Why does Alex think the robots are so successful when he first talks to Jonah?

How does Jonah indicate that the robots were not successful?

Why should one not adopt the goal to increase efficiency?

What is the "goal" for publicly owned manufacturing organizations?

What about such goals as: improve quality, supplying jobs, producing products, low cost production, produce efficiently, stay on leading edge of technology, high market share?

What three common financial measures express the goal to "make money"?

What three measures are useful at the operational level to express the goal?

Define throughput, inventory, and operational expense.

Express the "goal" in terms of throughput, inventory, and operational expense.

What is the result of high efficiencies on a non-constraint machine?

Do high efficiencies necessarily imply higher profit?

Why is it important that throughput be defined in terms of sales rather than production?

What does it mean to balance a plant?

Is it a good idea to balance a plant?

What causes a balanced plant to fail?

Why does the spread of the line of boy scouts discussed on page 100 always become longer as time goes on?

What characteristics of the hiking troop relate to the production characteristics of throughput, inventory, and operational expense?

Using the hike analogy on page 113, what happens in a plant if the fastest operations are put at the beginning of the production process, the slowest operations are put at the end, and all workers produce at a high efficiency?

What is Herbie in terms of TOC?

In terms of TOC what has been done when Herbie goes to the front of the line?

In terms of TOC what has been done when items are removed from Herbie's pack?

Why was Pete so happy even through the order was not delivered on time?

Define a bottleneck.

What does Jonah say “balance flow not capacities”?
What Herbies do Alex and the staff discover?

List the improvement projects suggested by Jonah.

What does lost time at a bottleneck cost?

What two things can be done to optimize a bottleneck?

What three steps will reduce the lost time on bottlenecks?

What priority system does Alex suggest for processing parts at the bottleneck (pg. 163).

What is the purpose of the tag system introduced on page 176?

What step is taken to off-load work from the NCX-10?

Why do the heat-treat and NCX-10 still have idle time after the priority procedures are implemented?

What additional steps are taken regarding the bottlenecks?

How will most of the changes look to division management who have a "cost mentality"?

What is the effect of the "efficient" operation of non-bottleneck machines?

What determines the level of utilization of a non-bottleneck machine?

What is the function of the drum and rope if used on a hike?

What is the drum for the production facility?

What is the rope for the production facility?

Why is a rope needed for assembly operations?

What is the next logical step after establishing the drum and rope for the production process?

What does cutting batch sizes in half for non-bottleneck operations accomplish?

How can the time material spends in plant be classified into four types?

What is time saved on a non-bottleneck machine.

After Alex Rogo succeeds in reviving the plant in Bearington, what is the next step that he must implement for his plant and division?
The Theory of Constraints

Now that we know the Goal, how do we use it to improve our system?

Step 1: Identify the system’s constraint(s).
- What is the Goal?
- What is Throughput?
- What is Inventory?
- What is Operating Expense?

Step 2: Decide how to exploit the system’s constraint(s).
- What is the constraint?
- How do we get as much throughput as possible?

Step 3: Subordinate everything else to the decisions of Step 2.
- Throughput?
- Inventory?
- Operating Expense?
Step 4: Elevate the system’s constraint(s).

- Throughput?
- Inventory?
- Operating Expense?

Step 5: If a constraint is broken in Step 4, go back to Step 1.

- What might happen if the constraint is elevated?

Summary: The Theory of Constraints

- Step 1: Identify the system’s constraint(s).
- Step 2: Decide how to exploit the system’s constraint(s).
- Step 3: Subordinate everything else to the decisions of Step 2.
- Step 4: Elevate the system’s constraint(s).
- Step 5: If a constraint is broken in Step 4, go back to Step 1.
A, B, C, D: 1 each
Available Time: 2400 Min/Wk
OE not including RM: $6000 per wk

Purchase Part $5/U
The Goal

Step 1: Identify the system’s constraint(s).

- What is the Goal?
- What is Throughput?
- What is Inventory?
- What is Operating Expense?

To Identify the Resource Constraint

- Compute the load on each production resource assuming market demands.
- Compare the resource loads with the resource capacities.
- Those resources for which the loads exceed the capacities are constraints (bottlenecks).
- If no production resource load exceeds its capacity,
  - the market demands are the constraints.
  - the constraints are external to the manufacturing system.
- What is a constraint?

Compute the loads and compare with capacities.

- Production P=100, Production Q=50
- A: Load =2000, Capacity = 2400 Minutes
- B: Load =3000, Capacity = 2400 Minutes
- C: Load =1750, Capacity = 2400 Minutes
- D: Load =1250, Capacity = 2400 Minutes
- What is the constraint?

Step 2: Decide how to exploit the system’s constraint(s).

Exploiting the constraint

- Assume a single constraint is identified.
- Rank the products in order of the ratio: *Throughput dollars per minute of constraint use*.
- Select the product mix so that the products with greater ratios are produced in preference to the products with smaller ratios.
- What goal is this method trying to achieve?
- How does this method achieve the goal?

What and how much to produce.

- P: TP/Unit = 45, B Min/Unit=15, TP/Min =
- Q: TP/Unit = 60, B Min/Unit=30, TP/Min =
- Produce as much P as possible.
- Use the remainder of the constraint resource for Q.
- Why do we use this rule?
- What is the profit for this product mix?
Step 3: Subordinate everything else to the decisions of Step 2.

Subordinating Production

- Production $P=100$, Production $Q=30$
- A: Load $=1800$, Capacity $=2400$ Minutes
- B: Load $=2400$, Capacity $=2400$ Minutes
- C: Load $=1650$, Capacity $=2400$ Minutes
- D: Load $=1150$, Capacity $=2400$ Minutes
- What determines the load on the non-constraints?

Step 4: Elevate the system’s constraint(s).

- Where should process improvements be focused?
- What is the benefit of elevating the constraint?
- What is the benefit of elevating a non-constraint?

Step 5: If a constraint is broken in Step 4, go back to Step 1.

- What might happen if the constraint is elevated?
- What happens if there are no more internal constraints?

Say we add another machine of type B.

- Production $P=100$, Production $Q=50$
- A: Load $=2000$, Capacity $=2400$ Minutes
- B: Load $=3000$, Capacity $=4800$ Minutes
- C: Load $=1750$, Capacity $=2400$ Minutes
- D: Load $=1250$, Capacity $=2400$ Minutes
- How much should we produce?
- What is the new constraint?
- How do we elevate the new constraint?
Summary: The Theory of Constraints

- Step 1: Identify the system’s constraint(s).
- Step 2: Decide how to exploit the system’s constraint(s).
- Step 3: Subordinate everything else to the decisions of Step 2.
- Step 4: Elevate the system’s constraint(s).
- Step 5: If a constraint is broken in Step 4, go back to Step 1.

Next Question: What are the effects of Dependent Events and Statistical Fluctuations?
Jonah: What is the combined effect of dependent events and statistical fluctuations?

Dependent Events
Statistical Fluctuations
Drum, Buffer, Rope Scheduling

What are dependent events?

What happens if we ask everyone to be efficient?
How can we control a system with dependent events?

• Step 1: Identify the system's bottleneck
• Step 2: Exploit the system's bottleneck
• Step 3: Subordinate everything else to the bottleneck

How can we improve a system with dependent events?

• Step 4: Elevate the system's constraint.

Focus on the bottleneck

• What is time worth on the bottleneck?
• What is time worth on the non-bottlenecks?

What are the benefits of this process

• Better process control
• Reduced inventories
• Reduced operating expenses
• Increased throughput
**Concepts:**

**Dependent Events**

- Can we have bottlenecks in systems with independent events?
- What is a bottleneck?
- How do we control with a bottleneck?
- What are the benefits of this control?
- Where should we focus improvement efforts?
- Should we have a bottleneck?

---

**Statistical Fluctuations**

- Should we balance the capacities in the line?
- What is the effect of statistical fluctuation?

- Where is the bottleneck?
- How do we improve?
Jonah: Balance flow not capacity

- It is good to have a bottleneck?
- Control production through the bottleneck.
- Subordinate the production in nonbottlenecks to assure that the bottleneck is never delayed.

Concepts (Statistical Fluctuations)

- What is the effect of statistical fluctuation?
- Is it good to balance the capacities in the line?
- Why is it helpful to have a bottleneck in the line?

Drum, Buffer, Rope Scheduling

What happens if Herbie cannot be put at the front of the line?
We need some way to control those who are in front of Herbie.

- How about a drum?
- How about a rope?
- Where is the buffer?

What is the equivalent in the manufacturing system?

Drum, Buffer, Rope Scheduling System

- Drum: A schedule for the Constraint resource
- Rope: The time interval between when material is required at the constraint and the release of the raw material to the first station
- Buffer: The difference between the rope and the minimum time required in the stages preceding the constraint

A Cycle in the Production System
How does the rope affect the cycle time?

- What happens when we increase the rope?
- Do we want the rope large or small?

How does the cycle time affect work in process (inventory)?

- Work in Process = (cycle time) * (Flow Rate)
- Time in machine C = 12 minutes.
- Flow rate = (1/12) units per minute.
- Cycle time = 1500 minutes.
- Work in Process = (1/12) units per minute * 1500 minutes = 125 Units.

How do we select the length (time) of the rope?

- Why would we like to keep the rope relatively long?
- Why would we like to keep the rope relatively short?
- Which is the most important effect?

Concepts (D, B, R)

- What is the drum?
- What is the rope?
- What is the buffer?
- How do we select the length (time) of the rope?
The Goal

Cut the Lot Size Lecture

Jonah: Cut the lot size

What encourages us to use large lot sizes?
What encourages us to use small lot sizes?
Under what circumstances can we cut the lot size without reducing throughput?

What encourages us to use large lot sizes?
• The lot size is the amount produced for each machine setup
• A setup uses time on the constraint
• Larger lots cause fewer setups
• To maximize throughput select the lot size as large as possible
• One Remedy: Reduce the setup time

What encourages us to use small lot sizes?
• Small lots reduce cycle time
• WIP is proportional to cycle time
• Reducing cycle time reduces inventory

When can we reduce lot size without reducing throughput?
• When the setup time is small
• When the constraint is outside the manufacturing process (when there are no internal constraints)
• Set the lot size as small as possible while not allowing a non-bottleneck to become a bottleneck
Large Lot, High Inventory Manufacture

- Lot size=1000
- Cycle Time=3.4 mo.
- Time to complete =3.4 mo.
- @720 hrs/mo.
- WIP=1000 units

Small Lot, Low Inventory Manufacture

- Lot size=200
- Cycle Time=0.7 mo.
- Time to complete =1.8 mo.
- @720 hrs/mo.
- WIP=400 units
**Benefits of small lot, low inventory manufacture**

<table>
<thead>
<tr>
<th>Better quality control</th>
<th>Faster response to engineering changes</th>
<th>Better delivery performance</th>
<th>Smaller finished goods inventory</th>
<th>Shorter delivery quotes</th>
<th>Smaller manufacturing investment</th>
</tr>
</thead>
</table>

**Answers to the lot size problem**

- Move constraint outside the manufacturing system
- Reduce the setup times on the internal constraints
- Set the lot size as small as possible while not allowing a non-bottleneck to become a bottleneck

**Advantages of Low-Inventory over High Inventory Manufacturing**

**Low Inventory leads to Low Cycle Time**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Low Throughput Time</th>
<th>High Throughput Time</th>
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<tbody>
<tr>
<td><strong>Quality Control</strong></td>
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<td>An operation near the begin-</td>
<td>Since the operation</td>
<td>Since a long time has</td>
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<td>ning of the process is intro-</td>
<td>was performed not</td>
<td>passed when the</td>
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<td>ducing some defect. The</td>
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<td>defect is finally</td>
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<td>defect is not discovered un-</td>
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<td>till the final inspection.</td>
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<td>corrected more</td>
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<td><strong>Engineering Changes</strong></td>
<td>The change is</td>
<td>The improvement won't</td>
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<td>Engineering has made a</td>
<td>incorporated in the</td>
<td>appear in the product</td>
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<td>modification to correct a</td>
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<td>Many units are</td>
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<td>Not many products</td>
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<td>incorporate the change.</td>
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<tr>
<td><strong>Delivery Performance</strong></td>
<td>Short throughput</td>
<td>Long throughput time</td>
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<td>Salespersons must promise</td>
<td>time allows</td>
<td>requires production</td>
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<td>delivery dates for products.</td>
<td>production starts to</td>
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<td>await firm orders.</td>
<td>projections that are</td>
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<td>Operations are</td>
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<td>more easily</td>
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<td>controlled to meet</td>
<td>in unsold product or</td>
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<td>delivery dates.</td>
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<td><strong>Finished Goods</strong></td>
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<td>Finished goods safety stock</td>
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<td>stocks are low.</td>
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<td><strong>Delivery Quotes</strong></td>
<td>The throughput time</td>
<td>Salespersons must</td>
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<td>A short time to delivery is</td>
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<td><strong>Manufacturing Investment</strong></td>
<td>Production operations</td>
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<td>in part determined by the</td>
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<td>capital investment in</td>
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<td>machines.</td>
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<td>reduced and fewer</td>
<td>Variability requires</td>
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<td>machines are</td>
<td>greater investment</td>
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<td>required.</td>
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</table>
Summary of The Goal

What is the Goal?
What is the combined effect of dependent events and statistical fluctuations?
What is a bottleneck, and how do you find it?
What do we do when management measures tell the wrong story?
What are the advantages of smaller lot sizes?
What Operational Measures Describe the Goal?
How do these measures relate to the goal?
How do the measures relate to decisions made in the plant?
What is a bottleneck, and how do you find it?
How can you increase the capacity of a bottleneck?
What does it cost to have a bottleneck idle?
How can we keep from having the bottleneck idle?
What do we do when bottleneck has moved out of the plant?
What do you think should be the goal?
The Goal

Questions Left by Jonah

What is the Goal?

What Financial Measures Describe the Goal?

What Operational Measures Describe the Goal?

How do these measures relate to the goal?

How do the measures relate to decisions made in the plant?

What is the combined effect in your plant of dependent events and statistical fluctuations?

What is a bottleneck?

What are the Five Steps of the Theory of Constraints

Step 1: Identify the system's constraint(s).
Step 2: Decide how to exploit the system's constraint(s).
Step 3: Subordinate everything else to the decisions made in Step 2.
Step 4: Elevate the system’s constraint(s).
Step 5: If a constraint is broken in Step 4, go back to Step 1. Don't allow inertia to become the system's primary constraint.

What is a bottleneck, and how do you find it?

How can you increase the capacity of a bottleneck?
What does it cost to have a bottleneck idle?

How can we keep from having the bottleneck idle?

Solution: Use Drum, Buffer, Rope to Schedule the system.

Drum, Buffer, Rope

Step 1: Identify the system's constraint(s).
Step 2: Decide how to exploit the system's constraint(s).
- Rank the products that use the constraint by
  \[
  \text{Throughput dollars per unit} = \frac{\text{Throughput dollars per unit}}{\text{constraint minutes used per unit}}
  \]
  Throughput dollars = unit selling price – unit raw material cost.
- Find the optimum product mix by deciding to manufacture the products with the greatest throughput per minute.
- Define the constraint *drum*. Propose a predetermined schedule for the constraint parts on the constraint.
- Identify the "free products" as those having no constraint parts.
- Define the free product *drum*. Schedule lot sizes and delivery times for the free products.
- Define the *rope* for the constraint. The rope is specified by the constraint buffer \((b_c \text{ hours})\). Release raw materials feeding the constraint \(b_c \text{ hours hours}\) before they are needed by the internal constraint.
- Define the *rope* for the free products. The rope is specified by the delivery buffer \((b_d \text{ hours})\). Release raw materials feeding the constraint \(b_d \text{ hours hours}\) before they are needed by the market constraint.
- Define the *rope* for the assembly of constraint parts to nonconstraint parts. The rope is specified by the assembly buffer \((b_a \text{ hours})\). Release raw materials feeding the constraint \(b_a \text{ hours hours}\) before they are needed by assembly.
- Watch the production process and take care of unexpected scheduling problems.
Run simulation 30 for one week. Buy raw materials and control all machines in an attempt to satisfy market demand. At the end of the week, fill in the table below.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Total Utilization</th>
<th>Product</th>
<th>Sales</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td></td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td></td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>Cyan</td>
<td></td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td></td>
<td>F</td>
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</tr>
<tr>
<td>Magenta</td>
<td></td>
<td>Net Profit =</td>
<td></td>
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<tr>
<td>Yellow</td>
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</tr>
</tbody>
</table>
1. The figure below describes the manufacturing process to produce two products P and Q. Each rectangle describes an operation a product must pass through. The time required per unit of product is shown in the rectangle. The machine on which the operation is performed is specified with a letter. Using the information in the figure, answer the questions below.

The figure shows:

- Each operation is associated with a time requirement per unit (e.g., C: 30 min./U).
- Raw Material costs are associated with each product: RM1 $20/U for P, RM2 $20/U for Q.
- Operating Expense not including Raw Material cost is $6000 per week.

What is the optimum quantity of each product that should be produced for the week? What is the profit for this product mix? Show the work that justifies your answer. An answer without the proper justification does not receive full credit.
2. The figure below shows the manufacturing processes, weekly market demands, unit revenues and raw material requirements for two products. The products pass through a series of operations indicated by the circles. The products are manufactured on five machines. The machine assignments are shown by letters within the operation circles. The processing time for each operation is shown in minutes per unit adjacent to the circle. All setup times are zero. Operation E is an assembly operation that combines a unit from each of its two inputs to make the finished product 2.

There are 5000 minutes per week available on each machine type. There is one of each type of machine.

a. Use the theory of constraints to identify the bottlenecks in the system. Show all work used to find the bottleneck.

b. For the bottlenecks discovered find the best product mix. Show in your answer the rational for selecting the product mix.
3. You are a manager of a plant that is constrained by the market. That is, there are no internal machine constraints limiting your production. You have a choice to produce an order in either one lot of 1000 units or ten lots of 100 units each.

a. Explain how and why the choice of lot size affects the level of inventory in the form of WIP (work in process). Does this effect favor large lots or small lots?

b. The operations of the manufacturing process require a setup time for each new lot. How does this consideration affect the choice of lot size? Does it favor small lots or large lots?

c. Explain how and why the lot size affects the cash flow for the plant. Does this effect favor large lots or small lots?

4. You are a consultant trying to convince potential customers of the value of the Theory of Constraints for managing their company. Each case below is the comment of a production manager to your sales pitch. Make up short statements to counter the arguments.

a. "My production facility has no constraints. The current production meets the demand and all the manufacturing departments have slack time. The theory of constraints is irrelevant for my situation."

b. "We could sell more product if we had more capacity in the final inspection department. Each part must pass through an automatic inspection machine. Because the machine is so expensive, we can't afford another. We used to use human inspectors, but the cost of the machine per unit of product inspected is much lower than the cost of human inspectors. The per unit cost of the parts increase if we use human inspectors."

c. "Our problem is not bottlenecks. We don't have any. Our problem is the time it takes to get products through the system. Although it only takes 2 hours to manufacture the product, a given order takes three weeks to make it through the plant. By the time the product is ready for delivery, the customer may not want it any more or may want to change the order."

d. "We don't need the Theory of Constraints any more. We used to be your customer when we went through a period of hard times. Things are better now and we're making a decent profit. Top management is putting us through a cost reduction campaign to improve profitability. Our problem now is to keep our efficiency numbers up so we don't have to fire any more workers."

e. "We're into Quality now. Our goal is to produce quality products, whatever the cost. Our final inspection is so good that we test for every possible defect. We throw away or rework 30% of the units we produce. That's how dedicated we are. Our customers are responding too. We could sell a lot more if we had more manufacturing capacity."