Chapter 5. Batching and Other Flow Interruptions: Setup Times and the EOQ Model

Buying Custom Shirts: The Demand Size

Custom shirts ordered online

Large variety of styles

Basically infinitely many sizes

Four weeks lead time

Custom Tailored Shirts: The Supply Side



Cutting Department

Draw a shirt pattern on a large paper. Fabric is overlaid in layers according to the number of orders. Then, the large patterned paper is laid on top of the fabric and the fabric is cut according to the pattern.

Sewing Department

Sewing Section – Cut pieces of fabric are sewn together and inspected

Assembly Section - Responsible for assembling shirts and measuring the size.

Finishing Department

Responsible for ironing shirts before folding, packaging and delivery to customers.

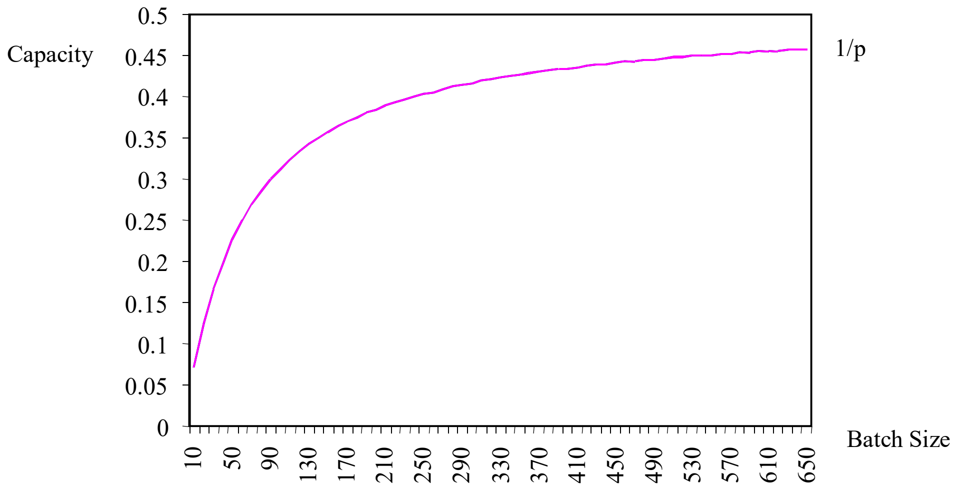
Source: http://hosting.thailand.com/MWT00255/process1.htm

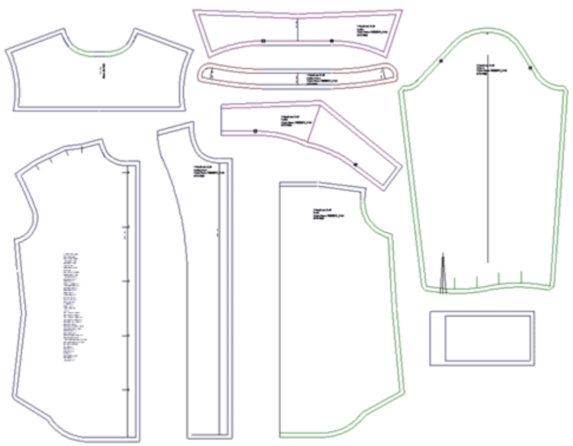
Process Analysis with Batching

• Capacity calculation for the resource with set-up changes:

$$\text{Capacity given Batch Size} = \frac{\textit{Batch Size}}{\textit{Set-up time} + \textit{Batch-size*Time per unit}}$$

• Capacity increases with batch size:



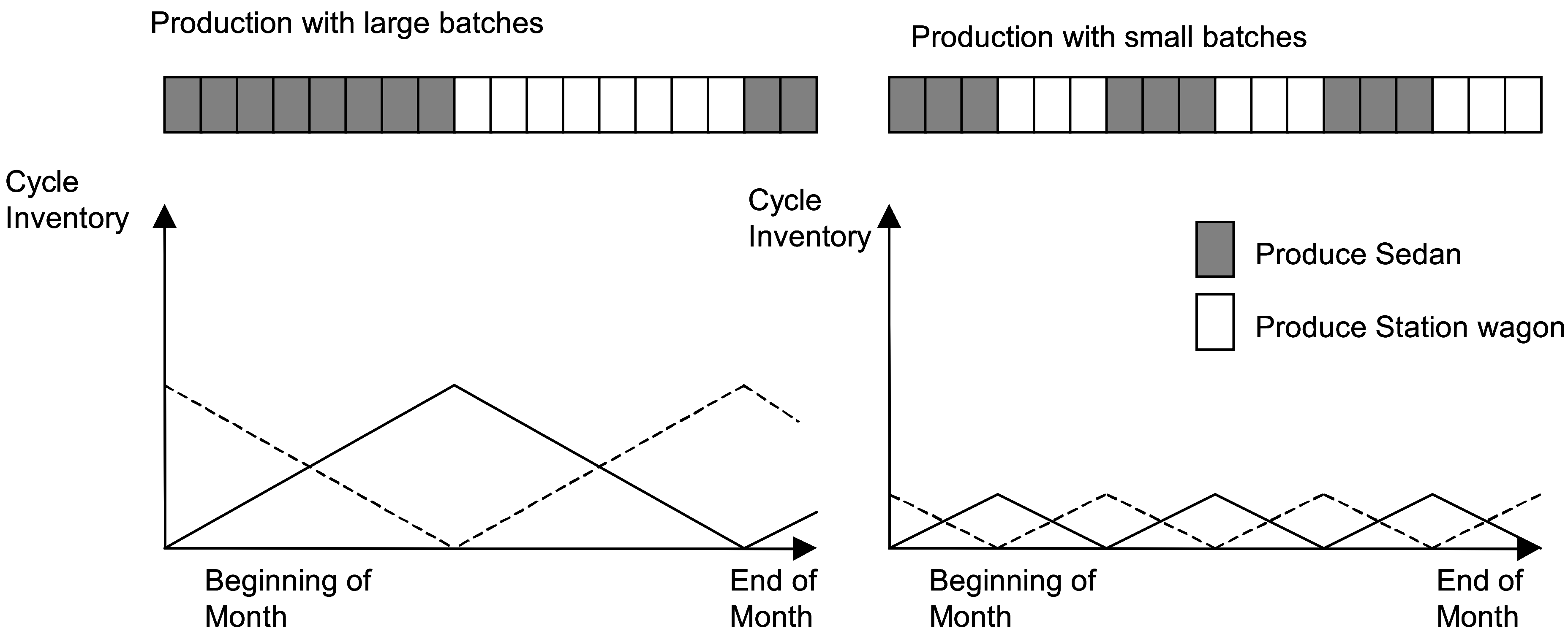


Example: Cutting Machine for shirts

20 minute cutting time (irrespective of the number of shirts)

4 minute/unit preparation time

The Downside of Large Batches (Figure 5.4)

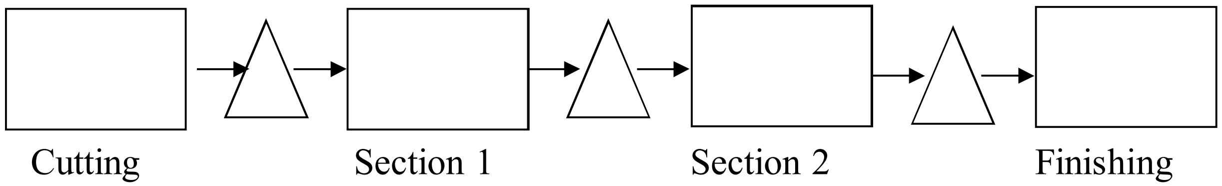


- Large batch sizes lead to more inventory in the process
- This needs to be balanced with the need for capacity
- Implication: look at where in the process the set-up occurs

If set-up occurs at non-bottleneck ⇒ decrease the batch size

If set-up occurs at the bottleneck ⇒ increase the batch size

Example Calculations



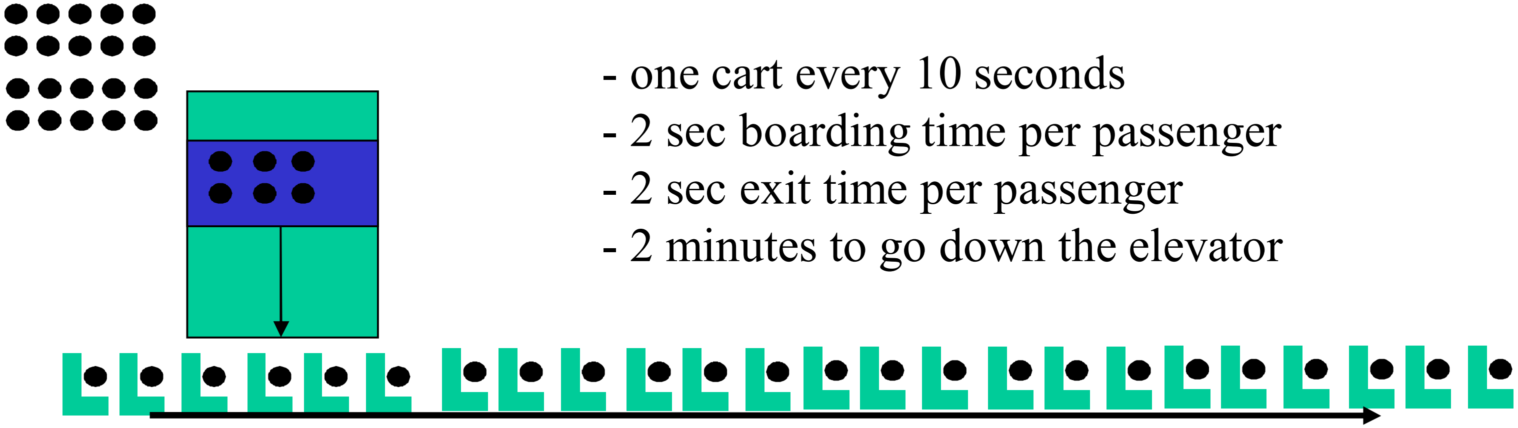
	Cutting	Section 1	Section 2	Finishing
Set-up time:	20 minutes	-	-	-
Activity time:	4 min/unit	40 min/unit	30 min/unit	3 min/unit
Resources:	1 Cutting machine	8 workers	5 workers	1 worker

What is the capacity of the cutting machine with a batch size of 15? ? unit/min

What is the capacity of the overall process?

How would you set the batch size?

How to Set the Batch Size – An Intuitive Example



- one cart every 10 seconds
- 2 sec boarding time per passenger
- 2 sec exit time per passenger
- 2 minutes to go down the elevator

$$\text{Capacity given Batch Size} = \frac{\textit{Batch Size}}{\textit{120sec + Batch-size*4sec}}$$

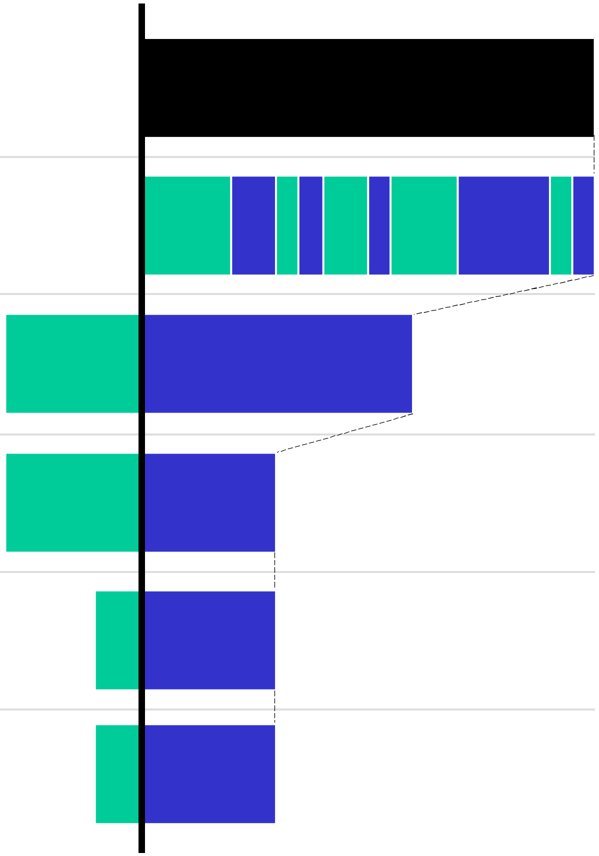
$$1/10\ [\text{units/sec}] = \frac{\textit{Batch Size}}{\textit{120sec + Batch-size*4sec}}$$

$$\text{Batch Size} = 20\ \text{units}$$

The 6-stage SMED approach (by Shingo)

▪External
▪Internal

Stage	Before/after shutdown	During shutdown
1 Measure total changeover time		
2 Determine internal and external activities		
3 Move external activities to before or after the shutdown		
4 Improve the internal activities		
5 Improve the external activities		
6 Standardize procedures		



Reduce set-up so that you can change models as often as needed
⇒ Mixed model production (Heijunka)

Source: McKinsey Ops Training Material

Process Analysis with Batching

• Equate the capacity of the step with setup with the capacity of the step from the remaining process that has the smallest capacity!

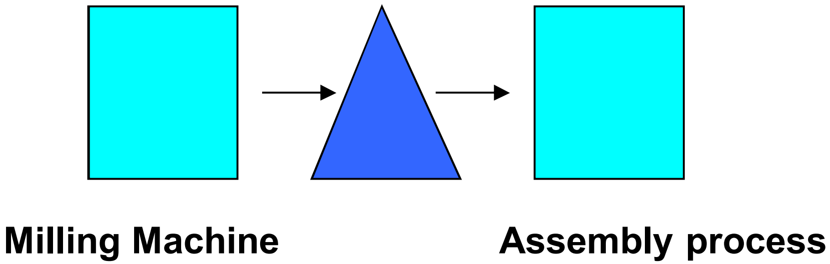
$$\text{Capacity given Batch Size (C)} = \frac{\text{Batch Size (B)}}{\text{Set-up time (S)} + \text{Batch-size (B)*Time per unit (p)}}$$

Flow Rate (F)

$F = B/(S+Bp) \Rightarrow B = FS/(1-FP)$

$$\text{Recommended Batch Size (B)} = \frac{\text{Flow Rate (F) * Setup Time (S)}}{\text{1- Flow Rate (F) *Time per unit (p)}}$$

Process Analysis with Batching



	Setup time	Activity time
Milling	120	2
Assembly	0	3

Capacity (B=12) Milling: 0.0833unit/min (bottleneck)
Assembly: 0.33unit/min

Capacity (B=300) Milling: 0.4166unit/min
Assembly: 0.33unit/min (bottleneck)

Recommended Batch Size?
(0.333*120)/(1-0.333*2)=120units!

Inventory and product variety - two soups

- Consider a process that makes two kinds of soup:

	Chicken	Tomato
Demand (gal/hr)	100	75
Setup time (hr)	0.5	0.5
Production rate (gal/hr)	300	300

- Define the flow unit to be 1 gallon of soup.
- Assume we iterate between chicken and tomato production.
- Define the batch to be the total quantity (in gallons) of chicken and tomato soup.
- What batch size minimizes inventory?

Two soup analysis

- Our target capacity (or flow rate) is 100 + 75 = 175 gal/hour
- Each batch involves producing Chicken and Tomato soup, so the total setup time is 2 x 0.5 = 1 hour per batch
- Processing time = 1/300 hours/gal
- So the recommended batch size is 420 gals

$$Batch\ size = \frac{Capacity \times Setup\ time}{1 - Capacity \times Processing\ time} = \frac{175 \times (2 \times 0.5)}{1 - 175 \times 1/300} = 420$$

- Produce in proportion to demand:
  - Chicken = (100 / 175) x 420 = 240 gals
  - Tomato = (75 / 175) x 420 = 180 gals

Three soups dividing demand

- Now suppose one kind of soup is added but total demand stays the same:

	Chicken	Tomato	Onion
Demand (gal/hr)	80	65	30
Setup time (hr)	0.5	0.5	0.5
Production rate (gal/hr)	300	300	300

- Suppose we produce chicken, tomato, onion and then repeat.
- Define the batch to be the total quantity (in gallons) of chicken, tomato and onion soup.
- What batch size minimizes inventory?

Three soups dividing demand - analysis

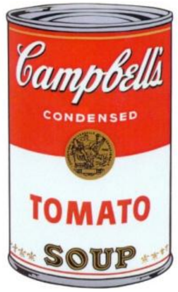
- Our target capacity (or flow rate) is 80 + 65 + 30 = 175 gal/hour
- Each batch involves producing Chicken, Tomato and Onion soup, so the total setup time is 3 x 0.5 = 1.5 hours per batch
- Processing time = 1/300 hours/gal
- **The recommended batch size increases by 50% to 630 gals!**

$$Batch\ size = \frac{Capacity \times Setup\ time}{1 - Capacity \times Processing\ time} = \frac{175 \times (3 \times 0.5)}{1 - 175 \times 1/300} = 630$$

- Produce in proportion to demand:
  - Chicken = (80 / 175) x 630 = 288 gals
  - Tomato = (65 / 175) x 630 = 234 gals
  - Onion = (30 / 175) x 630 = 108 gals

Three soups expanding demand

- Now suppose one kind of soup is added and demand for the others remains the same:



	Chicken	Tomato	Onion
Demand (gal/hr)	100	75	50
Setup time (hr)	0.5	0.5	0.5
Production rate (gal/hr)	300	300	300

- A batch is still a set of chicken, tomato and onion.

- What batch size minimizes inventory?

Three soups expanding demand

- Our desired capacity (or flow rate) is 100 + 75 + 50 = 225 gal/hour
- Each batch involves producing Chicken, Tomato and Onion soup, so the total setup time is 3 x 0.5 = 1.5 hours per batch
- Processing time = 1/300 hours/gal
- **So the recommended batch size increases by 221% to 1350 gals!**

$$Batch\ size = \frac{Capacity \times Setup\ time}{1 - Capacity \times Processing\ time} = \frac{225 \times (3 \times 0.5)}{1 - 225 \times 1/300} = 1350$$

- Produce in proportion to demand:
  - Chicken = (100 / 225) x 1350 = 600 gals
  - Tomato = (75 / 225) x 1350 = 450 gals
  - Onion = (50 / 225) x 1350 = 300 gals

Henry Ford’s famous proclamation

Customers can have any color they want, as long as it is black.

Process Analysis with Batching: Summary

- Batching is common in low volume / high variety operations
- Capacity calculation changes:

$$\text{Capacity given Batch Size} = \frac{\textit{Batch Size}}{\textit{Set-up time + Batch-size*Time per unit}}$$

- This reflects economies of scale (similar to fixed cost and variable cost)
- You improve the process by:

Setting the batch size:
(a) If set-up occurs at the bottleneck ⇒ Increase the batch size
(b) If set-up occurs at a non-bottleneck ⇒ Reduce the batch size
(c) Find the right batch size by solving equation

Reducing set-up times:
(a) SMED method separates between internal and external set-ups
(b) Do external set-ups off-line, i.e., while the process is still running
⇒ enables mixed model production (Heijunka:平準化)

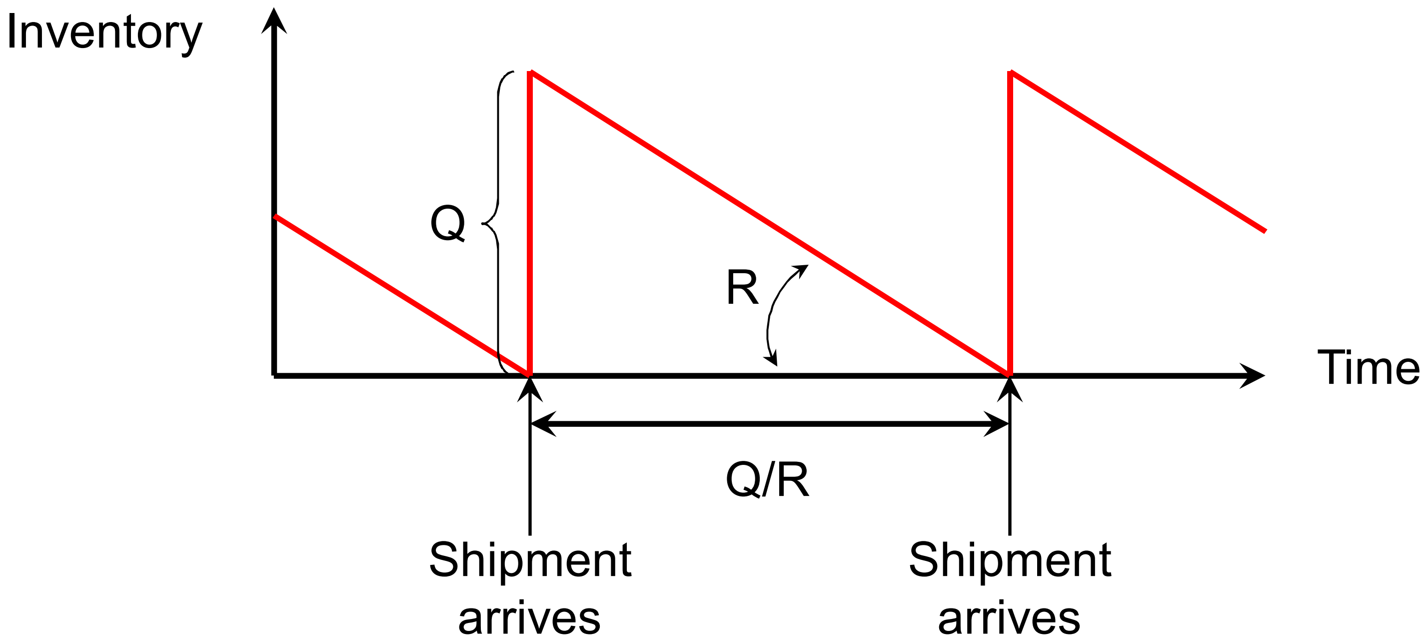
Set-up time reduction is also powerful in other settings, such as OR's or airplanes

Ordering handle caps for the Xootr

- Data:
  - $0.85 = cost to Nova Cruz to purchase each handle cap from its supplier in Taiwan.
  - $300 = customs fee for each shipment, independent of the amount ordered.
  - 700 = demand for handle caps per week.
    - Note, each "handle cap" is actually a pair, so one is needed per Xootr.
  - 40% = Nova Cruz's annual inventory holding cost rate.

- Question:
  - How many handle caps should they order each time they order from their supplier?

The inventory "saw-tooth" pattern



- Assume we can adjust the time when the shipments arrive so that they arrive when we have zero inventory (Zero Switch Rule).
- *Q* = Quantity in each order (what we need to choose)
- *R* = Flow Rate of demand (700 per week)
- *Q* / *R* = Time between shipments

Costs

- Purchase costs:
  - \$0.85 per unit x 700 per week = \$595 per week
  - Q cannot influence our weekly purchase cost!

- h = Inventory holding cost per unit time:
  - 40% annual holding cost, so …
  - 0.4 x \$0.85 = \$0.34 = cost to hold a unit for one year…
  - h = \$0.34 / 52 = \$0.006538 = cost to hold a unit for one week.
  - Average inventory = $Q / 2$
  - Average inventory cost per unit time = $h \times Q / 2$

- K = Setup cost:
  - This is the cost per order and it is independent of the amount ordered.
  - K = \$300
  - Q / R = time between orders, so …
  - Setup cost per unit time = $K / (Q / R)$

Objective and solution

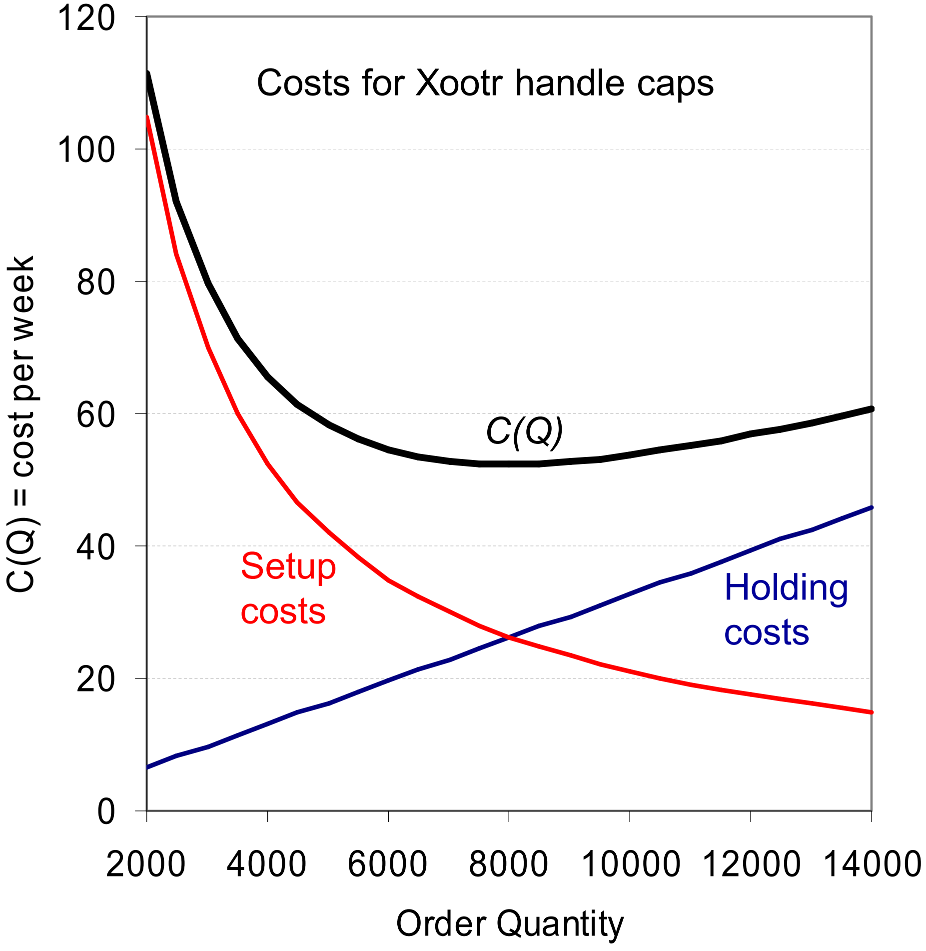
- Objective:
  - Choose Q to minimize the average (setup and holding) cost per unit time, *C(Q)*:

$$C(Q) = \frac{K \times R}{Q} + \frac{1}{2} h \times Q$$

- Solution:
  - Order the Economic Order Quantity (EOQ) = *Q**

$$Q^* = \sqrt{\frac{2 \times K \times R}{h(=ic)}}$$

$$= \sqrt{\frac{2 \times 300 \times 700}{0.006538}} = 8015$$



EOQ and economies of scale

- Setup and inventory holding costs per unit:

$$\frac{C(Q^*)}{R} = \sqrt{\frac{2 \times K \times h}{R}}$$

- Per unit costs decrease in the demand volume for an item:

Flow Rate, *R* (units / week)	EOQ, *Q**	Per-unit ordering and inventory cost, *C(Q*) / R* ($ / unit)	Ordering and Inventory Costs as a % of Total Procurement Costs
300	5247	0.11	13.5%
500	6774	0.09	10.4%
700	8015	0.07	8.8%
900	9088	0.07	7.8%
1100	10047	0.06	7.0%

Two different shopping experiences

Save money. Live better.

Costco vs. Walmart

	Costco	Walmart
Sales ($m)	70,977	374,526
Gross Margin/Sales	10.5%	23.5%
Net Income/Sales	1.8%	3.4%
Inventory turns	12.6	8.1
Number of SKUs per store	4,000	60,000
Sales per SKU ($m)	17.7	6.2
Sales per employee ($)	518,080	178,346
Sales per store ($m)	138.6	52.8

- Costco must be hyper efficient with restocking shelves because it has a much smaller margin. (소품종 박리다매형 소매점)
- Consequently, Costco has much less variety, and much higher volume per stock keeping unit (SKU)

Quantity discount for handle caps

- Should Xootr purchase 10,000 units per order if this gets them a 5% discount from the supplier?
- Use the equation for costs: $\text{TC}(Q) = C(Q) + cR = \frac{K \times R}{Q} + \frac{1}{2} ic \times Q + cR$

	Original EOQ	EOQ with 5% discount	5% discount with large Q	5% discount with very large Q
R	700	700	700	700
K	300	300	300	300
Purchase cost per unit	0.85	0.8075	0.8075	0.8075
h	0.006538	0.006212	0.006212	0.006212
Q	8,015	8,223	10,000	23,000
C(Q) (per week)	52.40	51.08	52.06	80.56
Purchase cost per week	595.00	565.25	565.25	565.25
Total cost per week	647.40	616.33	617.31	645.81

- Xootr should be willing to buy even 23,000 units to get the 5% discount?

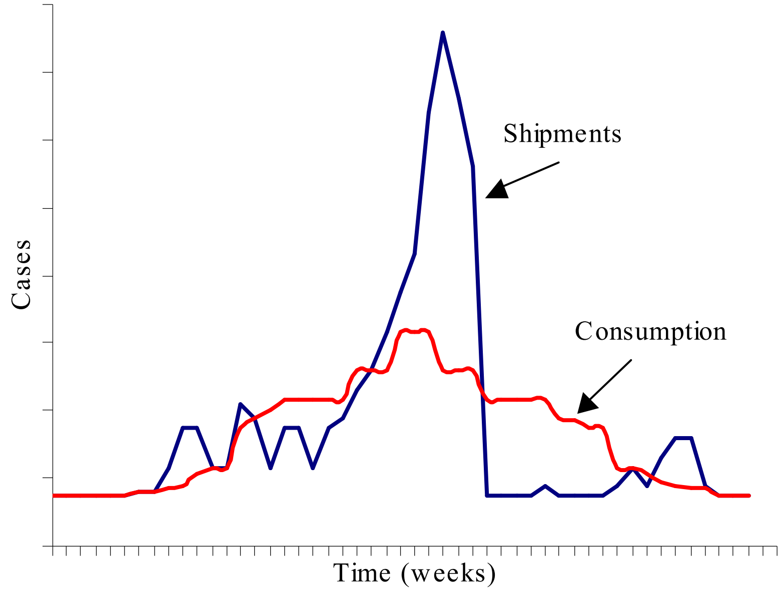
  $\Rightarrow$ We need a systematic algorithm to solve the discounted EOQ problem!

Trade promotions and forward buying

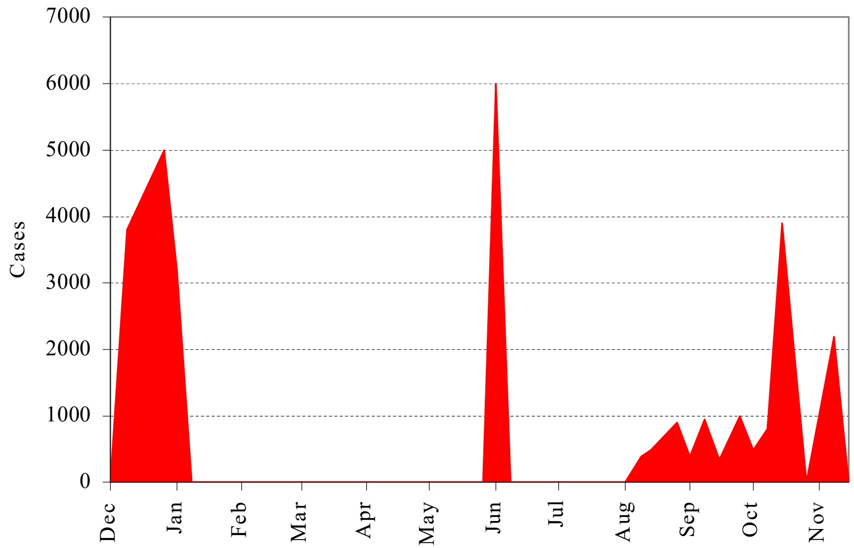
- Supplier gives retailer a temporary discount, called a trade promotion.
- Trade promotions are typically in the 2-8% range.
- Retailer purchases enough to satisfy demand until the next trade promotion.

- Example: Campbell's Chicken Noodle Soup over a one year period:

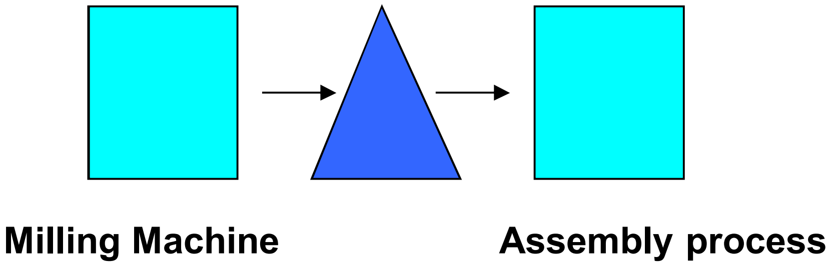
Total shipments and consumption



One retailer's buy



Converting setup times to setup costs

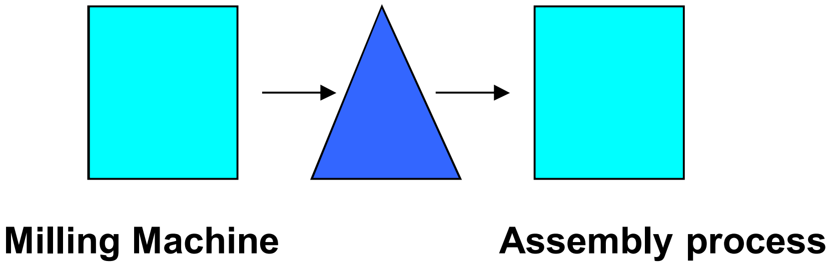


	Setup time	Activity time
Milling	120	2
Assembly	0	3

- Suppose the milling machine cost $9000 per month and Nova Cruz operates 35 hours per week, 4.33 weeks per month.
  - This translates into about $59 per hour = 9000 / (4.33 x 35)

- Suppose 1 component set (a steering support and 2 ribs) costs $10:
  - The annual holding cost rate is 40%.
  - The holding cost per hour of a component set is about 0.002198 per hour = 0.4 x $10 / (52 x 35)

Converting setup times to setup costs



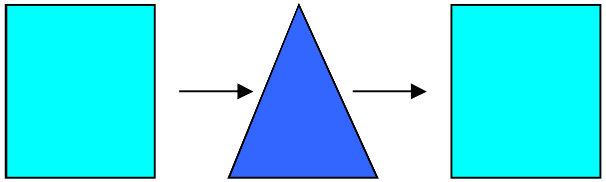
	Setup time	Activity time
Milling	120	2
Assembly	0	3

- If you apply EOQ:
  - R = 700units/week= 20units/hour, K = 2hr x \$59/hour = \$118, h = \$0.002198/unit, hour
  - Q* = sqrt(2 x K x R / h) = 1465units

- Milling machine's capacity with the EOQ batch size is 0.48 unit/min = 1465 / (120 + 2 x 1465)

- But the milling machine only needs to operate with a batch size of 120 to match Assembly's capacity of 0.33 unit/min

Converting setup times to setup costs



Milling Machine **Assembly process**

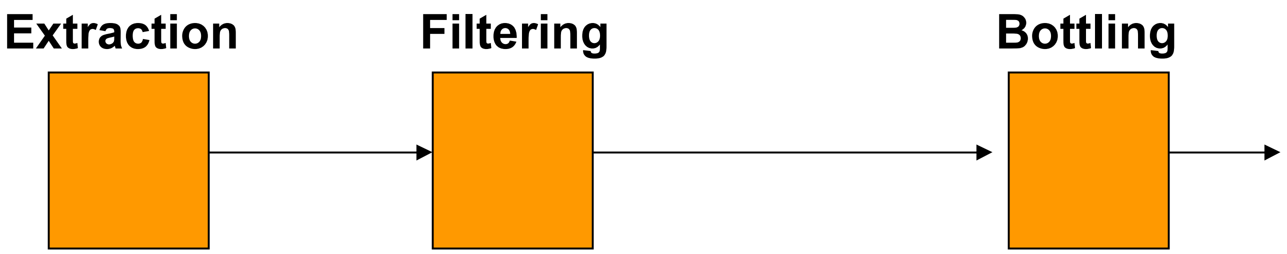
	Setup time	Activity time
Milling	120	2
Assembly	0	3

- The EOQ batch size is much larger than necessary, which creates more inventory than needed.
- The EOQ doesn't work in this setting because the setup cost is a sunk cost – Nova Cruz incurs $9000 per month whether they operate the milling machine or not.
- With the setup cost sunk, the objective should be to minimize inventory without constraining the process flow, which is a batch size of 120.

Buffer or Suffer

Blocking and Starving

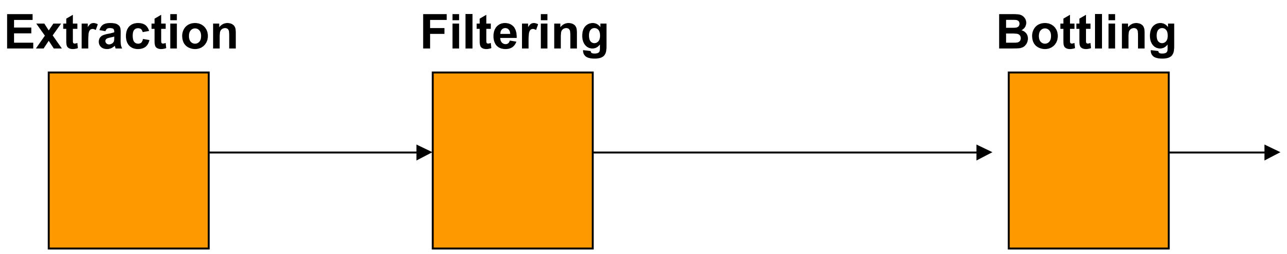
Orange juice production



	Extraction	Filtering	Bottling
Setup time	0	30 min	0
Max flow rate (barrels/hr)	80	100	120
Capacity (barrels/hr)	80	88.9	120

- No inventory is allowed between the tasks (i.e., no buffers)
- After **4 hours** of production Filtering must shut down for 30 mins before production can resume (for another 4 hours followed, etc.)
- The above capacities assume each step can work in isolation:
  - e.g., Filtering capacity = 4 x 100 / (0.5 + 4) = 88.9 barrels/hr.

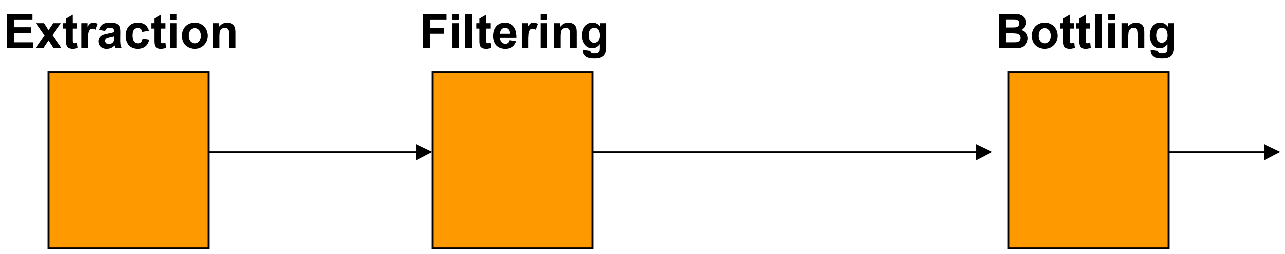
Where's the bottleneck?



Setup time	0	30 min	0
Max flow rate (barrels/hr)	80	100	120
Capacity (barrels/hr)	80	88.9	120

- It looks like Extraction is the bottleneck (because it has the lowest capacity) and the maximum flow rate through the process is 80 barrels/hr.
- But Extraction must also shut down for the 30 minutes when Filtering is idle because there is no place to put its output!

Process interruption - blocking



	Extraction	Filtering	Bottling
Setup time	0	30 min	0
Max flow rate (barrels/hr)	80	100	120
Capacity (barrels/hr)	80	88.9	120

- The process produces 4 x 80 = 320 barrels every 4.5 hours, so its capacity is 320 / 4.5 = 71 barrels per hour!
- If inventory were allowed between Extraction and Filtering, the process would produce 80 barrels per hour (Extraction would always be working).
- ⇒ In the presence of flow interruptions, buffers can increase process capacity. (Buffer or Suffer!)
- Lesson: add inventory to the process so that you don't "block" the bottleneck.

Summary

- Setup costs provide a motivation to batch – the EOQ formula gives the optimal batch size.
  - Be very cautious when converting a setup time to a setup cost.
  - Very large orders can be justified by seemingly small price discounts.

- If there are setup times, then capacity depends on the production schedule:
  - Capacity increases as the batch size gets larger.
  - Inventory increases as the batch size gets larger.
  - Utilization may increase as the batch size gets larger.
  - There is a tradeoff between capacity and inventory.

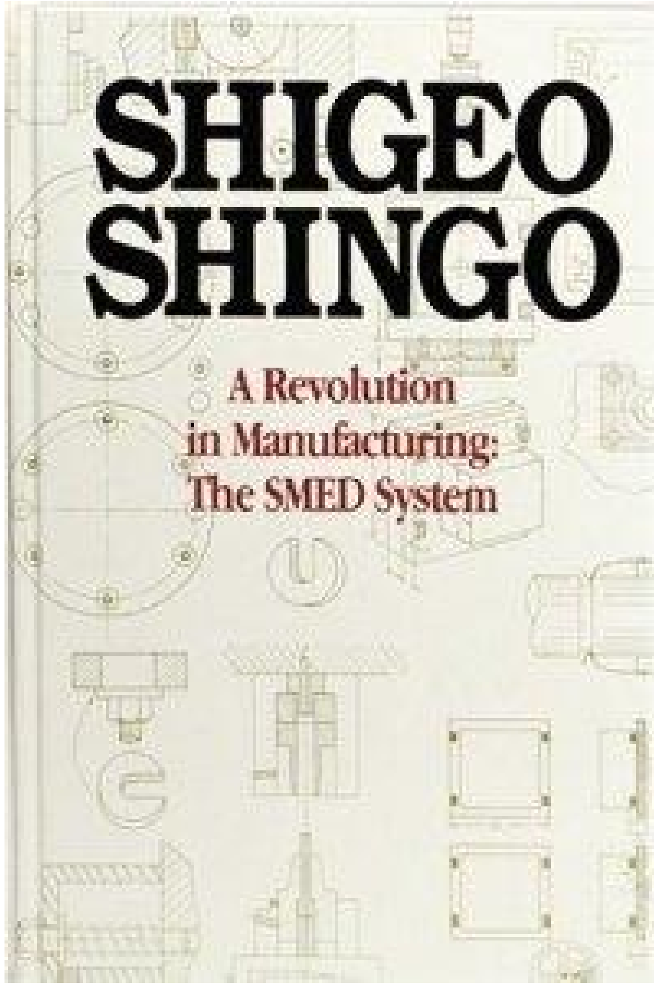
- Long setup times are not compatible with large product variety.

- Buffer or Suffer:
  - Setup times may cause process interruptions in other resources – use buffer inventory to decouple their production.

- ***Shingo Prize*** is the highest manufacturing excellence award in the U.S. The prize is given both to companies and individuals who contribute to the development of manufacturing excellence.

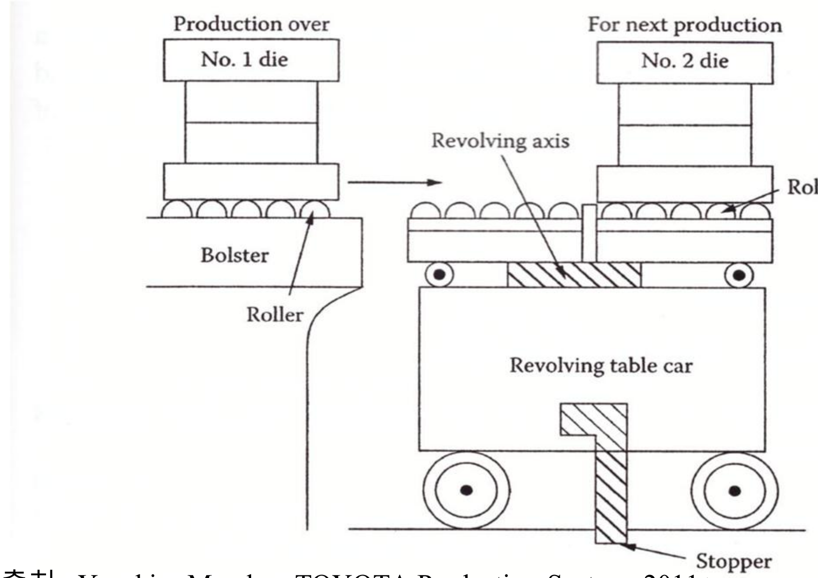
THE SHINGO PRIZE

for OPERATIONAL EXCELLENCE™


SHIGEO
SHINGO
A Revolution
in Manufacturing:
The SMED System

- 준비작업시간 단축의 예제

  ✓ Stamping 기계의 다이(die)를 교체하기 위해, 회전테이블 대차를 활용



<출처 : Yasuhiro Monden, TOYOTA Production System, 2011 >

- 준비작업시간 단축의 예제

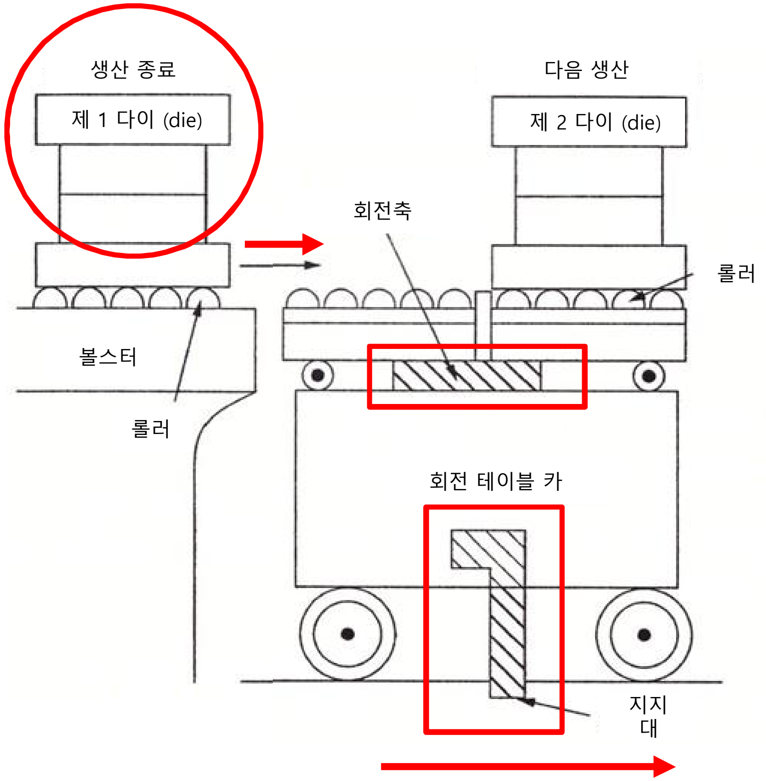
1. 홀더에서 1번 다이 분리

2. 회전 테이블 대차를 설비에 붙이고, 스토퍼로 고정

3. 1번 다이를 회전 테이블 대차에 옮김

4. 2번 다이를 회전축과 롤러를 이용해 볼스터로 옮김

5. 스토퍼를 분리하고, 회전 테이블 대차를 설비에서 때어내고, 2번 다이를 설치



<출처 : Yasuhiro Monden, TOYOTA Production System, 2011 >

생산 평활화

생산 평활화

- **예시를 통한 로트 생산과 혼류 생산의 비교**