Much lower than actual WIP!

Conclusion: actual system is much worse than PWC!

HAL Internal Benchmarking Outcome

Throughput vs WIP graph showing the 'Lean' and 'Fat' regions.
Labor Constrained Systems

Motivation: performance of some systems are limited by labor or a combination of labor and equipment.

Full Flexibility with Workers Tied to Jobs:

- WIP limited by number of workers \( n \)
  - capacity of line is \( nT_0 \)
  - Best case achieves capacity and has workers in “zones”
  - ample capacity case also achieves full capacity with “pick and run” policy

Full Flexibility with Workers Not Tied to Jobs:

- TH depends on WIP levels
  - \( TH(n) \leq TH(w) \leq TH(w) \)
  - need policy to direct workers to jobs (focus on downstream is effective)

Agile Workforce Systems

- bucket brigades
- kanban with shared tasks
- worksharing with overlapping zones
- many others

Factory Dynamics Takeaways

Performance Measures:

- throughput
- WIP
- cycle time
- service

Range of Cases:

- best case
- practical worst case
- worst case

Diagnostics:

- simple assessment based on \( r_c, T_0, \) actual WIP, actual TH
- evaluate relative to practical worst case